博士論文

STUDY ON MAINTENANCE MANAGEMENT AND RELIABILITY IN DISTRIBUTED ENERGY RESOURCE SYSTEM

分散型エネルギーシステムにおける維持管理と信頼性に関する研究

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STUDY ON MAINTENANCE MANAGEMENT AND RELIABILITY IN DISTRIBUTED ENERGY RESOURCE SYSTEM

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Preface

This thesis research was performed at the Department of Architecture, the University of Kitakyushu. This thesis presents a study on the maintenance management and reliability analysis of the Distributed Energy Resource (DER) system which has been applied for decades to solve the world energy utilization problem. This study has investigated on the DER system in the Kitakyushu Science and Research Park in Japan, the new maintenance prioritization indices are proposed in this research. Meanwhile, a design method of DER system for improving the system reliability is proposed and assessed.

Acknowledgements

This work could not have been completed without the support, guidance, and help of many people and institutions, for providing data and insights, for which I am very grateful.

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Abstract

Distributed energy resource system (DERs), which with a high utilization efficiency of energy and low environmental load, has been recognized by the society. The DER system has been developed and applied for decades, and the application of the DER system still has a growing trend. However, the DER system is a complex and repairable system with the power generation, energy conversion and energy management. Thus, the DER system may contain a lot of components, and to meet a variety of functions.

Maintenance management and reliability are the key factors of an equipment or a system to make the equipment or system complete the function within a production period. Each component has a different mode of operation and maintenance. If the maintenance management resources are insufficient or the maintenance strategy is unreasonable, it may cause equipment or system failure and loss; if the maintenance management resources are excessive, it can result the waste of cost. Therefore, this research focus on the maintenance management and reliability analysis of DER system. For the maintenance management, we are committed to finding an assessment method of maintenance priority to identify the weak components in the system. According to the assessment result to allocate maintenance management resources, it can help the managers make the reasonable maintenance strategy, and reduce the maintenance cost. For the reliability analysis, a reliability analysis was applied to the DER system, and a reliability design model is evaluated.

In chapter one, the development situation and technologies are reviewed, in addition, the maintenance and reliability of the DER system and the related technologies are reviewed, and the purpose of this research is proposed.

In chapter two, the reliability concepts, reliability analysis methods, maintenance analysis theories and methods are reviewed. The failure tree analysis (FTA) method, failure mode and effect analysis (FMEA) method and failure mode, effect and criticality analysis (FMECA) method are compared and analyzed. In addition, a Markov process with the state-space method is introduced. The maintenance prioritization analysis and optimization approach are reviewed and presented.

In chapter three, the maintenance management situation of the DER system in KSRP is investigated

and analyzed as the case study from five points, maintenance management strategy, operation status, replacement and failure, maintenance cost, effect analysis of maintenance on generation efficiency.

In chapter four, the maintenance strategy of the DER system in KSRP is analyzed and optimized. The main power generation units of the DER system in KSRP include the fuel cell and gas engine. Each power generators have related equipment, absorption chiller, heat exchanger, cooling tower, cooling pump, etc. The failure modes, failure cause and failure effect of components are investigated; and the Severity (S), occurrence (O), and detection (D) factors are evaluated. Then the maintenance strategy is optimized for improving the maintenance, and reduces the risk priority number (RPN). This result can give the reference for component maintenance optimization.

In chapter five, aims at selecting the component reliability importance indices to identify the priority of component maintenance of a DER system from the perspective of maintenance cost. Failure cost importance index (FCI) and Potential failure cost importance index (PI) are developed for the maintenance prioritization analysis of a DER system. A Markov model based on the state–space method (SSM) is used to analyze the reliability and availability of a DER system. A set of actual survey reliability data of DER systems is used to support the validity of the reliability importance indices. The results indicate that the FCI and PI might lead to different rankings of maintenance prioritization. The FCI and PI will help managers make a reasonable decision for maintenance on a cost basis.

In chapter six, the redundant design of the devices is adopted to a DER system. The k-out-of-n model is performed to calculate the reliability indices of the unit with redundant design; the reliability analysis of the whole DER system is presented. The unscheduled maintenance cost and down time cost due to the failure occurred is analyzed in the total cost analysis of the DER system. The results present that the redundant design can reduce the total cost and improve the availability of a DER system within a certain capacity. The most effect parameters for total cost of non-redundant DER system is the failure rate and mean repair cost of the device. This result can provide reference for the design of the DER system.

In chapter seven, the whole summary of each chapter has been presented.

Keywords: DER system, Maintenance management, Reliability, Availability, FMEA.

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Chapter 1. Previous Study and Purpose of This Study

1.1. Introduction

The basic aim of sustainable growth is energy. The current challenge is to offer sustainable energy solutions to entirely is increasing the energy and improving usage efficiency. Traditional power plants convert about 30% of the fossil fuel's available energy into electricity, and the majority of fuel energy content is lost at the power generation facility thorough waste heat. Modern economic systems depend on reliable electricity and low-cost delivery. At the same time, the need to address climate change is driving a dramatic transformation in the global power system.

Distributed energy resource system (DERs), which with a high utilization efficiency of energy and low environmental load, has been recognized by the society. A DER system is designed for the power generation of electrical power and used for an independent power generation grid or as an auxiliary power system. The DER system can provide the electricity, heating and cooling by using the different sub-system and technologies. Through the heat recovery technologies can provide the cooling of the waste heat to improve the primary energy usage efficiency. For a DER system, composed of power generation system, heat recuperation system, heat storage system, and heating system and cooling scheme. The power generation devices such as photovoltaic (PV), gas engine, fuel cell, wind turbines or other fossil fuel generators. In the development of the technology, more and more distributed energy system can be used for a small-scale, to provide the cooling, heating and electricity; such as a campus of university, office buildings, airport, hospital, hotel, and so on.

The DER system has been built up and applied for decades, a lot of application programs on the DER system are closed to the design life of the DER system. As indicated in the above presentation, there is a lot a device or components in a DER system. Thus, a DER system is a complex system which can meet multiple functions. When a device or component is failed, the whole system or a sub-system will be failed. The energy supply or a part of the function will be interrupted. Therefore, one of the main purposes of DER system utilization is to ensure the reliability and availability of components in DER system and keep components in good (or working) state. However, most previous studies are focused on the optimization and analysis of the DER system to reduce the total lifecycle cost; few articles discuss the reliability and availability of DER systems. Thus, in this research, the reliability, maintenance, management of the DER system are investigated and studied, in order to improve the availability and the system maintenance economics of DER system.

Maintenance, replacement and reliability are the key factors of an equipment or a system to make the equipment or system complete the function within a function or production period. For a DER system, the operation and maintenance (O&M) are the main actives during the lifecycle of a system. The total cost of operation and maintenance of equipment is about half of the total cost of a building [1]; and for an offshore wind system, the O&M cost account for approximately 30% of the total lifecycle cost [2]. However, maintenance is the key for the energy supply safety and system reliability. Generally, the maintenance is divided into two categories; one is the preventive maintenance (PM), another one is corrective maintenance (CM) [3]. Replacement is a main way to recover the function of the component or system; the replacement can be performed on the repair, preventive maintenance, overhaul maintenance and redesign of the system and so on. The purpose of maintenance and replacement is to improve the reliability of component and system, to reduce the operation and maintenance cost, to make the system more safety and efficiency.

Reliability is defined as the ability of an item to perform a required function under given conditions for a stated period [4]. There are some reliability indices can be used to evaluate the system's reliability and availability, for instance, failure rate, repair rate, mean time to failure (MTTF), mean time to repair (MTTR), mean time between failure (MTBF) etc. Estimating system reliability is an important and challenging for system engineers, designers and managers. It is important because that the system reliability relates to the company's reputation, system design costs, customer satisfaction and operational safety [5]. This is also a challenge because current estimation techniques require familiarity with the system and a high level of reliability analysis knowledge. Generally, reliability analysis needs a lot of experimental data and operational data. However, for a complex and repairable system, it is difficult to get a lot of operational data, it is a main challenging for system reliability.

DER system is a complex, maintainable, repairable and a long lifecycle system, a reasonable maintenance and replacement strategy can improve the system reliability and reduce the total lifecycle cost. Meanwhile, the experience of reliability may help to the engineers, designers and managers to operate or design a better new system.

This research reviewed the present situation of the development status and challenges of reliability, maintenance and replacement of the DER system. in addition, this research investigated the maintenance and reliability of a DER system which has been applied from 2000 in Kitakyushu Science and Research Park (KSRP), Kitakyushu City, Japan. The experience data is used to analyze the maintenance strategy, cost, system design based on reliability data. And a reliability and maintenance prioritization analysis were developed for the maintenance of DER system, it gives the guides for the complex system with different kinds of components.

In this chapter, the development status of DER system is reviewed, especially, the maintenance, replacement and reliability of DER system or the relate with DER system (power generator, or some equipment which can be used in the system) are reviewed. The purposes of this research are proposed in this chapter. A research flow is presented.

1.2. DER System

1.2.1. Background of DER System

Distributed energy resource (DER) system is defined as an energy system in which the power generation units are located close to the energy consumers [6], meanwhile, multiple technologies are combined and complement each other. A main advantage of DER is that different energy sources can be integrated together to better meet the needs of consumers, to supply the clean, reliable and affordable energy [7]. In different countries, the definition of DER system is different, for instance, the definition in China is "the DER system is an energy system that intelligently combines distributed energy resources close to the consumer side, increases the reliability and economy of energy services, and reduces environmental impact" [7]. The broader definition also includes other resources linked to the distribution network, such as combined heat and power (CHP) system or combined cooling heating and power (CCHP) system. As for the specific forms of distributed energy, it includes: natural gas distributed energy connected to the distribution network or located near the load center, distributed renewable energy and distributed energy storage, demand side response, energy efficiency technology and so on.

The DER system was developed for the following reasons. First, the DER system is an important part of electricity supply and power generation; it can be as the standby system for a building or region, such as hospital, campus, office building or others. Second, the DER system is derived by energy diversity and the utilization of localization energy, for instance, using hydrogen from steel mills as an energy source in Kitakyushu Smart Community which is located in Higashida area, Kitakyushu City, Japan [8]; or combine with the heating supply or cooling supply to improve the primary energy efficiency. In addition, in some remote areas with low population density, the cost of establishing long-distance transmission and distribution infrastructure is too high, and distributed energy is the most economical choice Finally, in regions where self-sufficiency is permitted, large energy users use distributed generation for price hedging (instead of distributed generation when system prices are high). In addition, in response to air pollution, climate change and energy security, countries are increasing their renewable energy targets, often contributing to the increase in distributed energy installations.

Many countries are promoting the development of DER system. China plans to build 15 GW (gigawatts) of distributed cogeneration of natural gas by 2020 [9]. Japan plans to add 16.9 GW of cogeneration capacity by 2030 [10]. Therefore, the government policy is a main way to drive the development of DER system. Another way to drive the development of DER system is the development of technologies, especially the renewable development to make the system more diversified and more environmentally friendly. In recent years, renewable energy has been vigorously promoted and developed. Fig.1-1 shows the electricity generation by the different technology of the world; and it shows a possible energy trend model for the future. The results show that the share of traditional fossil fuels such as carbon and oil in the power generation industry will remain unchanged or gradually decrease. The proportion of natural gas for the electricity generation will increase for in the coming decades. The use of nuclear energy in power generation will develop steadily. But solar PV and wind which used in the electricity generation will increase and get a big boost.

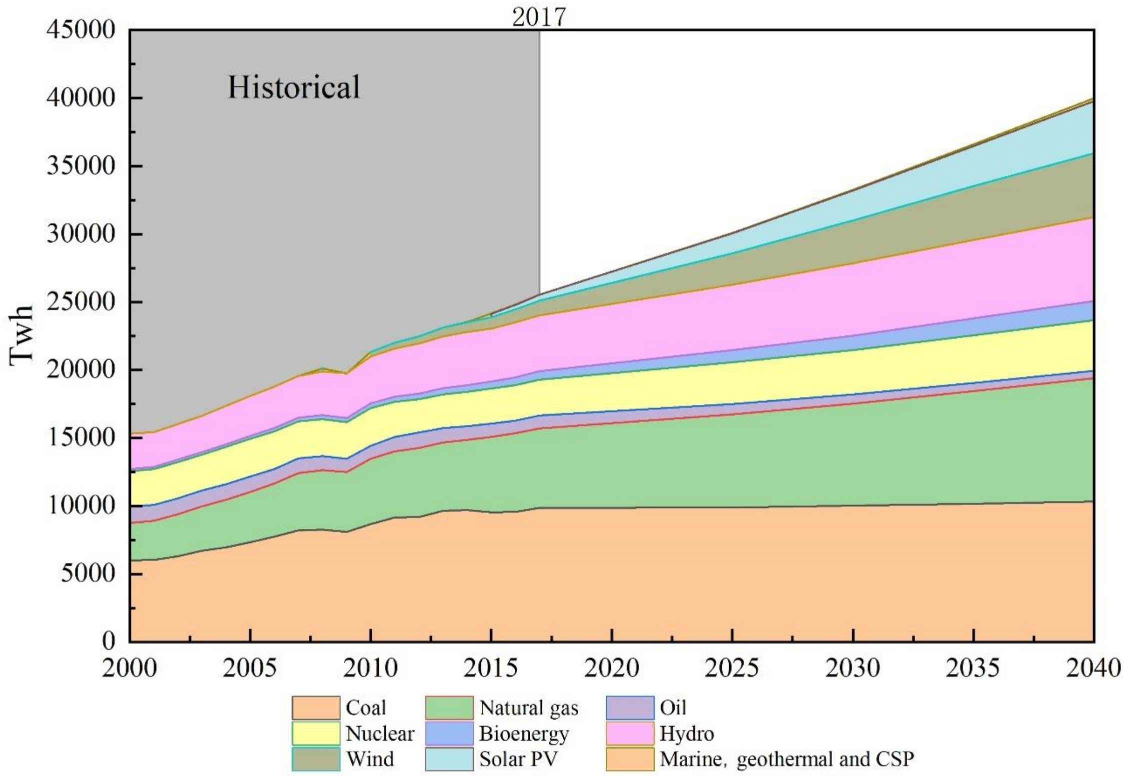

Fig.1-1 The electricity generation by the different technology of the world
(Resource: IEA data, World Energy Outlook 2018 [11])

The solar and wind electricity generation is regarded as an important party in hybrid distributed energy resource (HDER) system. The photovoltaic (PV) and wind farms (WFs) can constitute a part of the power generation of HDER system, to meet the peak demand or storage the produced electricity to energy storage system for future utilization [12, 13]. Therefore, the development and application of solar PV and wind can promote the development of DER system. The PV and wind electricity generation in some countries in 2016 and a predictive value in 2022 is shown in Fig.1-2. Fig.1-2 shows that only a few countries' electricity generation by the PV and wind is more than 10%, but the additional PV and wind share in 2022 present a good increasing of the two energy. Table 1-1 shows the Top five countries/regions for renewable capacity additions by technology in 2016. The electricity technologies include solar PV, onshore wind, Hydro-power, Bio-energy, Offshore wind, Geothermal, concentrating solar power (CSP) and Ocean. China is the largest market of the renewable energy, especially on the solar PV, wind energy and bio-energy.

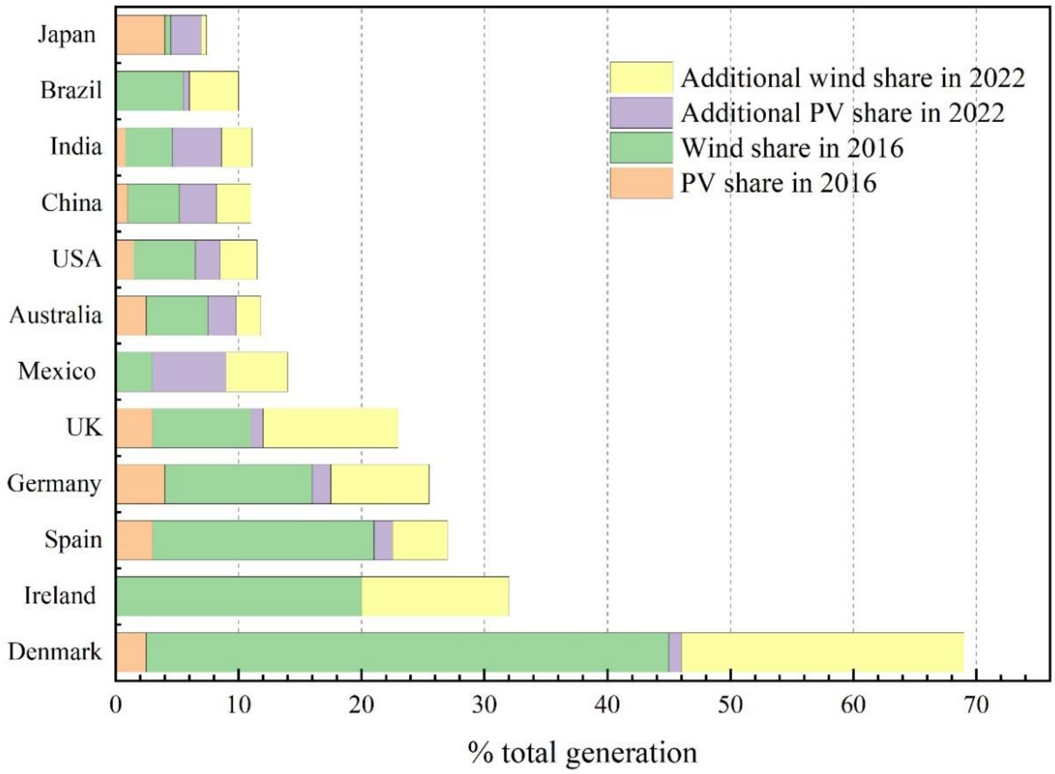

Fig.1-2 The PV and wind electricity generation in some countries in 2016 and a predictive value in 2022

(Source: RENEWABLES 2017 [14]. 2016 generation data for OECD countries based on IEA (2017b), World Energy Statisticsand Balances 2017, www.iea.org/statistics/)

Note: The shares represent variable renewable electricity generation as a percentage of total electricity output, not of total electricity consumption. In countries with high shares of variable generation, such as Denmark, generation and consumption differences may be large as a result of electricity trading.

Table 1-1 Top five countries/regions for renewable capacity additions by technology in 2016

Solar PV	**GW**	**Onshore wind**	**GW**	**Hydro-power**	**GW**	**Bio-energy**	**GW**
China	34.2	China	18.7	China	12.6	China	1.8
United States	14.8	United States	8.2	Brazil	5.3	Brazil	0.9
Japan	7.9	Germany	4.3	Ecuador	1.8	Denmark	0.6
India	4.0	India	3.6	Ethiopia	1.7	India	0.4
United Kingdom	2.4	Brazil	2.5	Peru	1.1	Japan	0.3
Offshore wind	**MW**	**Geo-thermal**	**MW**	**CSP**	**MW**	**Ocean**	**MW**
Germany	813	Turkey	197	Morocco	160	Canada	1.6
Netherlands	691	Indonesia	99	South Africa	100	France	1.0
China	592	Guatemaia	15	Australia	3	Norway	0.3
Viet Nam	83	Kenya	10	United States	2	Korea	0.2
United Kingdom	56	Nicaragua	10	France	2	China	0.2

Source: RENEWABLES 2017 [14]

The world energy development direction and the national energy policies of countries have provided the policy, safeguard for the development of distributed energy resource; With the development and application of new technology and new energy, it provides a technical guarantee for the development of distributed energy. So why is distributed energy acceptable to organizations and customers? Compared with the conventional energy supply system, the DER system has several advantages [15].

1) Close to the consumer side and variable capacity

As the general definition of the DER system, the system is close to the consumer side or the energy resources. That is the electricity come form rather than another region or city, the resources located in the business, the hospitals, college campuses or the communities which near the them serve. The distributed energy sits at different position on the grid. Maybe it not at the center of the electricity supply system, but it can at any position that the customers need. The capacity of power generation devices can be changed according to the demand of the customers or other needed.

2) Conserve energy

Distributed energy system is considered to be an effective energy saving system. First of all, renewable energy can be widely used in distributed energy system to reduce the dependence on traditional fossil energy. Secondly, equipment such as combined heating and power (CHP) can be used to improve the efficiency of primary energy. Third, because the system is sited close to the customer and other characteristics can reduce energy waste in the transport process to save energy.

3) Maximize clean energy

In the context of increasing energy demand and global warming emissions, it has become the consensus of global energy consumption that the emission of greenhouse gases should be controlled and reduced. To reduce the use of fossil energy, improve energy efficiency and increase the use of renewable energy is an important issue in today's world energy applications. Distributed energy system makes it possible to apply renewable energy to the greatest extent and is also one of the main ways to apply new energy.

4) Manage price

Distributed energy system is considered as one of the effective controls means to adjust peak power consumption and reduce grid load. Power can be stored during peak hours through storage or other technologies, released during peak hours or replenished to balance the grid with power generation equipment. It can choose effective price combination for the user.

5) Improve reliability and sell to the grid

Distributed energy system or microgrid system can effectively improve the reliability of the power grid. And another contribution is to improve the energy resilience. The difference between energy reliability and energy resilience is that energy reliability refers to the ability to prevent system interruption, while energy resilience refers to the ability of the system to recover from an interruption. Distributed energy systems can have the ability to sell excess power to the grid or to provide the electricity to the grid in an emergency.

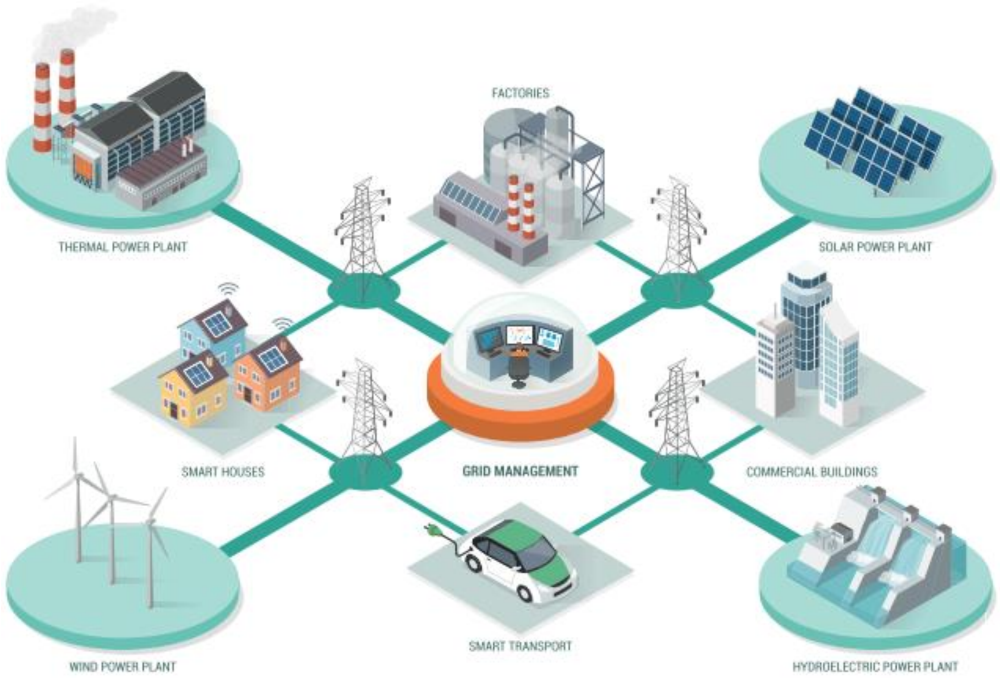

Fig.1-3 The micro-grid of DER system
(Source: The Evolution of Distributed Energy Resources, 2018 [15])

Distributed energy can control the energy supply according to the energy demand of consumer. Locally energy resources can be combined to control and manage multiple energy resources through an integrated management system. With the development of science and technology, smart grid system has been developed and applied [16]. Fig.1-3 shows a micro-grid of DER system which integrates multiple energy sources. The figure shows that the hydroelectrical power plant, thermal power plant, wind power plant, solar power plant and PV on the smart house are combined by the gird management system. A balance between the power generation and energy demand will be built for a better and reasonable system.

With the increasing demand for energy and the expectation of environmentally friendly social development, DER systems are likely to be greatly developed under the impetus of technological innovation. DER systems will also play an important role in the diverse use of energy and the establishment of smart communities. In fact, the global installation capacity of DER systems is constantly increasing. A report of the Navigant Research proposed that the DER system will be a core role for the future deployment of energy infrastructure which is refer to the technology advances, business model innovation, changing regulations, and sustainability and resilience concerns [17]. Although sometimes controversial, distributed energy systems have had a significant impact on the popularity of the power industry. According to the report from the Navigant Research that the global DER investment capacity is expected to grow from 132.4 GW in 2017 to the 528.4 GW in 2026 (Fig.1-4).

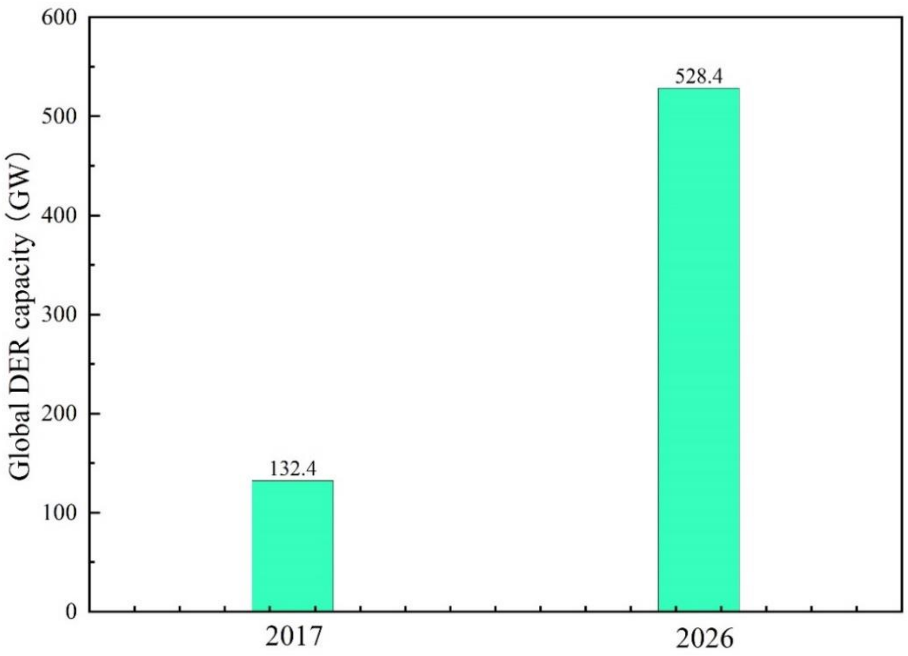

Fig.1-4 The Capacity forecasting for DER system

(Source: NAVIGANT RESEARCH [17])

1.2.2. Technologies of DER System

As described above, the DER system is a complex and repairable system. The application of distributed energy system improves the reliability of power supply system. But a complex system has high reliability problems. The complexity of DER system is mainly reflected in the following points. 1) Multiple energy resources input and multiple energy output is a reason of the complex, for instance, the input resources can include fossil energy (oil, coal, natural gas, etc.), hydrogen (H_2), biomass, solar energy, wind energy and so on; the multiple energy output may include the electricity, heating (for space heating, hot water and so on) and cooling. That may the DER system is more complex than the conventional power plant only uses one resource for power generation, or the thermal plant only uses one resource for the thermal generation. 2) The DER system may consist of multiple devices and components. For instance, the power generation can adopt a variety of devices, like gas engine, gas turbine, fuel cell, reciprocating engine and so on; if the system should meet the heating and cooling demand, the heart recovery devices, absorption chiller, adsorption chiller, electrical chiller, solar thermal, geothermal thermal gas engine and so on; in order to overcome the fluctuation of energy supply, the power system must have certain energy storage capacity, the storage device can classify to electrical storage device and thermal storage device. In addition to the power generation device, thermal generation, thermal convention and energy storage devices, some auxiliary devices and components also constitute the complexity of system, like DC-DC converter, DC-AC converter, pump, fans, pipe, wire and so on. Mudathir Funsho Akorede et al. [18] presented a block diagram of the main technologies of DER system is shown in Fig.1-5.

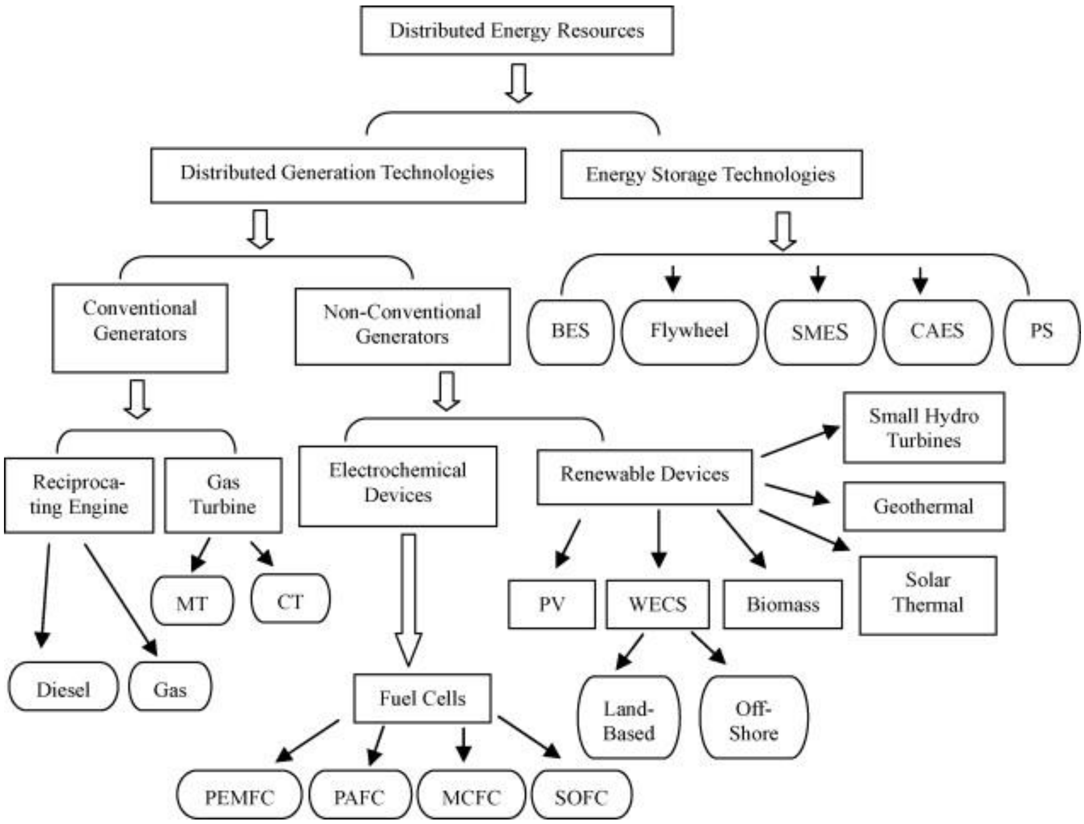

Fig.1-5 The main technologies of DER system [18]

(*Notes: MT: Micro-turbines; CT: Combustion turbines; WECS: Wind energy conversion system; BESS: Battery energy storage system; SMES: Superconducting magnetic energy storage; CAES: Compressed air energy storage; PS: Pumped storage; PEMFC: proton exchange membrane fuel cell; AFC: alkaline fuel cell; PAFC: phosphoric acid fuel cell; SOFC: solid oxide fuel cell; MCFC: molten carbonate fuel cell*)

A representative scheme of the DER system is shown in Fig.1-6. In this figure, the input energy includes solar energy, natural gas and the fossil energy, the output energy includes electricity, hot water, space heating and space cooling. In order to meet the energy demand, the combined heating and power (CHP), gas-fired boiler, PV, solar thermal, absorption chiller, air-source heat pump electrical storage, thermal storage can be adopted in the DER system. therefore, the DER system is a complex energy system which is connected by many kinds of equipment.

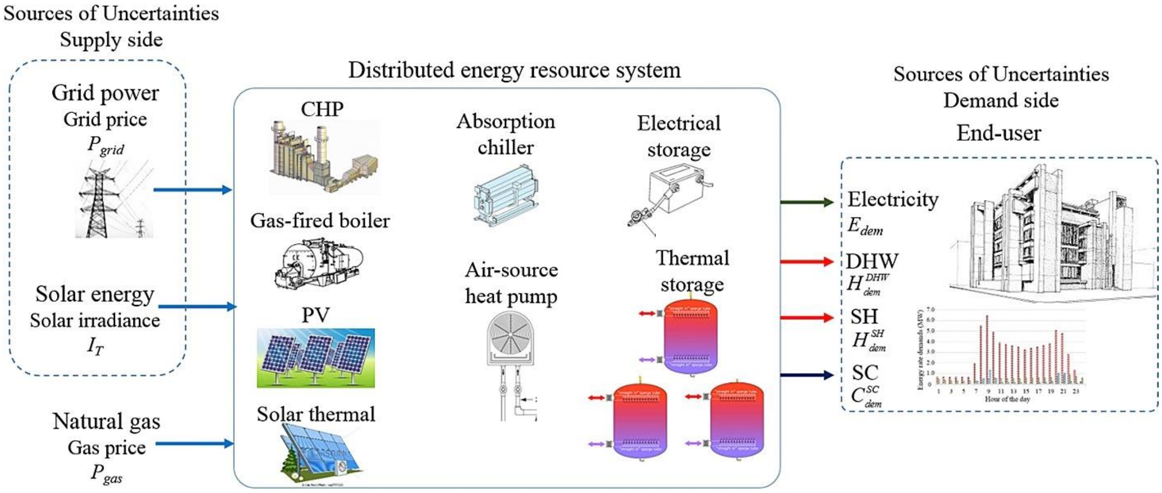

Fig.1-6 Representative scheme of the DER system [19]

The reliability of the whole system will be affected by the reliability of equipment and the number of equipment and components. A complex system also make maintenance more difficult. Thus, in this paper, the device of DER system is investigated, the main components are introduced. The devices were classified into power generation device, thermal generation device, storage device.

1.2.2.1. Power generation device

According to the different energy source and capacity requirement, the DER system will adopt difference power generation device. The combined heating and power (CHP) and combined cooling, heating and power (CCHP) system are the main ways to applied the DER system [20], many power generation devices can be used in the system, in addition, the renewable power generation devices can be adopted in the system. The investigation of power generation devices in this research include fuel cell (FC), gas turbines (GT), reciprocating engines, Stirling engine, gas engine, PV, and wind turbine.

1.Fuel cell (FC)

Fuel cell is power generation system which convert chemical energy from a fuel into the electricity through a chemical reaction with oxygen or other oxidizing agents [20, 21]. The power generation efficiency of fuel cell is about 40%, and when the system is adopted was heat recovery for the thermal supply, the total primary energy efficiency is approximately 80%. In [22], the maximum efficiency of 83% for energy trigeneration and heat recovery cycle can be achieved. Generally, the fuel cell uses the hydrogen and oxygen to generate electricity, it is seen as a clean source of energy, because only by-products such as water are produced in the process of producing electricity. However, it is difficult to consume a lot of energy in the process of making hydrogen. At present, many applications of hydrogen production technology are through electrolytic water or natural gas to produce hydrogen. New energy applications such as solar and wind energy can be used in the electrolytic hydrogen industry. Here exist various types of fuel cells, i.e., proton exchange membrane fuel cell (PEMFC), alkaline fuel cell (AFC), phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC) and the previously mentioned SOFC. The fuel cell is a complex system, fuel cell power plants contain a variety of functional units and many components. The main functional units include power section system (PSS), fuel processing system (FPS), air processing system (APS), thermal management system (TMS), water treatment system (WTS), nitrogen purge system (NPS), and cabinet ventilation system (CVS). Fig.1-7 is a system block diagram of fuel cell power plant. The Fig.1-6 shows that the main components include hydrogen tank, hydrogen circulation pump, motor, compressor, cooler, humidifier hydrogen, fuel cell stack, radiator and coolant pump, coolant flow loop, water tank, water separator and so on. It is only a case for the fuel cell system, equipment will vary with fuel and capacity.

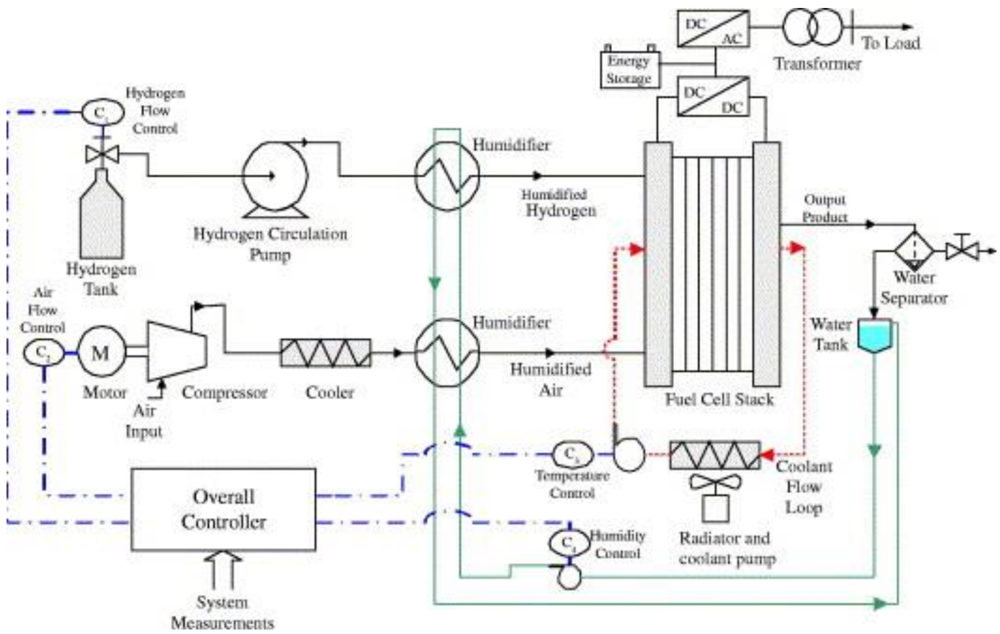

Fig.1-7 System block diagram of fuel cell power plant [23]

2.Gas turbines (GT)

The gas turbine is an engine which use the gas as the fuel and perform the oxidizer in a combustion chamber [24, 25]. The gas turbine has been applied for the power generation devices in a long history, maybe since 1930s. generally, the capacity size of GT ranges from 500kW to 250M, that means the GT can be used for large-scale cogeneration system. The power generation efficiency of a simple-cycle operation gas turbine can reach about 40% [26], the primary energy efficiency of gas turbine can be reach 70%-80% when the gas turbine is used into a CHP system [20]. In addition, the gas turbine has the high-quality exhaust, that means GT is better applied for the huge thermal demand DER system. Because of the fuel of the system is natural gas, therefore, it has a good function to reduce the greenhouse gas (GHG) emissions when compared with other liquid or solid fuel-fired prime movers.

The Fig.1-8 shows a block diagram of gas turbine electric power generation. The figure shows that the main components in the gas turbine electric power generation system include fuel valve, compressor, combustion chamber, gas turbine, reduction gear and synchronous generator.

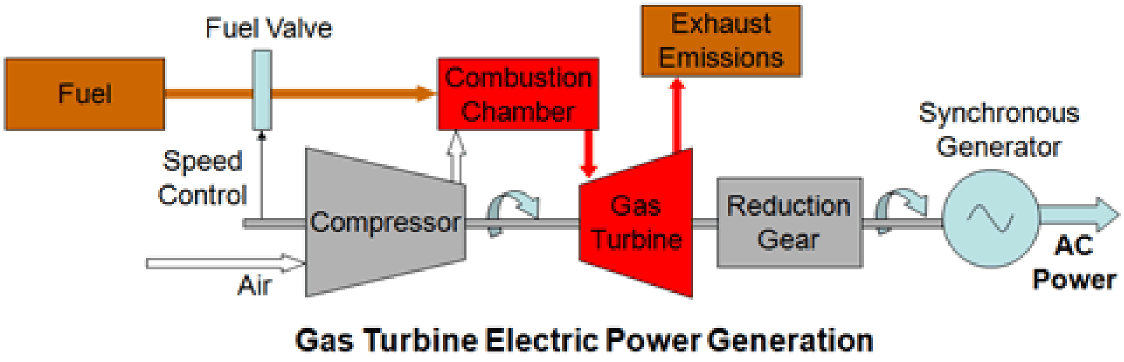

Fig.1-8 A block diagram of gas turbine electric power generation

(Source: Woodbank Communications Ltd homepage [27])

3.Reciprocating engine

The reciprocating engine is a subset of the internal combustion engine, which is the engine of the piston moving back and forth in the cylinder. Smaller models are basically designed for transport, although they can be converted by minor modifications to the generator, while larger models are designed primarily for power generation, mechanical drive and ocean propulsion [28]. There are two types of the reciprocating engines, one is the spark ignition, which can be driven the engine by the natural gas, propane, gasolines or landfill gas; another type is compress ignition, which can be driven by the diesel fuel or heavy oil. The advantage of reciprocating engine that it not so expensive and low capital cost compared with other power generators. But it regular more attention for the operation and maintenance. When the reciprocating engine use the diesel fuel or heavy oil as the fuel, it not good for the environment. The capacity size of the reciprocating engines can range from 10 kW to over 5 MW. It is better used for the small or middle size distributed generation system, can be applied to the CCHP system in the industry or other thermal requirement facilities. Reciprocating engine has a high value of waste heat recovery, through the exhaust heat of exhaust gas, jacket water waste heat, lube oil waste heat and cooling water waste heat utilization. Therefore, it is better to work with the absorption chiller to meet the thermal demand (for space cooling, heating or hot water).

A block diagram of reciprocating engine system is shown in Fig.1-9. The main components of the reciprocating engine include the air turbocharger, ignition source, exhaust value, intake value, piston, crankshaft, generator. When the reciprocating engine is combined with absorption chiller for the thermal demand, is should add the heat recovery or heat exchanger devices (exhaust gas heat exchanger, jacket water heat exchanger, lube oil heat exchanger and cooling water system).

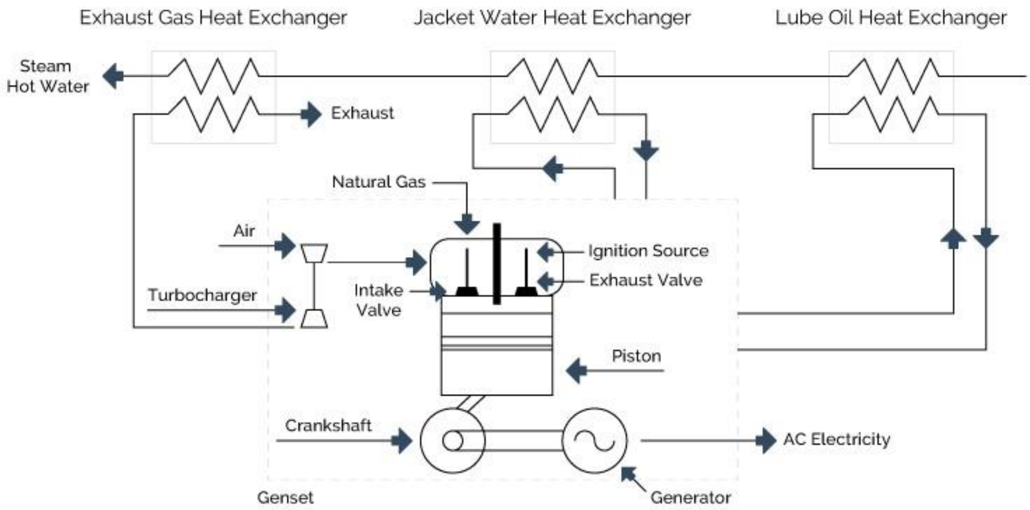

Fig.1- 9 A block diagram of reciprocating engine system
(Source: Energy Solutions Center webpage [29])

4.Stirling engine

The Stirling engine is an external combustion engine. There are two main categories of sterling engines: the kinematic Stirling engine and the free-piston Stirling engine. In addition, the engine can be divided into three configurations: Alpha type, Beta type and Gamma type [20]. Sterling engines can use almost all fuels, such as diesel, gasoline, natural gas or solar energy. Sterling Engine is continuously controllable in the process of operation, and the amount of greenhouse gas produced lower, pollution emission is small. Generally, the capacity size of Stirling engine is more than 100kW. According to the above introduction, the Stirling engine has the following advantages. 1) Less moving parts; 2) Lower noise; 3) Safer and more silent; 4) Flexible fuel; 5) Long service time; 6) Can be solar driven; 7) Operate quietly. However, there are some challenges for the Stirling engine when applied it into a DER system. Compared with the reciprocating engine, the power output of Stirling engine is lower. And for the same capacity of Stirling engine or reciprocating engine or other engines, the capital cost of Stirling engine is very high. That means that when sterling engines are used as power generation units for distributed energy systems, the economic benefits of wanting to go will be more stringent for other requirements, such as electricity prices, fuel prices, and so on.

A Stirling engine system is shown in Fig.1-10. The internal components and control system are presented in this figure. The components of Stirling engine include burner, engine, exhaust heat exchanger, alternator.

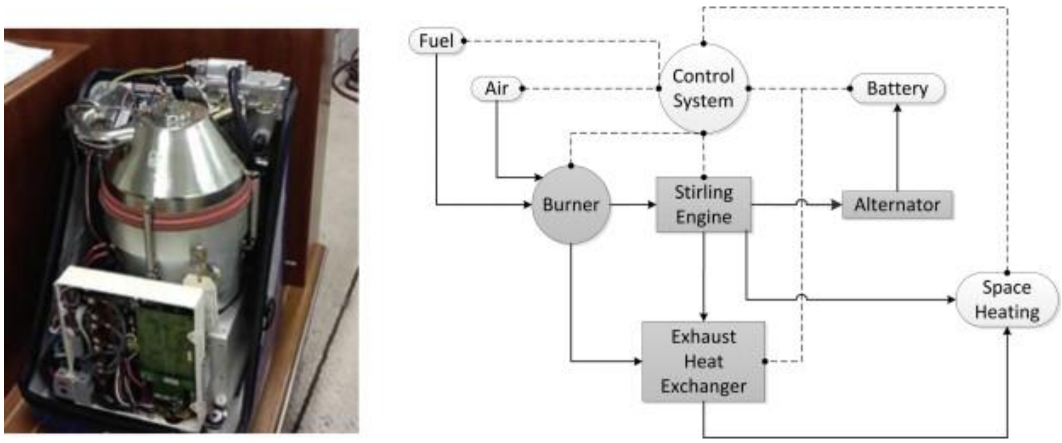

Fig.1-10 Internal components and control system of Stirling engine [30]

5.Gas engine

The gas engine has a high-power generation efficiency, an indicative value of efficiency of a gas engine is 38% [31] power generation efficiency and a 40% heat recovery efficiency when the equipment is applied in the CHP system with the heat recovery requirement. Although gas engines are commonly used as engines for cars, ships, aircraft, etc., they are also commonly used in power generation systems. For instance, a gas engine is applied in a DER system at the Kitakyushu Science and Research park [32]. The more details of gas engine will introduce in the chapter 3 and 4, the investigation of the DER system in Kitakyushu Science and Research Park.

6.Photovoltaic (PV)

Photovoltaic solar panels are made of a few separate battery packs, which are connected in series or in parallel to convert light radiation into electrical energy. Photovoltaic technology can be independent or connected to the grid. The output power of the photovoltaic panel is proportional to the surface area and floor space of the battery. Solar panels are divided into several categories. It is usually divided into monocrystalline silicon solar panels and polysilicon solar panels. Comparing the two types, monocrystalline silicon solar cells have higher power generation efficiencies and flexible arrangement, while polysilicon solar cell panel layout needs to be determined according to the solar radiation angle and the power generation efficiency is low. From a cost point of view, the price of monocrystalline silicon solar panels is higher than the price of polysilicon solar panels. The power generation of PV is greatly affected by the weather and belongs to the unstable generating device. Therefore, it is usually necessary to use the energy storage device at the same time, can balance the power grid electricity. PV can effectively utilize solar energy, the cleanest and most environmentally friendly energy source. A Photovoltaic (PV) system is presented in Fig.1-10. The main components of PV system include solar panel, charge controller, Battery Bank and inverter. The PV has the high capital cost, but with the technology development the capital cost may be reduced.

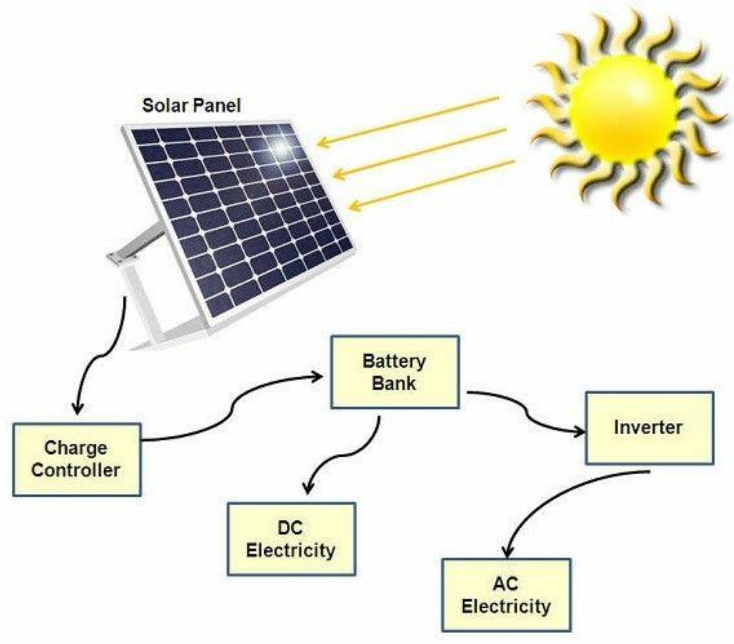

Fig.1-11 Photovoltaic (PV) system

(Source: The homepage of Yuyao Ollin Photovoltaic Technology Co., Ltd. [33])

7. Wind turbine

At present, wind energy is considered to be the most competitive of all renewable energy technologies. Wind turbines convert the kinetic energy of flowing air into electricity. Wind power systems are usually divided into offshore wind power systems and onshore wind power systems. Wind turbines are arranged in a relatively wide range of areas, covering a large area, in the maintenance and maintenance of equipment need to get more attention. Especially in the offshore wind power and mountains and other areas of wind turbines for non-maintenance and so on. A schematic diagram of a small off-grid wind power device is shown in Fig.1-12. The main components include wind wheel, gearbox, permanent magnet AC motor, rectifier, accumulator battery, inverter. The reliability of each component is related to the reliability of the whole system.

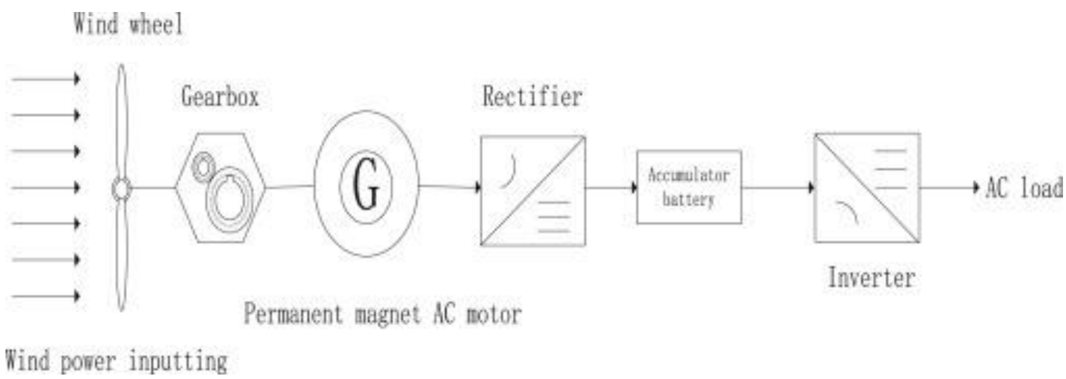

Fig.1- 12 A schematic diagram of a small off-grid wind power device [34]

1.2.2.2. Thermal generation device

A most efficiency to use the energy is to recovery the waste heat from the power generation unit instead of using electricity for direct refrigeration. Another way is to use the renewable energy to produce the heating or cooling. For instance, thermal generation devices are introduced, absorption chiller, adsorption chiller, gas boiler and so on. In this section, two devices are introduced.

1. Absorption chiller

Absorption Chiller is one of the most commonly used and commercialized thermal activation technologies in cogeneration systems. The difference between absorption chiller and steam compression chiller is the compression process. Because absorption chillers use heat compression to refract steam, rather than mechanically using rotating devices, they can be driven by steam, hot water, or high-temperature exhaust gases. Thus, greatly reduced. The power consumption of the traditional refrigeration system is low, and the noise of the refrigeration process is reduced. The capacity size of absorption chiller ranges from 10kW-1MW. Absorption chillers take many forms. A schematic of single-effect absorption chiller is presented in Fig.1-13. The main components include generator, condenser, absorber, evaporator, economizer, pump and so on.

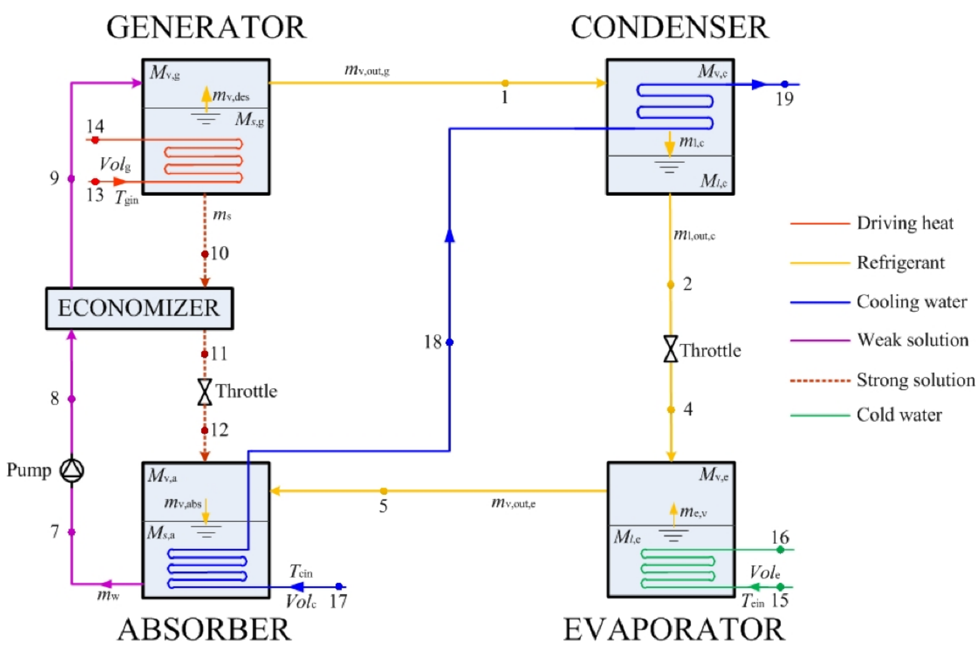

Fig.1-13 A schematic of single-effect absorption chiller [35]

2. Adsorption chiller

Similar to absorption chillers, adsorption chillers use the residual heat of the original motive to provide space air conditioning. An important difference between adsorption chiller and absorption chillers is that the former can be driven by low temperature heat sources. Adsorption chiller has several special, no noise, no solution pump, no corrosion crystallization fault, small size. Therefore, the adsorption is more suitable for use in distributed energy systems. The capacity size of adsorption chiller ranges from 5.5-500 kW. There are some limited of the adsorption chiller, one is the adsorption chiller can only be driven by high quality heat, another one is the adsorption chiller has the high capital cost.

1.2.2.3. Storage device

Power generation refers to the conversion of energy into electricity. However, conversion processes, such as solar, wind and hydroelectric power, depend on volatile sources of fuel. In this case, the power system must have a certain energy storage capacity in order to overcome the fluctuation of the energy supply. In other cases, energy storage provides a means to take advantage of excess energy production, such as the production of more excess by utility companies at night Power. Energy storage is usually achieved by converting electrical energy into another form of potential energy. As shown in Fig.1-5, large-scale energy storage options include battery energy storage (BES), flywheel, superconducting magnetic energy storage (SME), compressed air energy storage (CAES) and pumped energy storage [18]. As shown in Fig.1-14, a flywheel energy storage system includes motor generator, spinning wheel, vacuum containment, advanced magnetic bearing, power conditioner.

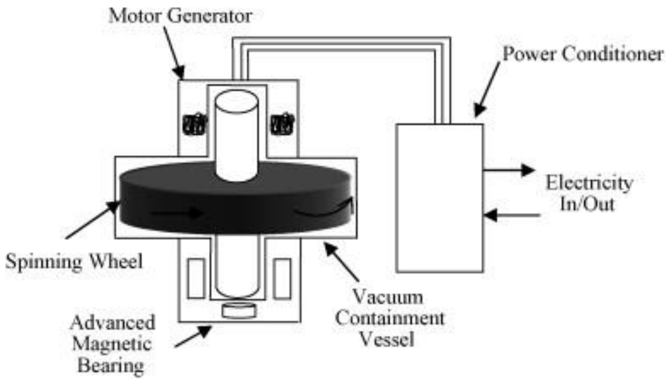

Fig.1-14 A flywheel energy storage [18]

2.1.1.

1.2.2.4. Auxiliary equipment

In addition to major power generation equipment, heat recovery equipment, thermal utilization equipment and storage equipment, there is a large number of auxiliary equipment in the distributed energy system to play a variety of functions, such as power conversion equipment, connecting equipment, power equipment, cooling water equipment. For instance, pump is an important equipment of the system, the pump can be used in the cooling water system as the cooler pump, used in the thermal system or the storage system for the energy Transportation. And the cooling system includes the cooling tower cooling pump or other devices. Each power generation device, thermal generation and utilization devices, heat exchangers should be using the cooling water devices. Other auxiliary equipment also includes fans, control discs, monitors, tubes, etc. Fig.1-15 shows a diagram of jacket water cooling system. the main components of jacket water cooling system include jacket water inlet and outlet line, 3-way valve, heat exchanger, jacket water circulating pump, raw water circulating pump.

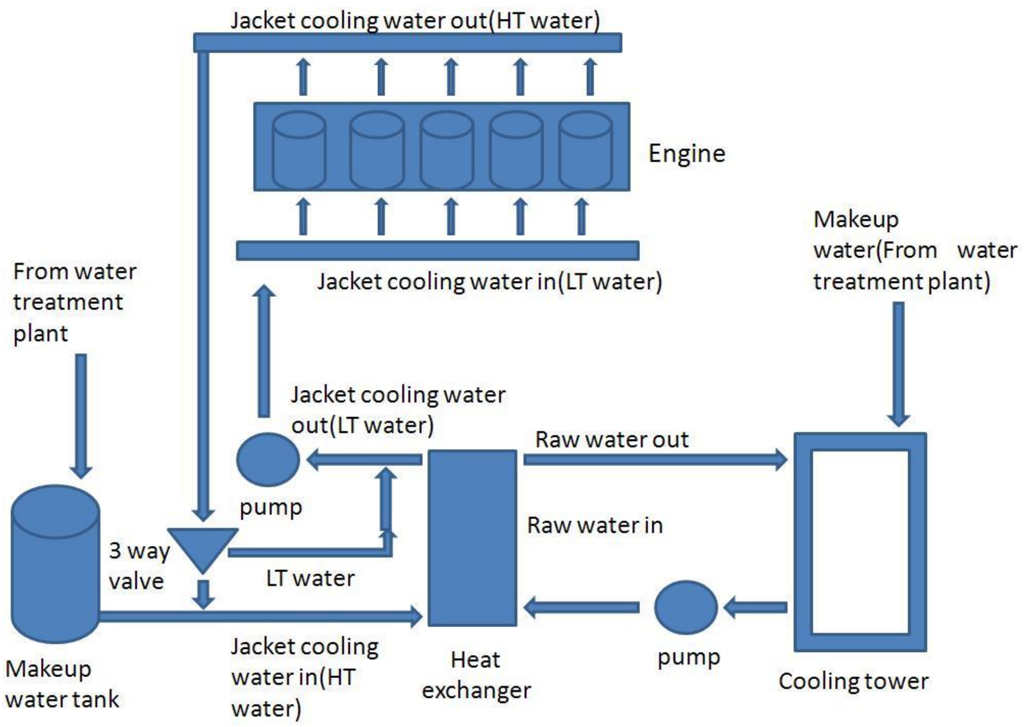

Fig.1-15 A diagram of jacket water cooling system [36]

The main devices and components that generally applied and performed on the DER system has been introduced in section 1.2.2. The results show that most of the devices are contained in a variety of components and are a complex system. therefore, Therefore, a distributed energy resource system consisting of these devices, such as in series or in parallel, is a complex system containing many components. The failure of any one component can cause the corresponding subsystem or the whole system to fail.

Maintenance is the main way to ensure the safety and reliability of system. However, for a complex and repairable system, a reasonable and a right maintenance strategy are difficult to be determined during different DER systems. Reliability and maintenance analysis of distributed energy resource systems and related devices are described in the next section.

1.3. Previous Study of Reliability and Maintenance

Reliability and maintenance are the main parts of equipment during the lifecycle. A lot of previous studies of the DER system have been focused on the reliability analysis and maintenance analysis. The reliability and maintenance include not only the equipment, for instance, gas engine, absorption chiller, pump, etc.) but also the management, strategies and so on. In this section, the reliability and maintenance studies of the DER system and the technologies are reviewed.

Adefarati et al. [37] evaluated the distributed generation (DG) system, which combines with the wind turbine generator (WTG), electric storage system (ESS) and photovoltaic (PV). A Markov model is proposed to access the stochastic characteristics of the major components of the renewable DG and compare the reliability with the conventional system. The result shown that the renewable resources can improve the reliability of the DG system and reduce the cost because the system reliability increased.

Binayak Banerjee et al. [38] analyzed the optimum value-based location of weak grid distributed system; this research point of this distributed system performance is reliable. The results of this analysis show that the location with the highest reliability of the weak grid distributed system occurs in the closest position to the customer, whether in terms of customer number, overall demand or customer priority. Neither the use of load reduction nor the use of renewable energy will change the location of the optimization. In addition, conventional resources are superior to intermittent resources based on an analysis of the maximum benefits that can be obtained from weak grid distributed system. This means that renewable energy will result in greater costs. The Markov model is a suitable approach to analyze the reliability of the system.

Borges et al. [39] proposed an optimization process which is solved by combining with the genetic algorithms (GA) to evaluate distributed generation impacts in the system reliability. The optimization process was applied to the hypothetical systems and an actual distribution system; the result shows that the presented method is suitable and robust.

Ting-Chia Ou [40] presented a novel unsymmetrical fault analysis for microgrid distribution systems. The method uses the actual three-phase model to deal with asymmetric faults. Two matrices based on the topological characteristics of the MG distribution network are established, and a hybrid compensation method for injection branch mismatch current caused by the fault is proposed, and the branch loss distribution flow and bus loss distribution voltage are analyzed directly. An asymmetric fault, the appropriate fault boundary conditions can be obtained. This method can be from the These two matrices are obtained, which are used to solve various types of individual or simultaneous asymmetric failures. This paper also discusses the modeling of micro-turbo power Generation (MTG) as a distributed generator (DG), which delivers the operation of two is landing and grid connection modes. The test results show that the method is effective, accurate, easy and asymmetric fault analysis.

F.J.G. Carazas et al. [24] proposed a method for reliability and availability evaluation of heat recovery steam generator system, the analysis step includes: function analysis and functional tree for the equipment analysis, failure modes and effects analysis, failure tree analysis, maintenance policies and availability analysis. The flowchart for a complex system availability evaluation is shown in Fig.1-16.

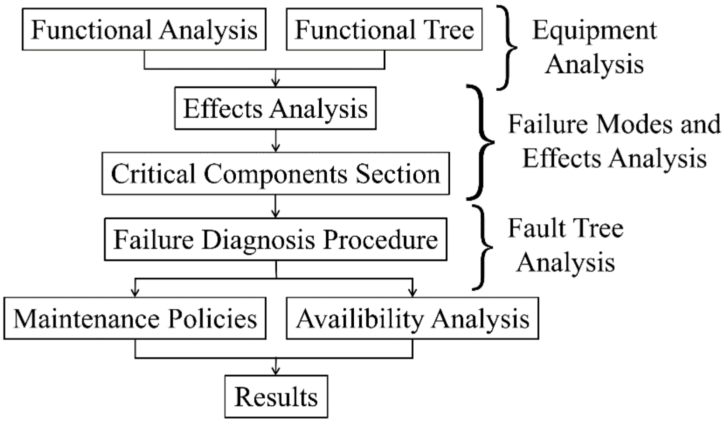

Fig.1-16 A flowchart for a complex system availability evaluation [24]

Daejun Chang et al. [41] studied the availability and safety of the propulsion systems for the LNG carriers, the analyzed LNG carriers include dual-fuel steam turbine mechanical propulsion, dual-fuel diesel electric (DFDE) propulsion, dual-fuel gas turbine electric (DFGE) propulsion, dual-fuel diesel mechanical (DFDM) propulsion, diesel mechanical propulsion with reliquefication. The results show that the maintenance cost of failed items and logistic cost should be given more attention.

The reliability of power system mainly depends on the reliability of the power generation department and transmission subsystem. In recent years, the electricity sector has shown a dynamic increase in the amount of electricity it receives from renewable sources, including, first and foremost, electricity produced by wind power plants. However, the efficiency of wind power plants depends to a large extent on wind speed. Andrzej Rusin et al. [42] carries out a reliability analysis of the Polish power generation system, comparing this result with the reliability of the North American power system. The analysis takes into account the generation capacity of the wind system, the planned investment and ongoing investment projects, the reliable prediction of the polish system, and the impact of the increase of wind power generation on the reliability of the distributed system. The results show that, from the perspective of system reliability, the share of wind power generation in the total power generation of the system is limited.

Saeed Samadi [43] proposed that renewable energy sources, such as wind or solar, are uncontrollable because their source of fuel is inherently intermittent. This has made it difficult to design power generation systems with renewable energy sources. Therefore, a mechanism is needed to predict their power output and to assess the reliability of the power generation system. Saeed Samadi found that the reliability of the power generation system declined as the penetration level of solar energy increased. In addition, with the increase in the penetration rate of solar power generation systems, the capacity credit of solar power plants is also declining.

Marquez et al. [44] proposed a general method using the Monte Carlo simulation to carry out the reliability and availability of the complex system. This method is illustrated and verified by the solution of the case study composed of two optional configurations of the generation device for the usability evaluation. The advantages of different device configurations are compared and discussed by using this model according to the situation of different device configurations to meet the initial availability requirements.

Nikhil Dev et al. [45] presented a systematic approach based on graph theory and matrix method is developed ingeniously for the evaluation of reliability index for a Combined Cycle Power Plant (CCPP). In this method, a complex system is divided into several subsystems in order to determine the parts that have the greatest impact on the reliability of the whole system. Based on the reliability and the correlation reliability of the system, the reliability graph, matrix and permanent function are established by the graph frame reliability analysis method. This method provides a reference for power plants when selecting suitable maintenance strategies.

Rajesh Arya [46] proposed an algorithm to determine the maintenance operation preference of a feeder section of the distribution network. A component importance measure called the diagnostic importance factor (DIF) is used for this purpose. To calculate the weighted cumulative diagnostic importance factor (WCDIF) for each feeder segment, a method has been developed that quantitatively represents the relative importance of maintenance activity priorities. The developed method includes distributed generation (DG) and load impact. The method has been implemented in two sample distribution systems and the grade table of feeder section for maintenance has been obtained.

Dongiovanni et al. [47] presented a new method to infer and evaluate the failure rate of components under different working conditions. And the nuclear power plant, Steam Turbine Group as the research object. Starting from the analysis method of fault tree, the fault tree analysis is transformed into Bayesian network. The relationship between the failure rate and different operating conditions is determined, which provides an effective reference for the operation of the unit.

Ali M. El-Nashar [48] proposed a method of integrating equipment reliability into the optimal design of electric power and seawater desalination cogeneration system. The reliability analysis of equipment is carried out by using the spatial state of Markov process and the design optimization is carried out by using the theory of thermal economics. The results show that the introduction of reliability reduces the normal running time of the equipment and improves the cost of the product. The author points out that reliability is important for equipment and should be considered in system design in any cogeneration system design.

Hamid Reza Feili et al. [49] proposed the failure mode and impact analysis (FMEA) as a technique to identify, classify and analyze the common failures of typical geothermal power plants. Calculate and confirm the priority of potential failures by conducting appropriate risk assessments of the occurrence, detection, and severity of the system's failure patterns. In this analysis, XFMEA analysis software is used to improve the accuracy and ability of the analysis process. Hamid applies this method to geothermal power plant, studies 5 main components of geothermal power plant, puts forward a method suitable for GPP development and improving reliability, and corrects each failure mode.

Haghifam et al. [50] presented a reliability and availability model for the combined heat and power (CHP) system. The authors proposed that in most studies these subsystems have not been classified and in many cases have been considered separately. In addition, there is little research on reliability from power generation points to users. Thus, they proposed a CHP reliability and availability model is based on the state space and the continuous Markov method with electricity-generation, fuel-distribution and heat-generation subsystems.

M.H. Khoshgoftar Manesh et al. [51] proposed an improving the approximated Markov method to perform it for the determination of availability and reliability of complex cogeneration systems. Markov method is one of the important analytical techniques of repairable systems. Usually the two methods to solve the reliability problem are analysis technology and stochastic simulation, but the two methods have their advantages and disadvantages. For complex maintainability systems, the application of the spatial state method will produce a large number of complex state space, the probability of starting is difficult to calculate. This new method can reduce the state number and set of explosive state space, and the results show that the method is effective. Fig.1-17 shows the competition between analytical and proposed procedures.

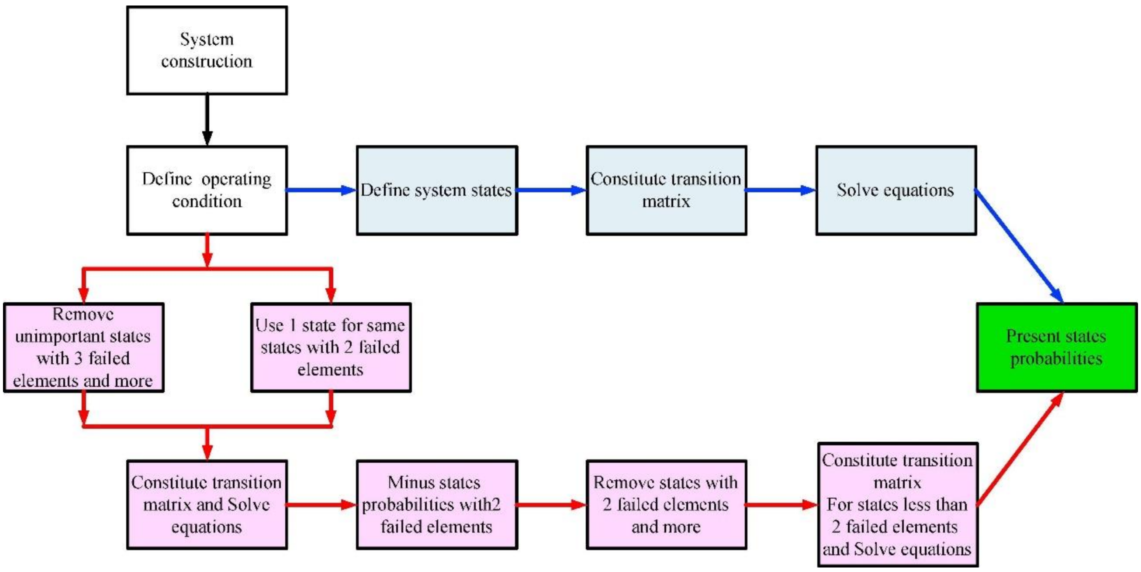

Fig.1-17 The improving the approximated Markov method [51]

Li et al. [52] proposed a multi-state analysis, modeling method for distributed power generation reliability evaluation. This method can be used to evaluate multiple energy generation technologies in distributed energy systems. Because of the randomness of power generation source and the randomness of power supply fault, the state is used to describe the randomness of the generator set.

Julwan Hendry Purba [53] proposed a basic event evaluation method of system fault tree based on fuzzy reliability. Fault tree analysis is widely used in probabilistic security evaluation. The fault tree analysis method can only be used when all the basic time of the system fault tree has a quantitative failure rate. However, due to insufficient data, environmental changes or the use of new components, failure rate data are difficult to obtain. This fuzzy reliability analysis method applies the concept of probability of failure to the qualitative evaluation of basic time and the concept of fuzzy set to the quantitative characterization of corresponding probability of failure. The results show that the fuzzy reliability method is a good choice for the traditional probabilistic reliability method when there is no corresponding quantitative historical failure data to determine the reliability characteristics of the basic events. This method overcomes the limitation of traditional fault tree analysis method in probabilistic safety assessment of nuclear power plant.

Hamed Sabouhi et al. [54] presented a reliability modeling of the combined cycle power plants. It is well known that the successful operation of a power plant always depends on the functions of the subsystems and components that make up it. However, due to the current financial constraints in the power industry, power plant operators are faced with a wide range of challenges in dealing with the maintenance and scheduling of power plant subsystems and asset management practices. Understanding the impact and critical degree of each subsystem and component of the power plant on the whole system will help managers to formulate strategies to ensure the smooth, safe and economic operation of the plant. In this paper, the reliability models of gas turbine power plant (GTPP) and steam turbine power plant (STPP) are firstly established to provide input for evaluating the reliability of the whole CCPP from the perspective of engineering systems. A reliability-oriented sensitivity index is proposed to identify the key components of the power plant, that is, the ones that have the greatest impact on the system reliability and availability objectives. After identifying the key components of the system, the effective maintenance strategy of power plant components can be determined, so that the available resources can be reasonably planned and the allocation of technology and economy can be made.

M. Tanrioven et al. [23] presented a method for modeling and calculating the reliability of Proton Exchange Membrane Fuel Cell power plant. This paper also uses a Markov Model with a state-space approach to calculate the reliability of the system. The state-space includes different states, such as operation state, failure state, maintenance state and so on. The transition rates between the functional state and failure state are called the failure rate and repair rate. The results show that the use of MATLAB soft 5-kilowatt single-machine PEM fuel cell can provide power for ordinary residential buildings.

With the development of computer hardware and software technology, digitalization is the development trend of large and complex systems such as nuclear power plants. It changes the way the Main Control Room (MCR) operator interacts with the system. In the face of these technological changes, operators need to continually improve the reliability level of the Situation Assessment (SA). In addition to evaluating the operator's SA reliability, managers and shift supervisors want to predict. The level of SA reliability for the operator. Yanhua Zou et al. [55] determined the influencing factors related to SA reliability, then established the SA reliability model, and finally combined the time series prediction method with the Dynamic Network Model (DNM), proposed a reliability prediction model.

Clety Kwambai Bore [56] presented a management method and application to the maintenance of geothermal power plants. The unit cost of geothermal energy depends on the cost of capital investment, Operation and Maintenance (O&M). The cost of capital is huge, but only in the initial stages of a power plant and can be optimized in the initial phase. O&M costs run through the entire life cycle of the power plant, determining the economic operation of the power plant. O&M costs are the largest component of operating and maintenance costs. In order to the Geothermal Power Plant (GPPs) economy, its maintenance functions should be optimized through careful selection and planning of maintenance strategies to meet the maintenance needs of the plant at the lowest cost. Clety Kwambai Bore studies have shown that there is no maintenance or management method that can effectively address the maintenance needs of any system, so combinations are always desirable. The results show that in order to optimize the maintenance of GPPs, it is necessary to design a suitable combination of management methods. Reliability Centered Maintenance (RCM) is used to design appropriate maintenance strategies, six Sigma to solve long-standing problems, lean application to identify and eliminate waste. A successful combination of the optimization of GPPs maintenance process, so that the plant economic operation has great potential.

Fernando Jesus Guevara Carazas and Gilberto Francisco Martha de Souza [57] presented a method for evaluating reliability and usability of gas turbine in power stations. This method is based on the concept of system reliability, such as function tree development, fault mode application and effect analysis, to determine the key components to improve system reliability, as well as reliability and maintainability evaluation based on a historical fault database. The method also proposes the application of RCM concepts to improve maintenance strategies for complex systems to reduce unexpected failures of critical components. The availability of complex systems, such as gas turbines, is closely related to the reliability and maintenance strategies of their components. This strategy not only affects the maintenance time of the parts, but also affects the reliability of the parts and affects the degradation and usability of the system. The result shows that the availability of each gas turbine is different and indicates that there are differences in their system installation and operation.

A reliable energy system should be available at any time, except at a predetermined time. Generally, how to provide redundancy to the system is determined by the designer through experience, and then the design determined in this way is often not the optimal design. Frangopoulos et al. [58] proposed a thermoeconomic model of the system with the reliability and availability analysis, in addition, the redundancy is performed in this design, and the profit and cost are considered in the design. The state-space method is used to analyze the reliability and availability of the system. The optimization model is performed for two levels, one is synthesis and design, another is operating under time-varying conditions.

Jichuan Kang et al. [59] presented a modified Failure Modes and Effects Analysis (FMEA) method to analyze the relationship between failure modes and its effect on the failure probability of the whole system. A series of high priority failure modes are determined by using the traditional FMEA method, and the corresponding connections are analyzed by using the reliability index vector method, and the correlation coefficients are obtained. This paper takes the complex structure of offshore floating wind turbine as the research object. The subsystems of offshore floating wind turbines are highly dependent on each other and have a negative impact under harsh operating conditions. The results provide recommendations on safety and reliability for the design of floating wind turbines.

Ivan Postnikov et al. [60] proposed a method for determining the optimal reliability parameters of heating system components, which can provide the required level of the heating reliability system. This method makes use of the average reliability parameters of each component of the system to analyze the economy and rationality of the improvement of the reliability between the system components. The solution method of this problem is based on hydraulic circuit theory, reliability index of heating node, Markov stochastic process model and general law of cogeneration and heat transfer process. The method also considers the change of heat load during heating and the redundancy of user time related to heat storage. Through the calculation experiment, the feasibility of the method for the actual heating system scheme is verified.

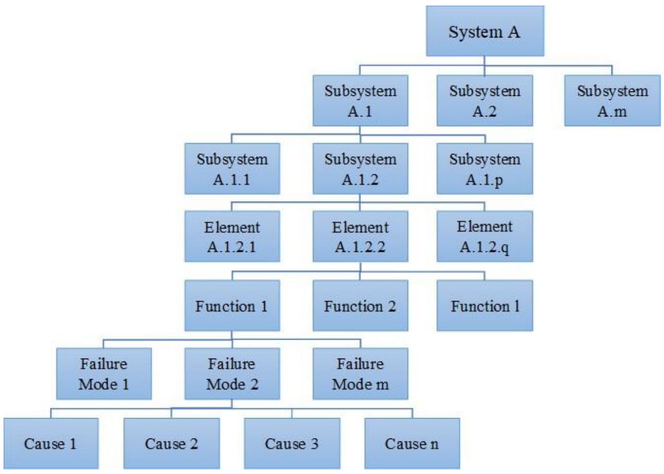

Fig.1-18 The steps of FMEA process [61]

Kapil Dev Sharma et al. [61] performed a Failure Mode and Effect Analysis (FMEA) for a Water Tube Boiler in Thermal Power Plant. FMEA is an inductive failure analysis tool designed to identify and evaluate potential failure patterns and impacts in products. The goal is to identify which behaviors can eliminate or reduce the likelihood of failure. This approach can be applied to the most critical and serious components of power stations with high risk priorities. The steps of FMEA process are shown in Fig.1-18.

Jiangjiang Wang et al. [62] presented an analysis of energy, economy and environment of Building Cooling, Heating and Power (BCHP) system from the point of reliability and availability. For a BCHP system, the failure of components and subsystems will lead to the interrupt of cooling, heating and electricity for the energy demand. The result of this research shown that the optimized non-redundant waste heat co-production system has the best comprehensive performance, but the utilization rate of cold and heat is lower than that of the separation. The redundant design will increase the reliability of the system, but the cost of will be increased, so the author thinks the economy will be very poor.

Jiangjiang Wang et al. [63] analyzed the reliability and availability of the redundant BCHP system. The state-space method combined with the probabilistic analysis of Markov model is used to calculate and analyze the reliability and availability of the system, and redundant design of BCHP system was introduced in this paper. The failure rate, repair rate, availability and mean failure time of redundant and non-redundant BCHP systems are derived and analyzed respectively. Then, the reliability analysis of redundant and non-redundant BCHP systems are compared with that of the SP (separate production) systems. Finally, the calculation results show that compared with SP system, the reliability of redundant BCHP system is obviously improved.

Masood et al. [64] indicated that without accurate and effective operation and maintenance procedures, well-designed cogeneration systems will not be able to operate effectively. Improper operation and Maintenance will shorten the service life of equipment, reduce cycle efficiency, increase fuel consumption and environmental pollution, and reduce the economic benefits of cogeneration systems. Proper operation and maintenance procedures are implemented for cogeneration systems and their components to extend project life and maintain optimal cycle efficiency, pollution reduction rates and economic benefits. However, the authors also focus on the manufacturer's documents. A well-designed operation and maintenance program include proper pre-commissioning, debugging, debugging, and shut down. In addition, it is critical for a successful operation and maintenance program to fill out the log tables correctly and analyze them, as well as to accurately troubleshoot them.

Milad Zamani-Gargari et al. [65] adopted the Markov approach to calculate the probability of availability of wind farms and energy storage system, and the reliability index is obtained by the Monte Carlo Simulation (MCS) method. Through the comprehensive simulation of Roy Billinton test system (RBTS) reliability test system, the capacity, wind speed level and energy storage scale of the wind farm are considered, and the effectiveness of this method is verified.

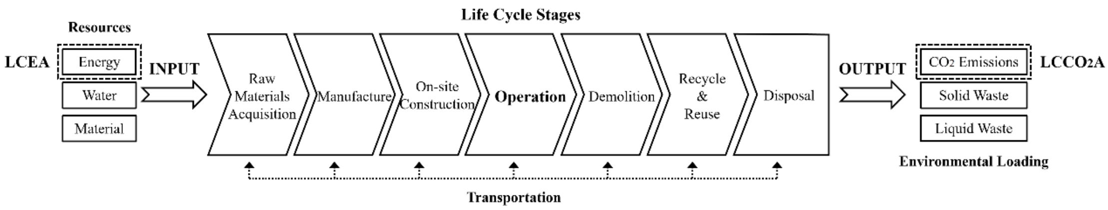

Fig.1-19 The Basic concepts of LCA, LCEA and LCCO2A [66]

Life Cycle Assessment (LCA) mainly assesses the overall impact of buildings on the environment throughout their life cycle. The Life Cycle Energy Assessment (LCEA) is an assessment of the energy use of buildings as resource inputs throughout their life cycle. Life Cycle Carbon Emission Assessment (LCCO2A) focuses on the assessment of carbon dioxide emissions as the output of the entire life cycle of a building[66]. The Fig.1-19 shows the basic concepts of LCA, LCEA and LCCO2A. It can be seen that the basic concept of LCA is to evaluate the environmental impact of products in different life cycle stages, namely "cradle to grave". The LCA assesses all resource inputs to the product, including energy, water and materials, and environmental loads, including CO_2 emissions, solid waste and liquid waste. However, the other two variables have different priorities, with the LCEA focusing on resource inputs and the $LCCO_2A$ focusing on CO_2 equivalent emissions. We can see that the operation is the main period of the total lifecycle assessment.

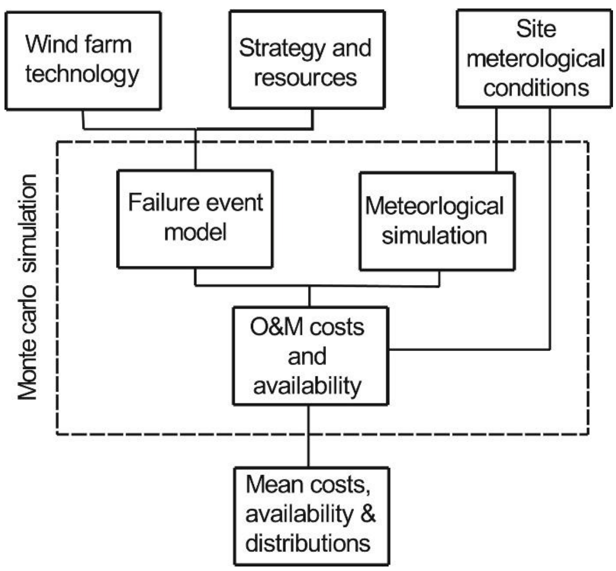

Fig.1- 20 Diagram of the Offshore Wind O&M tool [2]

Rebecca Martin et al. [2] performed a sensitivity analysis of offshore wind farm operation and maintenance cost and availability. Many offshore wind farms are built in stages, and important factors may be inconsistent at each stage. In order to determine the most important factors that affect the operation and maintenance of operating costs and availability. An Offshore wind O&M tool was developed in this research. The Fig.1-20 shows the diagram of the Offshore Wind O&M tool is shown in Fig.1-20. The Monte Carlo simulation process is shown in Fig.1-20, the main steps include failure event model, meteorological simulation and the O&M costs and availability.

The reliability and maintenance are very important for the operation of the DER system during the lifecycle. As shown above, a large amount of literature is devoted to the research on the reliability of distributed energy systems. The [37] to [45] are studied about the reliability of distributed generation systems, include the reliability of electricity production and supply. In particular, the reliability of renewable energy systems in distributed generation grid is studied. In addition, most researchers [46]-[56] are focusing on the reliability, maintenance and replacement of power generation plants, cogeneration system, combined heating and power system, combined cooling, heating and power system or other generation system. The studies of reliability and maintenance of power generation, thermal generation etc. are presented in [57]-[61], and some redundant design of CCHP system are presented on [62]-[63]. The analyzed equipment such as gas turbine, wind turbine, heat storage, offshore wind farm, water tube boiler, fuel cell and so on.

There are some methods are used to analyze the reliability and maintenance of components and the system, such as failure mode and effect analysis (FMEA) method, failure tree analysis (FTA), Monte Carlo Simulation (MCS) method, Markov model, Markov model combine with the state-space method, fault mode application and effect analysis, Bayesian network, Reliability Centered Maintenance, reliability condition maintenance and so on. In addition, the DER system includes a large of components and multiple subsystems, it is a complex and repairable system. For the system reliability and maintenance analysis, it may be a combination of methods and focus on some key components.

1.4. Purpose of This Study

Distributed energy resource (DER) system has been applied for decades, because of its high efficiency and low environmental load has been the concern and recognition of the community. And the application of the DER system can greatly improve the reliability of power supply system. In particular, the application of renewable energy, such as solar and wind energy, makes the DER system have a better development. The installed capacity of DER systems continues to increase in the worldwide. However, the application of the DER system also increases the complexity of functional system. For example, a typical application of DER system is a combined cooling, heating and power (CCHP) system (shows in Fig.1-21).

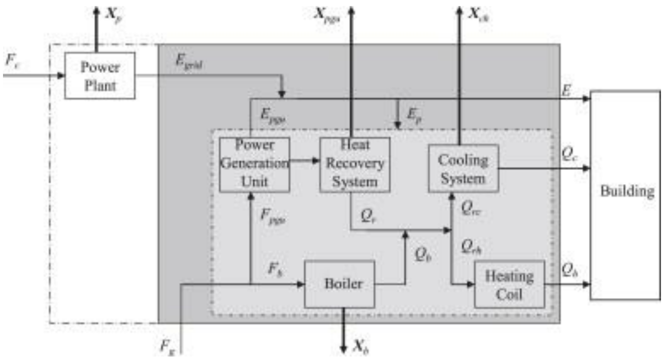

Fig.1- 21 A diagram of CCHP system [67]

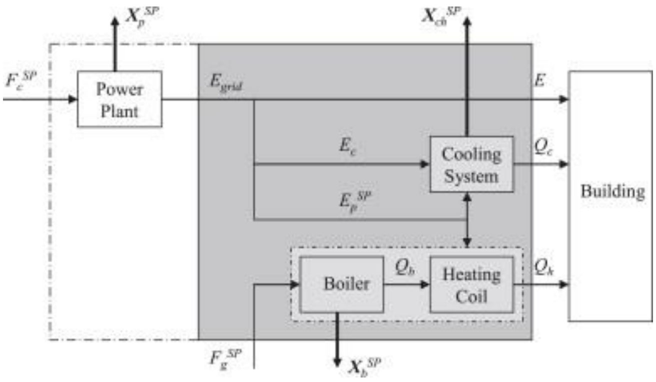

Fig.1- 22 A diagram of SP system [67]

Compare with the separation production (SP) system (shows in Fig.1-22), The CCHP system adds a few functional units, for instance, power generation units, heat recovery system, heat exchange units, and other auxiliary equipment. While improving the application function of a DER system, complex system and a large number of equipment also greatly increase the failure risk and maintenance difficulty level of the system. In addition, each device has a maintenance strategy based on the recommendations of its manufacturer. In this complex system, this may ignore the interaction between devices in terms of failure risk and maintenance strategy. However, in previous studies, more attention has been paid to the impact of distributed energy systems on energy, economy and the environment.

The research on reliability usually focuses on the effect of equipment on the DER system on the reliability of the whole power supply grid or the reliability of a certain equipment. The reliability analysis and maintenance strategy for the subsystems of the DER system are ignored. An imperfect and inappropriate maintenance strategy may result in greater failure risk and higher operation and maintenance (O&M) costs for the system.

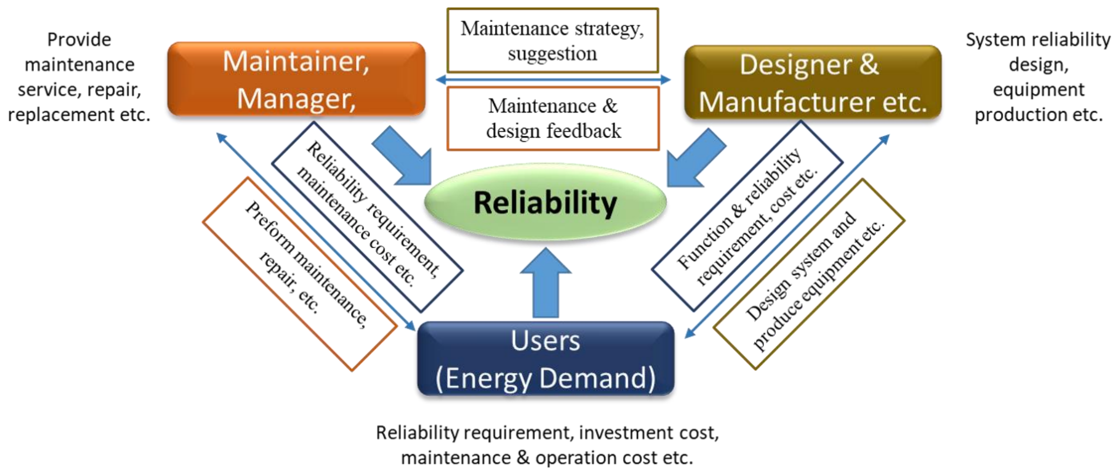

Fig.1- 23 Diagram of the relationship between system reliability and the associated aspects

The relationship between system reliability and the associated aspects is shown in Fig.1-23. There are three relationships are affected the reliability of the DER system, the relationship between the maintainer & manager and designer & manufacturer etc., the relationship between the maintainer & manager and users, and the relationship between the designer & manufacturer and users, it relates the maintenance strategy, maintenance cost and system reliability design, respectively.

In this paper, the operation and maintenance strategy of a DER system are investigated and analyzed for the reliability analysis and optimization. And then two reliability indices based on maintenance costs are developed. The redundant design is a way to improve the system reliability, the effect of reliability and total life cycle cost are analyzed in this paper. Therefore, this study not only establishes a reliability, maintenance priority, but also analyzes the reliability and cost of redundant design.

The research flow of this paper is shown in Fig.1-24. The purpose and content of each chapter is presented in the followings.

- ✧ Background

In chapter one, the background and current situation of DER system, as well as the main technologies are presented. Because the reliability of the DER system depends on the reliability of each device or component, therefore, it is necessary to introduce every major technology. The reliability and maintenance previous studies of the DER system are reviewed. And then the purpose of current research is proposed.

✧ Theoretical study

In chapter two, the basic concepts of reliability indices, types of maintenance and analysis methods are introduced. The reliability application areas are presented in here. The several reliability analysis methods, maintenance concepts, types of maintenance and maintenance prioritization are investigated and compared.

✧ Investigation and analysis

In chapter three, the real maintenance management strategies and operational status of the DER system in Kitakyushu Science and Research Park are investigated; the maintenance cost, failure and maintenance effect of power generation efficiency are analyzed.

✧ Maintenance optimization

In chapter four, the FMEA method is applied to the risk analysis and maintenance priorities analysis based on the real data.

In chapter five, we focus on the reliability and availability analysis and components maintenance prioritization analysis of the DER system Failure cost importance index (FCI) and potential failure cost importance index (PI) were developed for the maintenance prioritization analysis of the DER system.

✧ Reliability design

In chapter six, we propose a model for reliability and cost evaluation of non-redundant and redundant design DER system. The reliability analysis approach and cost calculation method based on the reliability indices are developed.

✧ Conclusion

In chapter seven, the conclusions are presented.

Study on Maintenance Management and Reliability in Distributed Energy Resource System

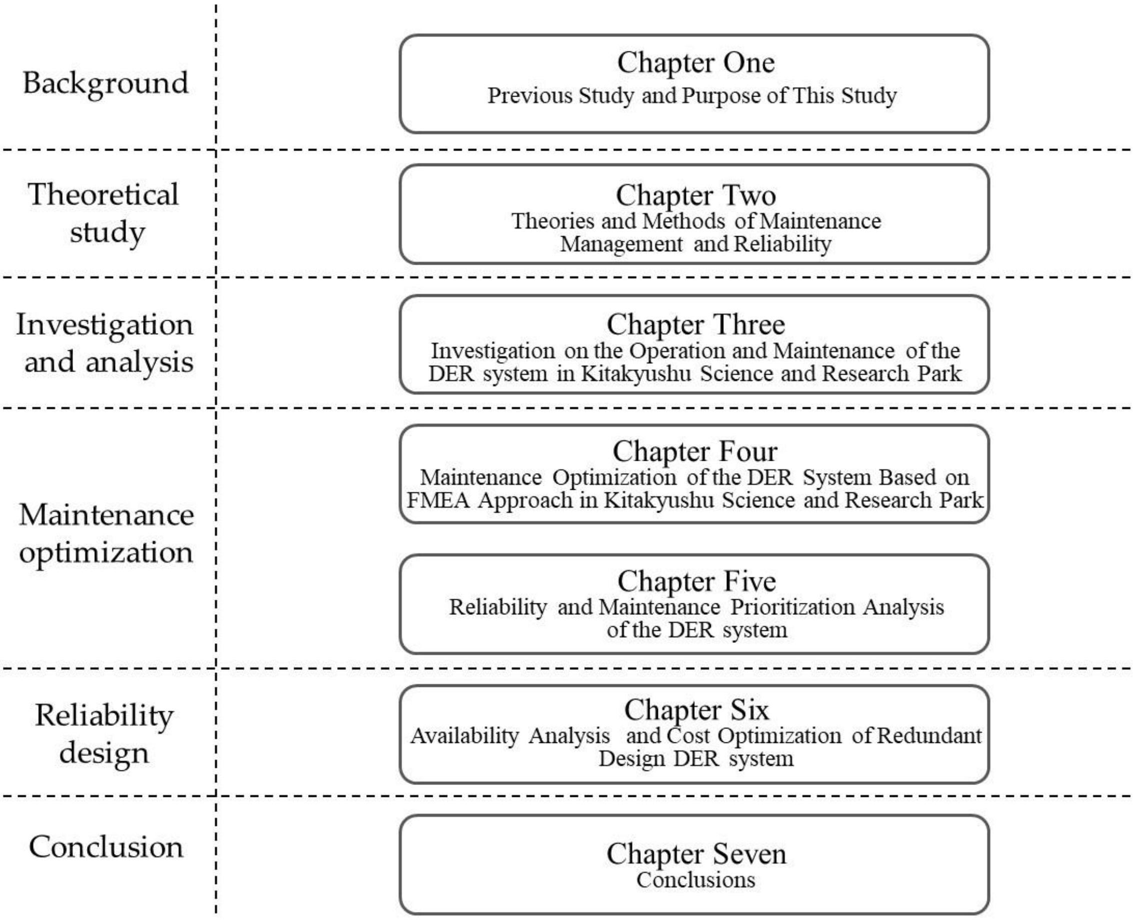

Fig.1- 24 Research Flow

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Chapter 2. Theories and Methods of Maintenance Management and Reliability

2.1. Introduction

Reliability and maintenance are the key elements of the system health and safety. Reliability as the human attribute has always been praised in the history [1]. As human also can get sick, the human can be seen as an evaluation objective of reliability from the psychological point of view. The reliability concept has been applied on the technologies after World War I. Robert Lusser derived the product probability law of series components, this theorem states that for a system, the whole system can only work when all the parts in the system are working. In other words, the reliability of the system is equal to the product of the reliability of each component. When the system is composed of a large number of components, the reliability of the whole system may be low even though the reliability of each component is high.

Reliability is defined as the ability of an item to perform a required function under given conditions for a stated period [2]. Reliability assessment and analysis is an indispensable portion in modern industry, which often runs through the whole life cycle of products or equipment, including design, construction, operation, repair, maintenance, replacement and redesign, etc. There are a variety of reliability indices that can be used for reliability assessment and analysis, for instance, failure rate, repair rate, mean time to failure (MTTF), mean time to repair (MTTR), mean time between failure (MTBF) and so on. For different equipment or products, the reliability indices are different. For instance, utilities typically use the following frequency and duration reliability metrics to quantify the performance of their systems, it includes System Average Interruption Frequency Index, System Average Interruption Duration Index, Customer Average Interruption Duration Index, Customer Average Interruption Frequency Index, Customer Interrupted per Interruption Index, etc. [3]. Some studies have been focused on the reliability importance indices to identify the importance components of the whole system. Reliability analysis also is known as survival analysis. When the study concerns are focus on the biological event with the object of humans or animals, it is usually called survival analysis. Availability is another index to show the safety and health of components and system, it is an indicator that a component or system can be used or continued to be produced in a given period of time. Therefore, the main reliability indices, reliability and availability are introduced in this chapter.

The DER system is a complex and repairable system. Some reliability analysis methods have been applied for complex and repairable system, such as the Failure Tree Method [4], Failure Modes and Effects Analysis (FMEA) [5], Monte Carlo Simulation (MCS) Method [6], Reliability Block Diagram (RBD) [7], Markov Model [8], State-Space Method [9], Weibull Analysis [10] and so on.

Maintenance is the main way to keep the components or a system on the health and safety. Over the years, with the development of industrialization, science and technology, the importance of operation maintenance and maintenance management has been increasing [11]. The spread of mechanization and automation has reduced the number of workers and the cost of personnel, but has increased the number and cost of equipment and construction. Now, the on-line monitoring system is a way to help manager to confirm the status of the equipment during the operation and maintenance. In addition to energy costs, maintenance costs may be the largest part of any business budget, especially in the energy industry. However, the main problem facing maintenance management is whether maintenance management outputs are more effective in terms of their contribution to corporate profits and whether maintenance management is more effective in terms of the manpower and materials used, which is difficult to answer. In the previous studies, some maintenance technologies have been introduced and applied, for instance, Preventive Maintenance (PM), Corrective Maintenance (CM), Reliability Centered Maintenance (RCM), Condition Based Maintenance (CBM), Total Productive Maintenance (TPM), Predictive Maintenance, Effectiveness Centered Maintenance (ECM), Strategic Maintenance Management (SMM), Risk Based Maintenance (RBM) and so on.

In this chapter, the basic reliability indices and analysis methods are introduced, and the main maintenance assessment and analysis methods are presented based on the previous studies. The application and characters of the analysis methods are discussed.

2.2. Reliability Concepts

2.2.1. Failure Rate, Repair Rate, MTTF, MTTR and MTBF

Failure rate, repair rate, mean time to failure (MTTF), mean time to repair (MTTR), mean time between failure (MTBF) are the general reliability indices for components and system reliability engineering. The failure is defined as a component or system loss the function during the operating period lead to the production cannot be carried out. Failure rate is the frequency which a component or a system fails during a period, expressed in failures per unit of time. It is often denoted by the Greek letter λ (lambda) [1]. Repair rate is the frequency that the failed component or system gets repaired, the unit of repair rate is same with failure rate. It is often denoted by the Greek letter μ (mu).

There are three common basic categories of failure rates: Mean Time Between Failures (MTBF), Mean Time to Failure (MTTF), and Mean Time to Repair (MTTR). The relationship among MTBF, MTTF and MTTR is shown in Fig.2-1. The Fig.2-1 shows that MTBF is the sum of MTTR and MTTF. Although MTBF was designed for use with repairable items, it is commonly used for both repairable and non-repairable items. For non-repairable items, MTBF is the time until the first failure after t_i.

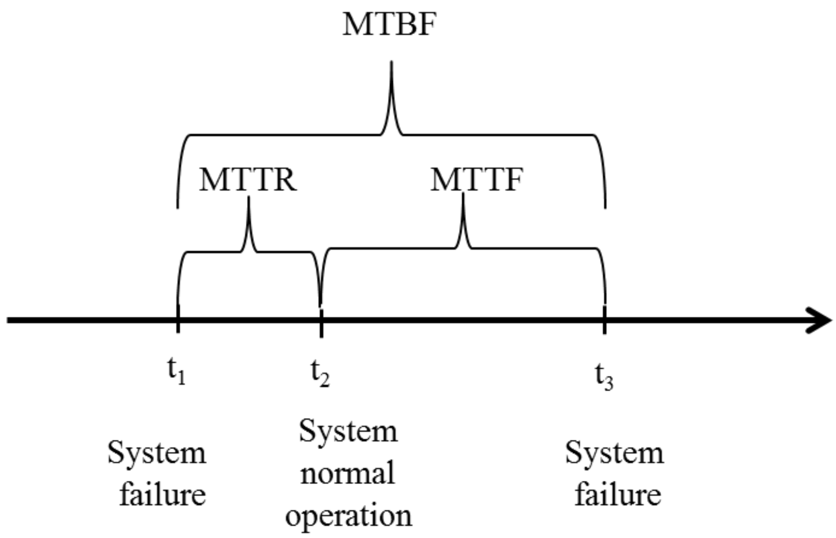


Fig.2-1 Differentiating of the MTBF, MTTF and MTTR

Mean time to failure (MTTF)

Mean time to failure is the mean time expected until the first failure of a piece of equipment. And it is a basic measure of reliability for repairable systems. For constant failure rate systems, MTTF is the inverse of the failure rate, λ. Thus, the failure rate can be presented as:

$$\lambda = \frac{1}{MTTF} \tag{2-1}$$

For repairable systems, MTTF is the expected span of time from repair of the failure to next failure.

Mean time to repair (MTTR)

Mean time to repair is defined as the total amount of time spent performing all corrective or preventative repairs divided by the total number of those repairs, or defined as mean time to repair (MTTR) is the mean repair time of the component or system gets repaired. It is the expected span of time from a failure to the repair or maintenance completion. The term is typically only used with repairable systems. MTTR is the inverse of the failure rate, μ.

$$\mu = \frac{1}{MTTR} \tag{2-2}$$

Mean time between failures (MTBF)

Mean time between failures is a basic measure of reliability for repairable items. MTBF can be described as the time passed before a component before a component, assembly, or system fails, under the condition of a constant failure rate. The time between failures (TBFs) are means the time passed from one failure point to next failure point. Another way of stating MTBF is the expected value of time between two consecutive failures, for repairable systems. It is commonly used in maintainability and reliability analysis.

The MTBF can be calculated as the following:

$$\mathrm{MTBF} = \frac{\sum(t_n - t_{n-1})}{n} \tag{2-3}$$

Where the t_n is the n^{th} failure time, and $n \geq 1$.

As presented in Fig.2-1, MTBF a cycle time of the component or system failed and then repaired. Therefore, the MTBF can be expressed as:

$$MTBF = MTTF + MTTR = \frac{1}{\lambda} + \frac{1}{\mu} \tag{2-4}$$

For a component or system which has a much higher repair rate than failure rate, the MTBF can be approximated by the MTTF.

$$\mathrm{MTBF} \approx \mathrm{MTTF} = \frac{1}{\lambda} \tag{2-5}$$

The Fig.2-2 shows the reliability bathtub curve. Bathtub curve refers to from the product began to be used to scrap termination of the entire life cycle, the changing rule of its reliability. The bathtub curve can be divided into three stages: early life, useful life and wear out life. Early life means the failure rate of equipment or system is decreases with time changed. Useful life means the failure rate of equipment or system is approx. constant with time changed, the failure also called occasionally failure. And the wear out life means the failure rate of equipment or system is increasing with time changed.

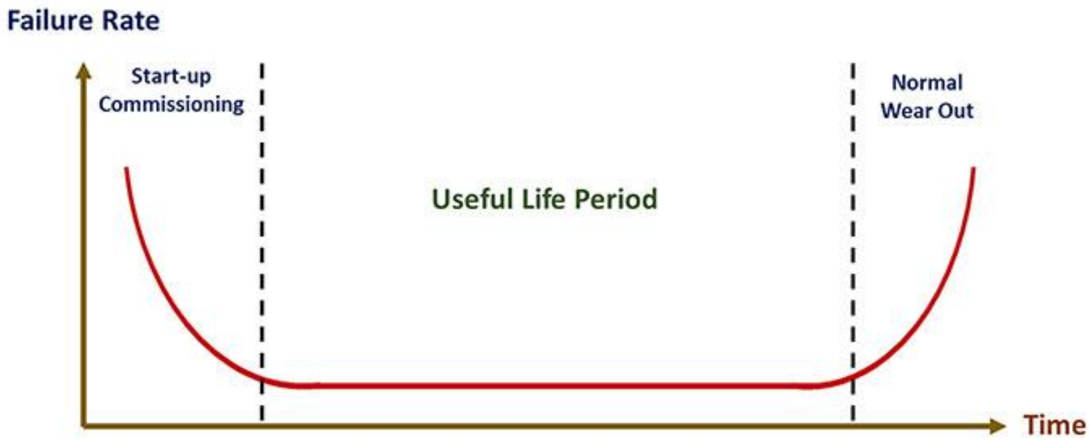


Fig.2-2 Bathtub curve [12]

2.2.2. Reliability and Availability

Reliability analysis also is known as survival analysis. When the study concerns are focus on the biological event with the object of humans or animals, it is usually called survival analysis [13]. When the study concerns are machines or equipment in an industrial setting, it is usually called reliability analysis. The survival analyses focus on a nonparametric estimation approach. The reliability analyses focus on a parametric approach.

A variety of the distribution function is used in the reliability analysis. They are also called reliability distribution; the most using distribution functions include Exponential distribution, Weibull distribution, Normal distribution (Gaussian distribution), and Lognormal distribution. The Exponential distribution is usually used for the modeling, which the failure rate is a constant. The Weibull distribution is usually used for the modeling, which has many product failure mechanisms or a complex system, and the failure can be repaired. The Normal distribution also called the Gaussian distribution, which is most widely—used general purpose distribution. Lognormal distribution is usually used for the model, which the lives of the units whose failure modes are of a fatigue-stress nature.

Probability density function (PDF)

Probability density function (PDF) gives the probability that a component fails at time t, or could be described as the probability of failure that an event occurs between time t and time $t + dt$. It is expression by $f(t)$ usually. Fig.2-3 shows the PDF of exponential distribution determined by the Eq. (2-6).

$$f(t) = \lambda \cdot e^{-\lambda t} \tag{2-6}$$

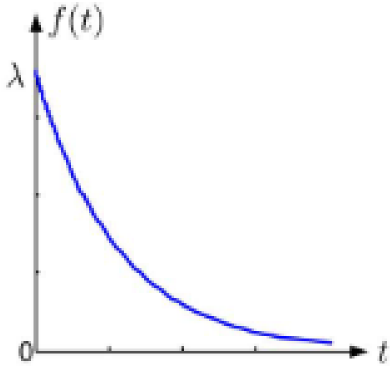


Fig.2-3 Probability density function [14]

Cumulative distribution Function (CDF)

CDF is the probability of failure that an individual survives between time 0 and time t. It is expression by F(t) usually. It can show as following:

$$\mathrm{F(t)} = \int_0^t \mathrm{f}(x)dx \tag{2-7}$$

Reliability function, R(t)

R(t) is usually expressed as Survival function S(t). It is the probability that the individual survives after time t. It is defined T is the entire life cycle, the R(t) is probably when the T is more than it (T>t). The function can be estimated by the non-parametric Kaplan-Meier curve or one of the parametric distribution functions. It can be expressed by the following equation:

$$\mathrm{R(t)} = \mathrm{S(t)} = \int_t^\infty \mathrm{f}(x)d(x) \ = 1 - F(t) \tag{2-8}$$

As shown in Fig.2-4, the system reliability decreases exponentially as time increases [15]:

$$\mathrm{R(t)} = e^{-\lambda t} \tag{2-9}$$

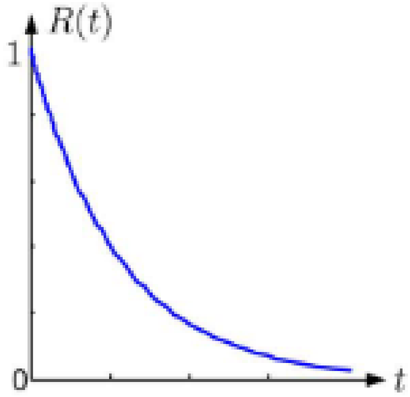


Fig.2-4 Reliability function [14]

Hazard function, h(t)

According to the reliability function, the failure rate can be expressed as the hazard rate. hazard rate is the probability of failure that rate between the time t and time $t + dt$ in survivors. It can be expressed with the following equation:

$$h(t) = \frac{f(t)}{R(t)} = \frac{f(t)}{1-F(t)} \tag{2-10}$$

Cumulative hazard function, H(t)

Cumulative hazard function is the integral of the Hazard function from time 0 to t. It can be expressed as the following equation:

$$H(t) = \int_0^t h(x)dx = -\ln[R(t)] \tag{2-11}$$

Availability

Availability is defined as the ability of a project (in the integrated aspects of its reliability, maintainability, and maintenance support) to perform its required functions at a specified time point or within a specified time period.

$$A = \frac{MTTF}{MTTF+MTTR} = \frac{\mu}{\lambda+\mu} \tag{2-12}$$

Here, the MTTR sometimes can be substituted by the Mean Downtime (MDT) to make it clean to show the downtime. In addition to reliability and availability, there are other concepts that describe the reliability of a component or system. Such as maintainability, safety, security, dependability and quality [1].

Maintainability is defined as the ability of an article to remain or be restored to a state capable of performing its prescribed functions under prescribed conditions of use, when maintenance is carried out using prescribed procedures and resources.

Safety is defined as freedom from conditions that may result in death, injury, occupational disease or damage or loss of equipment or property.

Security is defined as the reliability of preventing deliberate hostilities.

Dependability is defined as a collection of terms used to describe availability performance and its impact factors: reliability performance, maintainability performance, and maintenance support performance.

Quality is defined as the sum of the characteristics and characteristics of a product or service that relate to its ability to meet stated or implied requirements.

2.2.3. Application Areas

The primary goal of reliability research should always be to provide information as a basis for decision making. Before the reliability study is launched, the decision maker should clarify the decision problem, and then the research objectives and boundary conditions and restrictions should be specified, so that the relevant information needed as the input of the decision in the correct format, and time.

Reliability technology has broad application prospect. Some of the areas listed below illustrate the widespread use of reliability techniques. In this chapter, some application areas of reliability are introduced and reviewed. The application area and specification are shown in Table 2-1. The application areas include the Risk analysis, Environmental protection, Quality, Optimization of maintenance and operation, Engineering design, Verification of quality/reliability [1].

According to the reliability analysis, the potential accidental events can be derived, the application reliability analysis methods such as Checklists, Preliminary hazard analysis and so on. The causal analysis can be applied to identify the causes which lead to the accidental events occurred. The following reliability analysis methods can be used to do the casual analysis, like Fault tree analysis, Reliability block diagrams, influence diagrams, Failure mode, effects, and criticality analysis (FMECA) method, Reliability data sources and so on. The consequence analysis can be applied to predict the consequence which after the accidental events occurred. The following reliability analysis methods can be used to do the consequence analysis, like Event tree analysis, Consequence models, Reliability assessment, Evacuation models and Simulation.

The reliability assessment of system is applied to maintain or improve the system reliability and production/operation regularity. For instance, the Reliability Centered Maintenance (RCM) approach is a main tool to improve the cost-effectiveness and control of maintenance in all types of industries, and hence to improve availability and safety. Reliability assurance should be an important topic during the engineering design process. The reliability assessment also applied the system redesign or replacement.

DER system is a complex, repairable and long-life cycle system, the functions of the DER system are to generate the electricity and to meet the energy load (electricity, heating and cooling). Therefore, the risk analysis, environmental protection, quality (supply the energy to customers), optimization of maintenance and operation (for the long-life cycle and repair system) are requested for the DER system. When the system or components are needed to replace or redesign, the reliability assessment and analysis are necessary. In addition, the DER system also produces the carbon emissions during the power generation process. Therefore, the reliability assessment and analysis are benefit for the environmental protection.

Table 2-1 The application area of reliability

Application area	Application specification
Risk analysis	➢ Identification and description of the potential accidental events. ➢ To find the potential causes of the accidental events which lead to the accidental events occurred. ➢ To design the various barriers and safety functions system to avoid the accidental events occurred and to reduce the consequences of accidental events.
Environmental protection	➢ Reliability and regularity studies can be used to optimize production processes in environmental industries such as sewage treatment plants. Can reduce the harm to the environment in the production process. ➢ An environmental risk analysis is carried out based on the reliability assessment and analysis.
Quality	➢ Reliability may in some respects be considered to be a quality characteristic. Reliability is a key part of quality management. Therefore, the reliability management is the main part of the total quality management (TQM).
Optimization of maintenance and operation	➢ To maintain or improve the system reliability and production/operation regularity. ➢ The RCM approach is a main tool to improve the cost-effectiveness and control of maintenance in all types of industries, and hence to improve availability and safety. ➢ Reliability assessment is also an important element of some applications, such as life cycle cost, life cycle profit, logistic support, spare part allocation and manning level analysis.
Engineering design	➢ Reliability assurance should be an important topic during the engineering design process. ➢ The reliability assessment also applied the system redesign or replacement.
Verification of quality/reliability	Reliability is used to assess the quality and reliability.

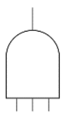
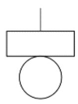
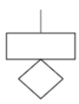
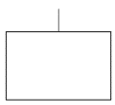
2.3. Reliability Analysis Methods

2.3.1. Fault Tree Analysis Methods

In cases where complex multi-component systems must be handled, system reliability needs to be obtained as objective function or constraint function. Fault tree analysis is one of the most commonly used techniques to evaluate the reliability of complex systems [16].

The fault tree is a logical diagram that shows the correlation between a potential accident event in the system and the cause of the event. This could be due to environmental conditions, human error, normal events (events expected to occur during the system lifecycle), and specific component failures [1]. Fault tree analysis can be used for qualitative and quantitative analysis, or both qualitative and quantitative analysis. The Boolean logic relation and symbol of the fault tree allow the complexity of the decomposition system, and then build the overall graphics structure of the top-level fault.

Table 2-2 Fault tree symbols [1, 16]

Items	Symbol	Meaning of Symbol
Logic gates	 Or-gate	The Or-gate presents that the output event occurs if any input events occur.
	 And-gate	The And-gate presents that the output event occurs only when all the input events occur at same time.
Input events	 Basic event	The basic event represents a basic component failure that requires no further development of failure causes.
	 Undeveloped event	The undeveloped event represents an event that is not examined further because information is unavailable or because its consequence is insignificant.
Description	 Comment rectangle	The comment rectangle is for supplementary information.
Transfer symbols	 Transfer-out	The transfer-out symbol indicates that the fault tree is developed further at the occurrence of the corresponding transfer-in symbol.
	 Transfer-in	

The symbols of the fault tree analysis are shown in Table 2-2. The symbols include the Logic gates, Input events, Description and transfer symbols. The Or-gate presents that the output event occurs if any input events occur. The And-gate presents that the output event occurs only when all the input events occur at same time. The symbols are used to describe and analyze the reliability relationship between the failures and events.

A lot of literatures presented the application of Fault tree analysis, and it is widely used in various systems or equipment reliability analysis. Fault tree analysis is used to identify the delay risk, and a cost-benefit mitigation strategy for low volume and high value supply chain is proposed [17]. It is evaluated on the basis of a list of materials for the products under study. Liu et al [18] proposed the method of combining fault tree analysis and quantitative analysis to investigate the high-speed railway accidents. Andrija Volkanovski et al [19] presented a fault tree analysis method for the power system reliability evaluation. The quantitative evaluation of fault tree is an important aspect of power system reliability evaluation, which can identify the most important components in power system.

2.3.2. Failure Mode and Effect Analysis

Failure modes and effects analysis (FMEA) was one of the first highly structured and systematic techniques for failure analysis. It is a systematic method for analysis and ranking the risks associated with various products or processes, failure modes, prioritizing them for remedial action, acting on the highest ranked items, reevaluating those items and returning to the prioritization step in a continuous loop until marginal returns set in. It involves reviewing as many components, assemblies, and subsystems as possible to identify failure modes, and their causes and effects. For each component, the failure modes and their resulting effects on the rest of the system are recorded in a specific FMEA worksheet. Failure modes and effects analysis has been used on different types, such as functional analysis, design analysis, process analysis and so on. FMEA is to divide a device to multiple subsystems, and then analysis the failure reason or modes for every subsystem. The method not only can clear the system conditions, it also can know the conditions of every subsystem. Failure modes and effects analysis procedure commences with reviewing design details, illustrating equipment block diagram and recognizing all potential failures, respectively.

A large number of FMEA methods are used to analyze the reliability analysis and maintenance priority of the system. Fenando and Gilbetro presented an application of FMEA to identify critical components for system reliability and maintainability evaluation of Gas Turbines which are used in the power plants [20]. Kang Jichuan, et al. [21] presented and evaluated a correlation FMEA method of the floating offshore wind turbine risk assessment. The reliable index vector method is employed to calculate correlation of failure modes, and to obtain the weakest failure basis of the FOWT system. Probability Network Evaluation Technique (PNET) was used to get the weakest failure modes set of the system based on those coefficients. The relative importance of risk factors O, S and D have been considered and evaluated in a linguistic manner rather than by precise numerical values, which makes the prioritization of failure modes more realistic and objective. For example, the historical data can be applied to determine the weights of risk factors, or a higher weight can be assigned to the factor that is more concerned about, which can make the results more aligned to the practical situation [5]. Sharma and Srivastava compared between the quantitative results of FMEA and reliability field data from real tube systems. These results are discussed to establish relationships which are useful for future water tube designs [22].

Most FMEA approach applications use the risk priority number (RPN) to evaluate and present the risk of failure and maintenance importance index. There are three factors are used to calculate the RPN, include Severity, Occurrence and Detection. Severity (S), occurrence (O), and detection (D) factors are rated separately using numerical scales, usually ranging from 1 to 10 [23]. The details of the three factors can be descripted as the follows [24]:

Severity (S): Result generated from failure.

Occurrence (O): Opportunity or probability of a failure.

Detection (D): Opportunity for an unidentified failure because of the difficulty in detection.

The RPN can be expressed as:

$$\mathrm{RPN} = \mathrm{S} \times \mathrm{O} \times \mathrm{D} \quad (2\text{-}13)$$

Generally, the process steps of FMEA approach presented as the following:

1) System detail and function analysis;
2) Draw the functional tree and equipment block diagram;
3) Identify the failure mode and failure effect based on the failure data;
4) Confirm the Severity (S), occurrence (O), and detection (D) factors;
5) Calculate the RPN;
6) Propose the maintenance decision.

In addition, the FMEA method is used to analyzed the failure mode, failure position and failure reason of the system or components failures. The failure analysis process flow is shown in Fig.2-5.

The failure analysis process by the FMEA method as the following:

Step1: to collect and identify all internal and external factors, components and their relationships, parameters.

Step 2: to get the description of power generation system, and build the system block diagram.

Step 3: to determine the failure modes, failure positions, and find the failure reasons.

Step 4: to analyze the failures.

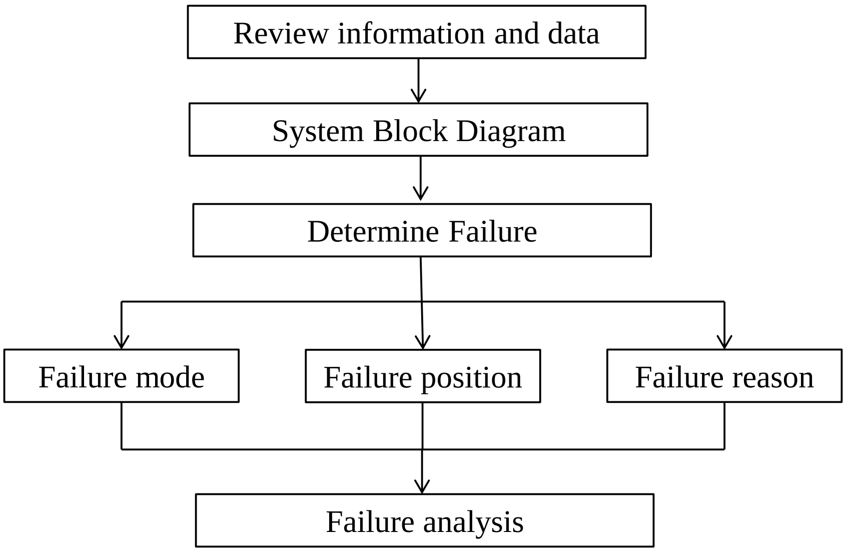


Fig.2-5 Failure analysis process flow by the FMEA method

2.3.3. Failure Mode Effects and Criticality Analysis

Failure mode effects and criticality analysis method (FMECA) is an extension of failure mode and effects analysis. FMECA method extends the FMEA method through including the criticality analysis, not only analysis the failure modes and effects [25]. The criticality analysis may be quantitative or qualitative, depending on the availability of supporting part failure data. The FMECA method can assess the severity of failures in different subsystems, and evaluate the effects of different failures on the overall system. It can help to find the defect of system, and adopt corresponding measures to improve system reliability. The FMECA methods procedure typically consists of the following steps: define the system; define ground rules and assumptions in order to help drive the design; construct system block diagrams; analyze failure effects/causes; feed results back into design process; classify the failure effects by severity; perform criticality calculations; rank failure mode criticality; determine critical items; feed results back into design process; identify the means of failure detection, isolation and compensation; perform maintainability analysis; document the analysis, summarize uncorrectable design areas, identify special controls necessary to reduce failure risk; make recommendations; follow up on corrective action implementation/effectiveness.

According to the output of Table 2-3, the FTA method is good at showing how resistant a system is to single or multiple initiating faults. It is not good at finding all possible initiating faults. FMECA methods can systematic establishment the relationship between failure causes and effects, and can point out the individual failures. But it will have a more complexed work when the ranges of failures are large. This research chooses the FMEA method to analyze the failures of power generation unit. The mainly works are to do the failure modes analysis of the failures have occurred.

Table 2-3 Compare the function of FTA, FMEA and FMECA

Analysis method	Advantages	Disadvantages	Characteristic
FTA	Can show how resistant a system is to single or multiple initiating faults.	Cannot find all possible initiating faults; Complex.	A deductive, top-down method, analyzing the effects of initiating faults and events on a complex system.
FMEA	Comprehensiveness, structured, detailed approach.	Process time consuming, human error is limited.	Can obtain the failure modes, analysis the subsystem, results in action to reduce failures.
FMECA	Comprehensiveness, Systematic establishment the relationship, can point out individual failure.	Extensive labor required, large number of trivial cases considered, inability to deal with multiple-failure scenarios.	Can obtain the risk assessment; and also, can obtain the by severity assessment of subsystem.

2.3.4. Reliability Block Diagram

Reliability block diagrams are usually used to describe the relationship between the functions of a system and the functions of its components [16]. Reliability block diagram is a graphical analysis technique that represents the system being analyzed as a connection between multiple components according to the logical relation of reliability [26]. Reliability block diagrams do not necessarily represent how components are physically connected in the system. It shows only how the functioning of the components will ensure the functioning of the system. This is why the reliability block diagram represents the logical relationship between the functionality of the system and its component functionality. The basic reliability block diagram contains two types of connections, series structure and parallel structure. Fig.2-6 is shown the reliability block diagram of series system; Fig.2-7 is shown the reliability block diagram of parallel system. In general, reliability chart boxes are read from left to right, as shown in Fig.2-6, the single flows through the components from component 1 to component

3. If any components fail, the function of the system will not be got. But for a parallel system, as long as any one component can work, the whole system is considered to be working. As shown in Fig.2-7, the components are standby to each other.

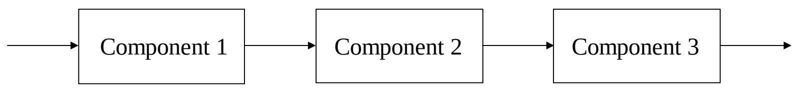


Fig.2-6 Reliability block diagram of series system

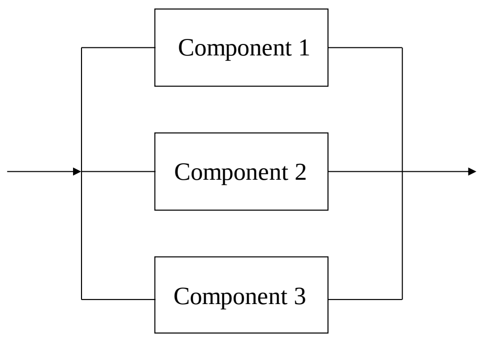


Fig.2-7 Reliability block diagram of parallel system

However, for a complex and repairable system, such as distributed energy systems, power generation systems. The system function is not simple series structure and parallel structure, as shown in Fig.2-8. And a system may contain multiple subsystems. Hence, it may to have both series and parallel structures in a system. If the whole system includes multiple function subsystems, each function subsystem must be considered individually, and a separate reliability block diagram has to be established for each system function. Reliability block diagrams are suitable for systems that do not repair components, and the order in which failures occur does not matter. When the systems are repairable and/or the order in which failures occur is important, Markov methods will usually be more suitable.

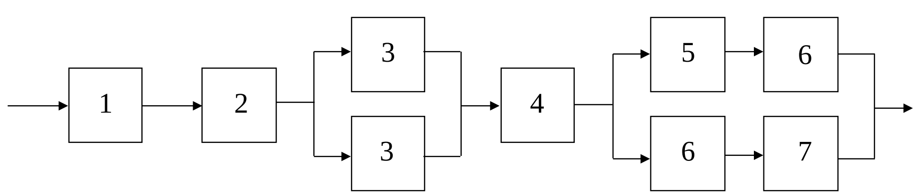


Fig.2-8 System function illustrated by a reliability block diagram

2.3.5. Markov Process with State-Space Method

Some reliability analysis methods with stochastic processes are used to analyze the reliability of a repairable system, such as Homogeneous Poisson Processes, Renewal Processes, and Markov

Processes etc. the most widely used analysis method is the Markov Processes, which can be used to model systems with several states and transitions between the states [1]. Reliability assessment methods of multistate systems are based on two different approaches: analytical stochastic process and the Monte Carlo simulation method. The Markov process is the main analytical stochastic process, since it can be used to perform the reliability analysis of a system that has changed continuously or discretely with the passage of time and space. The State-Space Method (SSM) is applicable for the assessment of reliability, availability, and maintainability of large and complex systems, and it is considered an irreplaceable method for evaluating repairable and complex systems.

Markov chain is a stochastic process $\{S(t), t \geq 0\}$ with Markov property. The random variable $S(t)$ denotes the state of the process at time t. The collection of all possible states is called state space. The time may be discrete taking values in (0, 1, 2⋯}, or continuous. When the time is discrete, we have a discrete-time Markov chain; and when the time is continuous, we have a continuous time Markov chain. A continuous-time Markov chain is also called a Marko process [27].

The state of a system depends on the state of its individual components; each component has two states: functioning (1) and failed (0). Since each component has two states (functioning or failed), when a system has *n* quantity of components, the system still will have at most 2^n possible states. The state of a system is transferred randomly with time in those states. A Markov model based on a state–space method (SSM) is performed for the reliability analysis of a system with two components. The Markov model and possible states of the system are shown in Fig.2-9 and Table 2-4, respectively. The failure rate (λ) is represented by the transition rate of one component from a functioning state to failed state. Similarly, the repair rate (μ) is represented by the transition rate of one component from a failed state to a functioning state. Thus, the failure rate and repair rate of a component is used to describe the transition rate between two states of the system. The reliability and availability analysis model using the Markov process and SSM can be decomposed into the following steps:

1) List and classify all system states; the same state should be merged, and the non-related state should be removed.

2) Construct the state space diagram of system; confirm the transition rate between states.

3) Calculate the probabilities of the states during a lifetime.

4) Calculate the reliability and availability indices, such as the failure rate (generally represented by mean time to failure), repair rate (generally represented by mean time to repair) and availabilities of components.

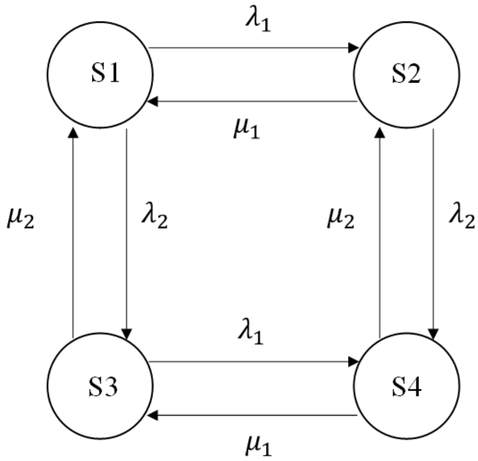


Fig.2-9 Markov model of a system with two components

Table 2-4 Possible states of a system with two components

Items	Component 1	Component 2
Failure rate	λ_1	λ_2
Repair rate	μ_1	μ_2
State 1	1	1
State 2	0	1
State 3	1	0
State 4	0	0

There are two states for every component: a functioning state (1) and a failed state (0).

A steady-state distribution system is used to limit the Markov processes. Generally, a set of linear, order differential equations are established to determine the probability distribution of the system. The probability distribution equation is shown:

$$P(t) = [P_1(t), P_2(t), \dots, P_n(t)] \tag{2-13}$$

where the $P_i(t)$ is the probability of the system in state i at time t and $P(t)$ is the state probability matrix at time *t*.

A density matrix, Q, is defined as the following:

where, $q_{ij} = \lambda_{ij}(\mathrm{i} \neq j)$, and $q_{ii} = -\sum_{i \neq j} \lambda_{ij}$.

$$Q = \begin{bmatrix} q_{11} & q_{12} & \cdots & q_{1n} \\ q_{21} & q_{22} & \cdots & n \\ \vdots & \vdots & \ddots & \vdots \\ q_{n1} & q_{n2} & \cdots & q_{nn} \end{bmatrix} \tag{2-14}$$

The following state equations are presented for the steady–state probability of the system:

$$\begin{cases} P \cdot Q = 0 \\ \sum P_i = 1 \end{cases} \tag{2-15}$$

Thus, for a system with two components as shown in Fig. 2-9 and Table 2-4, the state transition density matrix is presented as:

$$\text{Q}= \begin{bmatrix} -(\lambda_1+\lambda_2) & \lambda_1 & \lambda_2 & 0 \\ \mu_1 & -(\mu_1+\lambda_2) & 0 & \lambda_2 \\ \mu_2 & 0 & -(\mu_2+\lambda_1) & \lambda_1 \\ 0 & \mu_2 & \mu_1 & -(\mu_1+\mu_2) \end{bmatrix} \tag{2-16}$$

Based on Equation (2-15), the following equations can be acquired:

$$\begin{cases} -(\lambda_1+\lambda_2)P_1+\mu_1 P_2+\mu_2 P_3=0 \\ \lambda_1 P_1-(\mu_1+\lambda_2)P_2+\mu_2 P_4=0 \\ \lambda_1 P_1-(\mu_1+\lambda_2)P_2+\mu_1 P_4=0 \\ \mu_2 P_2+\mu_1 P_3-(\mu_2+\mu_1)P_4=0 \\ P_1+P_2+P_3+P_4=1 \end{cases} \tag{2-17}$$

The state probabilities of the system are obtained through solving the Equations in (2-17), with the following results:

$$P_1 = \frac{\mu_1\mu_2}{(\lambda_1+\mu_1)(\lambda_2+\mu_2)} \tag{2-18}$$

$$P_2 = \frac{\lambda_1\mu_2}{(\lambda_1+\mu_1)(\lambda_2+\mu_2)} \tag{2-19}$$

$$P_3 = \frac{\lambda_2\mu_1}{(\lambda_1+\mu_1)(\lambda_2+\mu_2)} \tag{2-20}$$

$$P_4 = \frac{\lambda_1\lambda_2}{(\lambda_1+\mu_1)(\lambda_2+\mu_2)} \tag{2-21}$$

2.4. Maintenance Analysis Theories and Methods

2.4.1. Maintenance Concepts

Maintenance is essential to keep buildings, infrastructure and equipment in optimum condition for normal use [28]. According to the Classic view, the role of maintenance is to repair damaged items. This view limits maintenance to repair behavior after a failure occurs. Those methods are called reactive maintenance, fault maintenance, or corrective maintenance. A maintenance definition has been proposed by Geraerds (1985) is widely recognized, "the all maintenance activities aimed at keeping an items in, or restoring it to, the physical state considered necessary for the fulfillment of its production function" [29]. In addition, there is another definition that considers the strategic dimension of maintenance. That is to say it should then include decisions that shape the organization's future maintenance needs [30]. The details of maintenance concepts are shown in Table 2-5.

Table 2-5 The maintenance concepts on the different definition

Items	Definition	Maintenance activities
Maintenance from classic view	Maintenance is to repair damaged items. That is to perform the repair behavior after a failure occurs.	Reactive maintenance; fault maintenance; corrective maintenance or called repair.
Maintenance from production system	The all maintenance activities aimed at keeping an item in, or restoring it to, the physical state considered necessary for the fulfillment of its production function.	The maintenance activities include: routine servicing, periodic inspection, preventive replacement, condition monitoring etc.
Maintenance from strategic dimension	The engineering decisions and associated actions necessary and sufficient for the optimization of specified capability.	Equipment replacement decisions, design modifications, and so on.

Obviously, compared with the classic view of maintenance, production maintenance expands the scope of maintenance, including not only passive repair maintenance and fault maintenance, but also periodic inspection, condition monitoring, component replacement and preventive replacement in the process of maintenance to ensure the safety and reliability of production. However, while production maintenance improves system reliability, security, and availability, it also increases the cost and complexity of maintenance. The maintenance and management of equipment often cannot be completed by one part, which requires the cooperation of several departments or even several companies. For example, for a production system with multiple equipment, routine inspection and component replacement can be performed by the operator (user), while regular inspection of equipment may be performed by the outsourcing service provider, and overhaul of equipment may be required by the manufacturer.

Maintenance from strategic dimension view, these maintenance activities include equipment replacement decisions and design modifications to improve equipment maintainability and reliability. Therefore, the strategic decision for maintenance can be considered a level above production maintenance. The Maintenance Engineering Society of Australia (MESA) defines this maintenance as "the engineering decisions and associated actions necessary and sufficient for the optimization of specified capability" [29]. Therefore, the scope of maintenance management should cover every stage of the life cycle of technical systems (plant, machinery, equipment and facilities): specification, acquisition, planning, operation, performance evaluation, improvement and disposal. The characteristics of maintenance capabilities include functionality, capacity, rate, quality, responsiveness, and degradation. And the maintenance capabilities also known as physical asset management (PAM). The relationship of the three maintenance concepts is presented in the Fig.2-10.

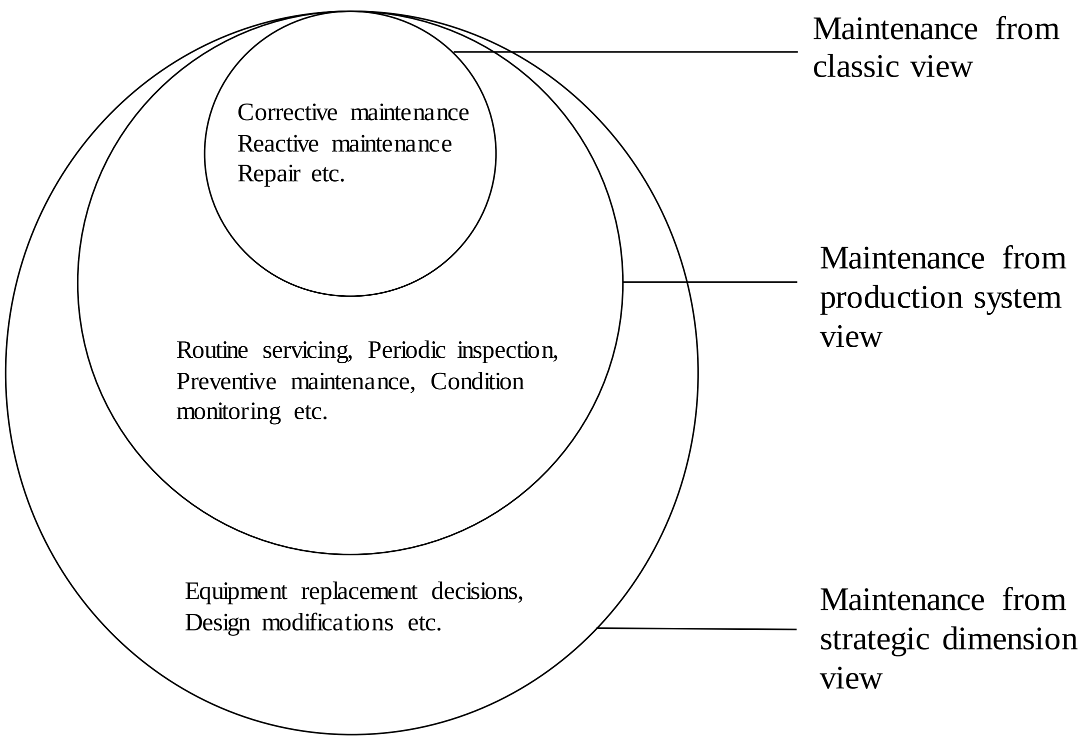


Fig.2-10 The relationship of the three maintenance concepts

For the DER system maintenance management, because a DER system is composed of multiple subsystems and a large number of components, the requirements for and maintenance vary greatly. Some components do not require routine maintenance, only regular replacement, while some components require routine maintenance or even real-time monitoring. Therefore, this chapter introduces the commonly used methods in system maintenance. In addition, For the maintenance of a system, there is the problem of maintenance priority, and a maintenance priority method is also introduced here.

2.4.2. Types of Maintenance

There are a variety of maintenance types to ensure the normal operation and production of equipment, the organization decides to use one or more maintenance types according to the maintenance budget, resources, personnel level, maintenance objectives and so on.

The types of maintenance can be divided into preventive maintenance and corrective maintenance. The classification of maintenance types is shown in Fig.2-11. Preventive maintenance is the maintenance activities that is performed before the failure occurs. Generally, the preventive maintenance divided into two kind of maintenance, one is the time-based maintenance and another is the condition-based maintenance. The corrective maintenance is a type of proactive maintenance, it performed after the failure occurs. It includes generally corrective maintenance and emergency maintenance. More details are introduced as the followings.

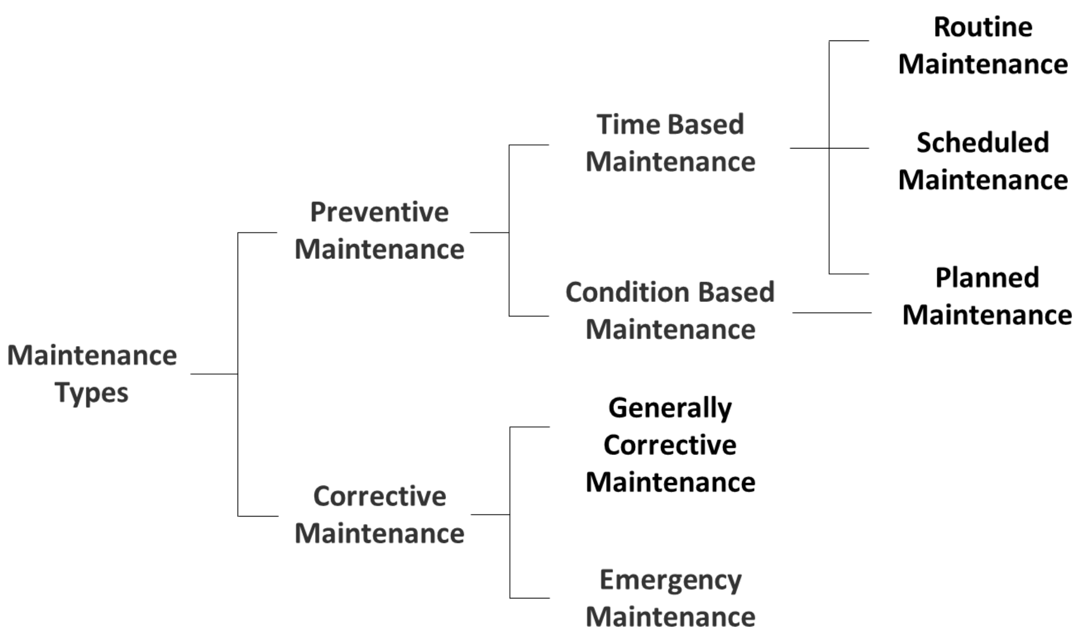


Fig.2-11 Classification of maintenance types

Time Based Maintenance

Time-based maintenance is a type of preventive maintenance that performs equipment or system maintenance based on a time schedule, time intervals are set by engineers or managers according to maintenance requirements, resources, etc. The time period can be daily, weekly, monthly or a certain running time. According to the different forms of organizational planning, maintenance according to the time can be divided into three aspects, Routine maintenance, Scheduled maintenance and Planned maintenance.

Scheduled Maintenance

Scheduled maintenance includes work that is scheduled to be done on the calendar. The most common types of periodic maintenance are calendar-based preventive maintenance tasks. These are all arranged in advance. For example, the equipment should be inspected once a month or per 1000 operation hours and so on. But schedule maintenance doesn't mean it has a plan for the maintenance.

Planned maintenance

Planned maintenance is defined as the maintenance is prepared for in advance of the maintenance are performed. That is, before maintenance is performed, the organizer or maintainer has planned to use the available resources to complete the planned maintenance, not only the maintenance-level plan, but also the maintenance time plan (such as time: few days etc.). Planned maintenance can include planned repairs, overhauls, etc. Planned maintenance is less frequent and performer may be more professional. More Planned maintenance means better completion of the scheduled maintenance.

Routine Maintenance

Routine maintenance is a type of maintenance that is performed more frequently than scheduled maintenance. Maintenance activities may be performed at intervals of a day or several hours. In addition, routine maintenance is performed by operators, doormen and other staff, while preventive maintenance is performed by technicians. Non-routine maintenance includes reactive maintenance as needed based on the condition of the asset or maintenance as needed only.

Condition Based Maintenance

Condition Based Maintenance (CBM) is the core of predictive maintenance, and it is a form of active maintenance to predict initial failure of equipment. It monitors the actual situation of the asset to determine what maintenance is required and should be maintained only if some metrics show performance degradation or impending failure. These metrics for checking the machine may include non-intrusive measurements, visual checks, performance data, and scheduled tests. State data can then be collected at a certain interval or continuously (just like What the machine does when it has an internal sensor). Condition Based Maintenance processes help identify and correct problems in the early stages, which can significantly improve equipment reliability and reduce costs. CBM can be applied to both mission-critical and non-mission-critical assets.

Emergency maintenance

Emergency maintenance occurs when the asset requires immediate attention to keep the facility running or safe. This is the most reactive and intrusive type of maintenance because it pulls technicians away from other work, reducing progress compliance. In extreme cases, depending on the scope of the repair, the importance level of available parts and assets, emergency maintenance can enable the organization to push few days later. In order to reduce unscheduled and unplanned emergency maintenance, the organization uses various forms of proactive maintenance.

Corrective maintenance

Corrective maintenance is essentially part of emergency maintenance because something needs to be corrected or repaired in the event of an emergency. In this way, corrective maintenance is primarily reactive. However, it can also be proactive. If an asset with a status monitoring sensor detects a problem, a work order is created and a technician is sent to correct it. Preventive maintenance is considered corrective maintenance if there is a problem that needs to be repaired. This is rare because PM is usually performed when the asset is in good working condition.

Other Types of Maintenance

In addition, there are other types of maintenance, For instance, Breakdown Maintenance, Deferred Maintenance, Total productive maintenance and so on.

Deferred maintenance is the repair of infrastructure and assets, which have been delayed and backlogs due to budgetary constraints and lack of funding. Breakdown Maintenance is the maintenance of a faulty or unusable device. This is different from preventive maintenance, where preventive maintenance is performed to keep something running, because the goal of fault maintenance is to fix something that is completely out of work. Total production maintenance (TPM) is the integrity of machines, equipment, processes, and employees that add business value to the organization through machines, equipment, processes, and employees, maintaining and improving the integrity of production and quality systems.

2.4.3. Maintenance Prioritization

Maintenance management is the compulsory cost and core business that equipment management organization must face. If the implementation is not good, it will have very serious consequences, such as the stagnation of production and the increase of maintenance cost. A sound maintenance strategy will effectively reduce unnecessary losses. The previous article described several types of maintenance. In general, proper maintenance management may require consolidation of centralized maintenance types. However, for complex systems, different devices have different maintenance requirements. Thus, how to determine the type of maintenance required by the device in the system is very important.

Maintenance priorities are one method to identify maintenance types and maintenance policies [31]. Proper maintenance prioritization enables organization to ensure their maintenance performance remains in the acceptable level [28]. In industrial production, the priority is the allocation of resources, management or the expression of preference, a particular order or order grouping (whether supply, production, or customer order), to deal with the current pressure operating efficiency and/or customer service, the purpose is to reduce these pressures, at the same time to promote, or to reduce the harmful effects of the broader economic and strategic objectives of the company [32]. Shen and Spedding [33] see maintenance priorities as a way to address the lack of allocation. This approach is often used to relieve the pressure of temporary maintenance requirements, allowing more urgent project requirements to be addressed first. In addition, this approach can be applied to the decision-making process of maintenance strategies and to corrective maintenance after a failure occurs.

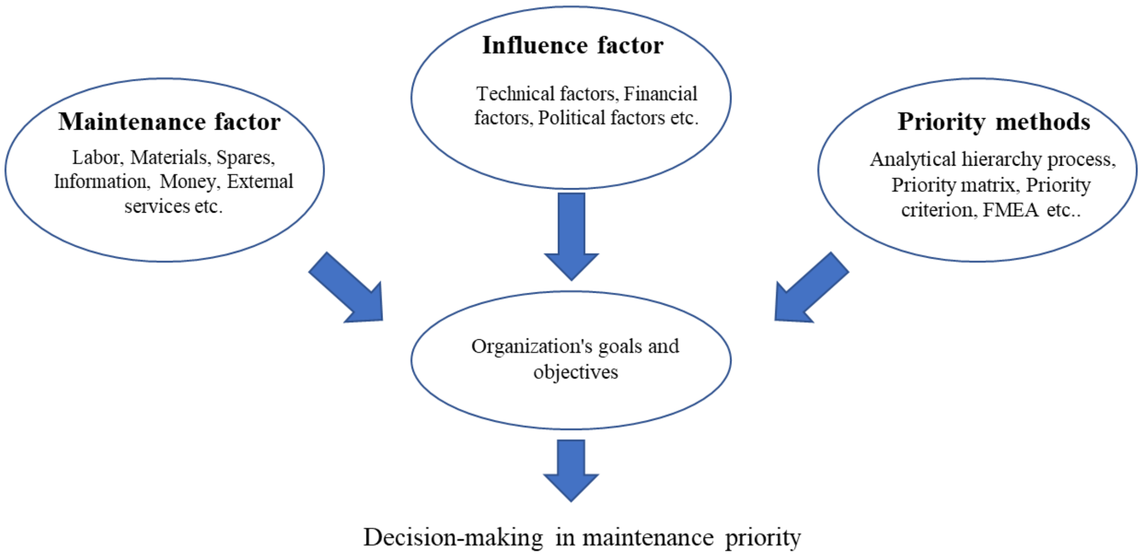


Fig.2-12 A decision-making model of maintenance prioritization

A decision-making model of maintenance prioritization is shown in Fig.2-12. The maintenance factor, influence factor and priority methods are inputted into the decision-making model of maintenance prioritization, according to the organization's goals and objectives, a maintenance priority will be made for the maintenance activities. The maintenance factors include Labor, materials, spares, information, money, external services etc. The influence factors include Technical Factors, Financial factors, Political factors etc. There are many methods can be used for the maintenance prioritization, such as analytical hierarchy process [34], Priority matrix [35], Priority criterion [36], FMEA and so on. FMEA method has been introduced in chapter 2.3.2.

In making decisions about maintenance priorities, decisions are determined not only by the given conditions, but also by the experience and ability of the decision maker. The decision-making method can provide a good reference for decision makers.

The organization's goals and objectives are the most important determinants of maintenance priorities. Schraven et al [37] proposed that the lack of understanding and clarity about the organization's goals and objectives, which are the primary guide to the business, can affect maintenance performance. Setting appropriate maintenance goals and objectives is critical because it sets a benchmark for evaluating maintenance performance and provides the necessary justification for setting maintenance priorities.

Among many goals and objectives, the main purpose of maintenance is to improve the reliability, availability and security of the system, ensure the production and output of the system, and maximize the interests of the organization. Minimal cost and maximum benefit are the primary conditions for maintenance optimization and maintenance priority decisions. Reliability is one of the primary purposes of maintenance. Reliability importance indices are one of the important factors used to find the most important reliability nodes and equipment in the system. Therefore, the reliability importance index is also one of the important factors to evaluate the reliability maintenance priority.

Reliability importance indices can be used to determine project prioritization of components in a system. Several reliability importance measures (RIM)—Birnbaum's measure [38, 39], Fussell–Vesely's measure [40], Criticality importance measure [41] for instance—have been proposed in previous studies. Based on those reliability importance measures; several importance indices were developed. Reliability importance is a function of maintenance results like operation time, failure, and repair characteristics of components in a system [42].

Marcantonio Catelani et al. described two metrics for the component reliability importance assessment on complex systems—credible importance potential (CIP) and improvement potential (IP) [43]. Rong Gao and Kai Yao presented some formulas for the calculation of the importance index of components of uncertain reliability systems [44]. Patrik Hilber and Lina Bertling presented two indices which evaluated the total interruption cost and those indices were applied and simulated on an electricity distribution network [45].

The Birnbaum's measure was developed in 1969, and it is defined as follows:

$$I_k^B(t) = \frac{\partial R_{sys}(t)}{\partial R_k(t)} = \frac{U_{sys}(t)}{U_k(t)} \quad (2\text{-}22)$$

where, I_k^B is the Birnbaum importance (BI) of the k^{th} component, $R_{sys}(t)$ is the reliability of system at time t, $R_k(t)$ is the reliability of k^{th} component at time t, $U_{sys}(t)$ is the unreliability of the system, $U_k(t)$ is the unreliability of the k^{th} component at time t.

Birnbaum's reliability importance measure presented that a component would be failed at time t. Component criticality importance (CI) [46] can be used to determine the probability that the component would be failed before time t.

$$I_k^C(t) = \frac{\partial R_{sys}(t)}{\partial R_k(t)} \cdot \frac{U_k(t)}{U_{sys}(t)} = I_k^B(t) \cdot \frac{U_k(t)}{U_{sys}(t)} \quad (2\text{-}23)$$

The reliability importance index can provide a good reference for decision makers and a basis for designers and decision makers to make maintenance priority decisions.

2.5. Summary

In this chapter, the basic concepts of reliability indices, types of maintenance and analysis methods are introduced. The reliability application areas are presented in here. The several reliability analysis methods, maintenance concepts, types of maintenance and maintenance prioritization are investigated and compared.

The basic reliability indices include failure rate, repair rate, Mean Time to Failure (MTTF), Mean Time to Repair (MTTR), Mean Time Between Failure (MTBF). Reliability and Availability computing methods are also described here. For instance, Probability Density Function (PDF), Cumulative Distribution Function (CDF), Reliability function, Cumulative hazard function.

The reliability application areas include risk analysis, environmental protection, quality, optimization of maintenance and operation, engineering design, verification of quality/reliability. DER system is a complex, repairable and long-life cycle system, the functions of the DER system are to generate the electricity and to meet the energy load (electricity, heating and cooling). Therefore, the risk analysis, environmental protection, quality (supply the energy to customers), Optimization of maintenance and operation (for the long-life cycle and repair system) are requested from the DER system.

Several reliability analysis methods are introduced and compared, the result shows that the FMEA methods are a suitable method to perform the complex and repairable system. The FMECA method will increase the difficulty of analysis.

The different levels of maintenance definitions are introduced and compared in this chapter. The various types of maintenance are described. The reliability importance index is one of the methods for determining the maintenance priority of complex systems.

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Chapter 3. Investigation on the Operation and Maintenance of the DER System in Kitakyushu Science and Research Park

3.1. Introduction

Maintenance management is an orderly and systematic approach of administrative, financial, and technical framework for assessing, planning, organizing, monitoring and evaluating maintenance and operation activities and their costs on a continual basis. Maintenance plan also depends on the maintenance experience; and the purpose of maintenance plan is to make sure the equipment can be operated on the system requirement functions. Therefore, an analysis of system maintenance strategy, system operation status, failure, maintenance cost and effect of the function are necessary.

The DER system is used to meet the electricity demand, space heating demand, space cooling demand and hot water demand of KSRP. A DER system refers to an energy system where energy is produced close to end use, typically relying on a number of modular and small-scale technologies. The system in Kitakyushu Science and Research Park includes the PV, fuel cell, gas engine, gas-fired absorption chiller, heat exchanger and gas boiler. In addition to the main equipment, the system also includes a large number of auxiliary equipment, such as various pumps (cooling water, heating supply, cooling supply, circulation, etc.), cooling towers, injectors, valves, pipes, etc.

In this chapter, the maintenance management strategy, operation status, replacement, failure, maintenance cost, and effect of power generation efficiency of the DER system in KSRP are investigated and analyzed.

3.2. The DER System in Kitakyushu Science and Research Park (KSRP)

3.2.1. Background of KSRP

The Kitakyushu Science and Research Park (KSRP) located in the western of Wakamatsu, Kitakyushu City, Fukuoka. The Kitakyushu City is an industrial city in Japan. The KSRP is in the west part of Wakamatsu District and in the northwest part of Yahatanishi District, the total area of development is approximately 335 hectares. Fig.3-1 is the Plan of Kitakyushu Science and Research Park. The KSRP was opened in April 2001. And the purpose of the KSPR is to gather national, municipal and private universities, which focus on science and engineering into the same campus, and the aims are the "future development of technology and the creation of new industries" and "becoming a center for academic research in Asia". The KSRP has some universities and facilities for industry-academic cooperation. There are four universities in KSRP; it includes the Faculty of Environmental Engineering of the University of Kitakyushu, Kyushu Institute of Technology, Graduate School of Information, Production and Systems of Waseda University. The Eco-campus was built as an environmental symbiosis, water recycling and generation of electricity and heat campus. It has some research institutes and companies in the park. Besides that, it has some buildings, such as collaboration center, semiconductor center, library, technology development and exchange center and so on [1, 2].

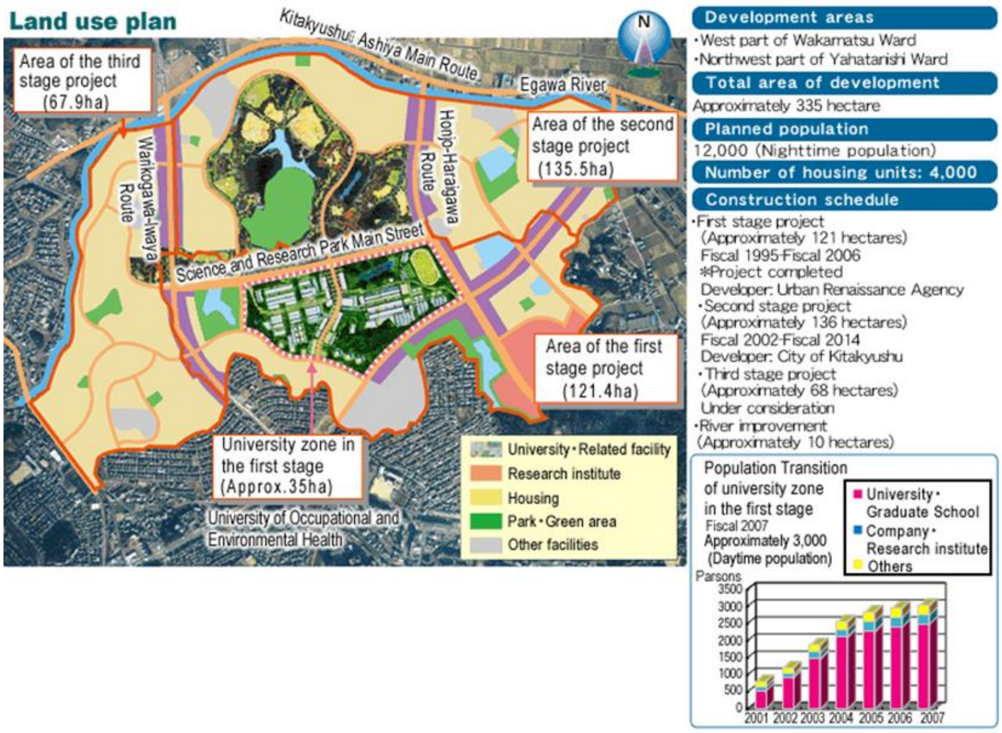


Fig.3-1 The land use plan of Kitakyushu Science and Research Park

(Source: Kitakyushu Science and Research Park website [1] and report 2012 [2])

Table 3-1 The main buildings and facilities in the KSRP

No.	**Building**	**Manager**
1	The Teaching Building, the University of Kitakyushu	the University of Kitakyushu
2	Special Experiment Ward, the University of Kitakyushu	the University of Kitakyushu
3	Instrumentation Center, the University of Kitakyushu	the University of Kitakyushu
4	Graduate School of Information, Production and Systems, Waseda University	Waseda University
5	Information, Production and Systems Research Center, Waseda University	Waseda University
6	Graduate School of Life Science and System Engineering, Kyushu Institute of Technology	Kyushu Institute of Technology
7	Energy Center	FAIS
8	Collaboration Center	FAIS
9	Semiconductor Center	FAIS
10	IT Advancement Center	FAIS
11	Business Venture Support Center	FAIS
12	Technology Development and Exchange Center	FAIS
13	Media Center (Library)	FAIS
14	Conference Center	FAIS
15	Gymnasium	FAIS
16	Dining hall	FAIS
17	Parking Space (Several parts)	FAIS
18	Stadium	FAIS

***FAIS: Kitakyushu Foundation for the Advancement of Industry, Science and Technology

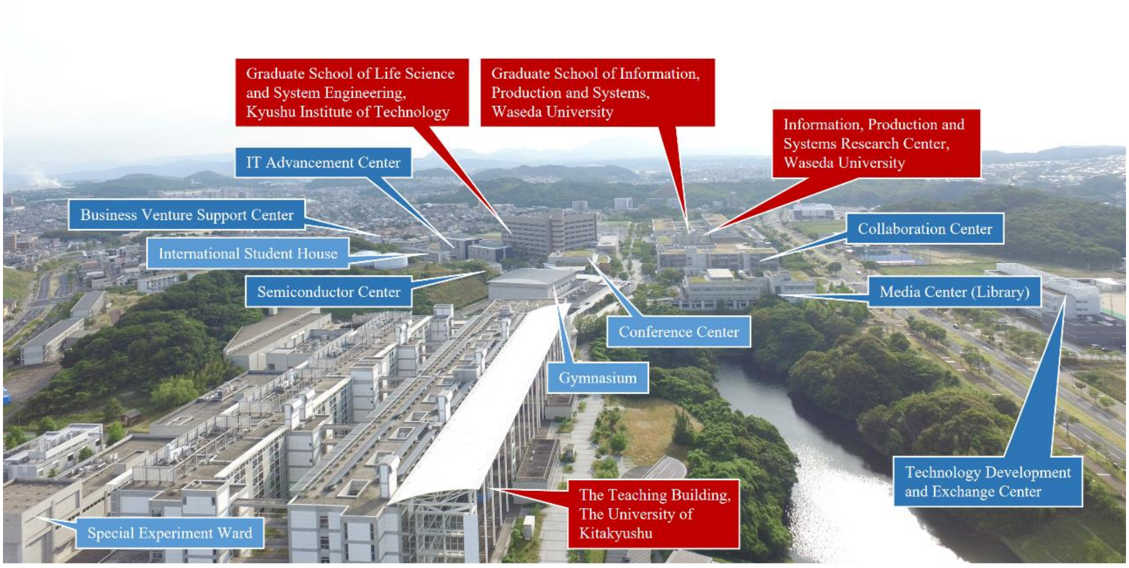


Fig.3-2 The plan of the main buildings and facilities in KSRP

(This picture was taken on 3rd June, 2019)

The main buildings and facilities in the KSRP are shown in Table 3-1. And the Fig.3-2 shows the plan of the main building and facilities in KSRP. The main teaching buildings include The Teacher Building, the University of Kitakyushu, Special Experiment Ward, the University of Kitakyushu, Instrumentation Center, the University of Kitakyushu, Graduate School of Information, Production and Systems, Waseda University, Information, Production and Systems Research Center, Waseda University, Graduate School of Life Science and System Engineering, Kyushu Institute of Technology. The office and research buildings include Collaboration Center, Semiconductor Center, IT Advancement Center, Business Venture Support Center, Technology Development and Exchange Center. The public buildings include Media Center (Library), Conference Center, Gymnasium, Dining hall. Some public facilities include Parking Space (Several parts) and Stadium. The university buildings are managed by the corresponding university; and the remaining buildings and facilities are managed by FAIS. In addition, the other facilities like street lamps, benches, etc. are also managed by the FAIS.

The Energy Center is the main part of building an environmentally pro-active campus supports the educational research activities in KSRP. The function of Energy Center is to supply the energy (electricity, heating, cooling and hot water), water; and to dispose of sewage water. Therefore, there are many and complex equipment are many of the facilities are located in Energy Center. For instance, power generation system, cooling and heating system, equipment monitoring system, middle water treatment system, water supply system, power exchange system, standby power equipment, maintenance centers, component stores and so on.

The energy center supplies electricity, heating, cooling and hot water to some buildings and facilities within the KSRP. It supplies energy just to some buildings and facilities rather than to all buildings and facilities of KSRP. As shown in Fig.3-3, the blue line is the energy supply line from the Energy Center.

In order to build an eco-campus, several technologies and measures were used to reduce the energy consumptions, improve the energy efficiency and the water use efficiency. Especially, in the faculty of environmental and engineering of the university of Kitakyushu campus, some technologies were used, such as the natural wind, natural light, green roofs and walls, underground heat storage system for air conditioning and heating, generation of electricity and heat, water recycling system and so on.

The distributed energy resource (DER) system in KSRP is the main technology to meet the energy demand and improve the environmental profit. The more details are introduced in next section.

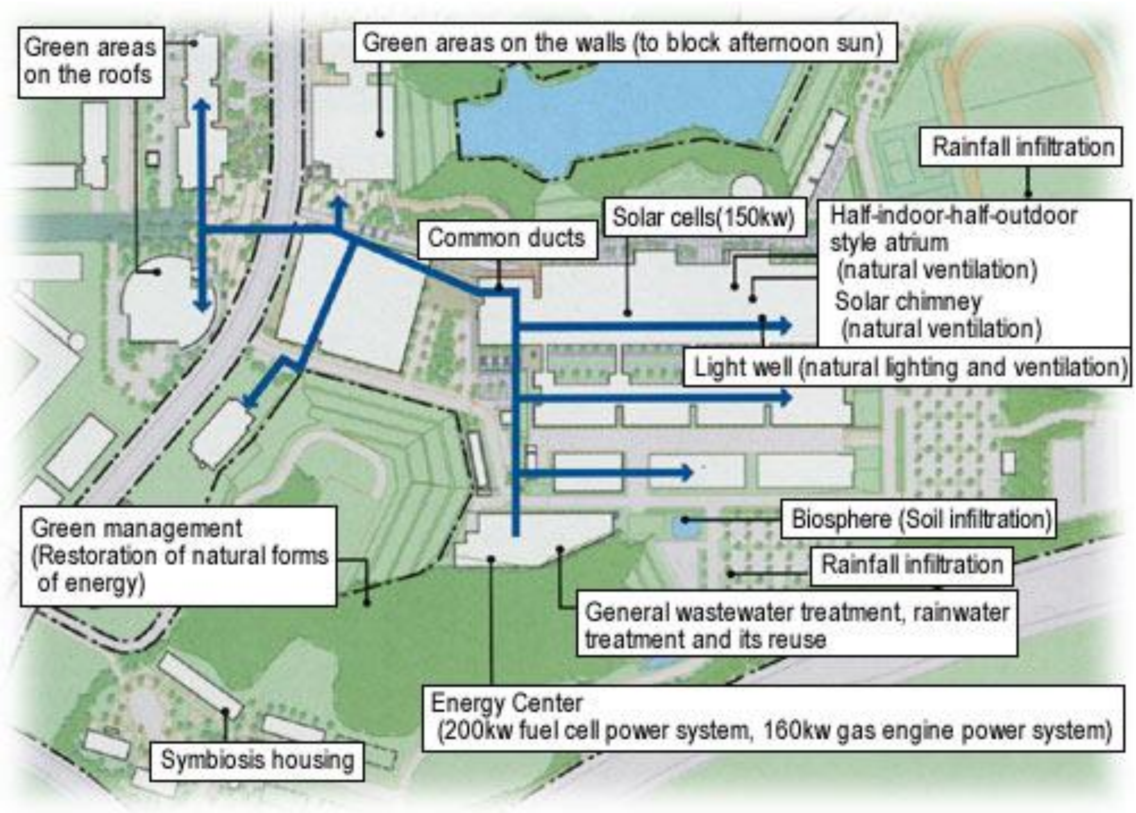


Fig.3-3 The eco-campus planning of KSRP
(Source: Kitakyushu Science and Research Park website [1])

3.2.2. Technologies of DER System in KSRP

The DER system is used to meet the electricity demand, space heating demand, space cooling demand and hot water demand of KSRP. A DER system refers to an energy system where energy is produced close to end use, typically relying on a number of modular and small-scale technologies [3]. The DER system has the highest efficiency of energy utilization and low environmental load. In the DER system of KSRP, the electricity is met by gas engine (the capacity is 160kW) and fuel cell (the capacity is 200 kW, and the fuel cell was stoppage in 2011 until now), PV and the electrical grid utilities of Kyushu. Gas boiler and waste heat from gas engine and fuel cell meet the heating load. And the waste from gas engine and fuel cell meets the cooling load.

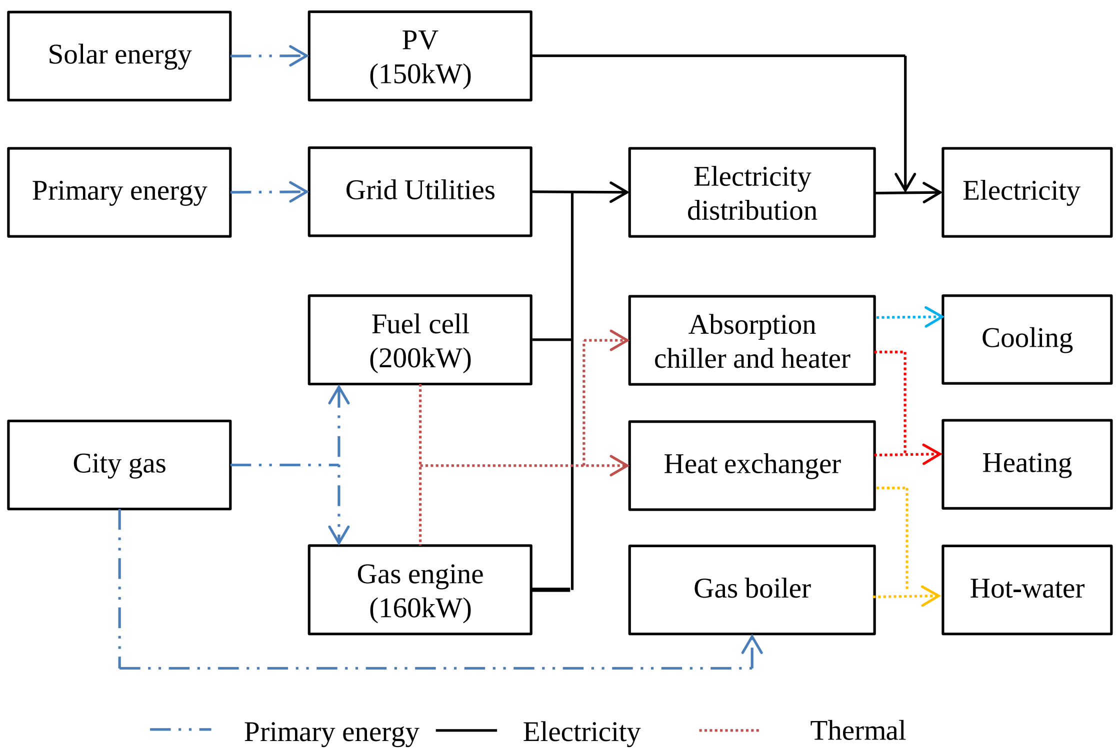


Fig.3-4 Schematic illustration of the DES in KSRP

Fig.3-4 is the schematic of the distributed energy system installed in the Environmental Energy Center of Kitakyushu Science and Research Park. As we known, the energy load of a building or campus include electricity load, space cooling load, space heating load and hot-water load. The system in Kitakyushu Science and Research Park includes the PV, fuel cell, gas engine, gas-fired absorption chiller, heat exchanger and gas boiler. In addition to the main equipment, the system also includes a large number of auxiliary equipment, such as various pumps (cooling water, heating supply, cooling supply, circulation, etc.), cooling towers, injectors, valves, pipes, etc.

In this system, the city gas is used to supply the gas engine and the fuel cell to produce the electricity.

In order to reduce the fossil energy consumption and carbon dioxide (CO2) emissions, and improve energy efficiency; gas engine and fuel cell were used to produce the electricity as a small-case power generation system. The gas engine has 160 kW capacity; and the fuel cell has 200kW capacity. The capacity of the 150kW solar PV is used to meet some electricity demand in the system. When the electricity load is low or the electricity production is not enough, the electricity from grid utilities is used to meet the load. A part of waste heat was sent to the absorption chiller and heater to meet the cooling load; and a part of waste heat was sent to heat exchanger unit to meet the heating space load and hot-water load. And the gas boiler is used to meet the hot-water load in this system.

The use of DER system can improve the efficiency of primary energy utilization. Table 3-2 provides a detail of the heat recovery efficiency and generator set efficiency of gas engine and fuel cell in DER system when the equipment and system are running at full capacity.

Table 3-2 Details of system [4]

Type	**Fuel cell**	**Gas engine**
Capacity	200kW	160kW
Power generation efficiency (with 100% load)	40%	28.7%
Heat release efficiency (with 100% load)	20%	47.7%
	Collecting hot water at 90℃	
	20%	
	Collecting hot water at 50℃	
Operational mode	Run for 24 hours during the years	Run for 24 hours
	Priority to run	Run for 8:00~22:00

The capacity of fuel cell is 200kW; the power generation efficiency is 40% and a heat recovery efficiency of 20% for two circuits, one of the high temperatures of 90℃ and another at 50℃. A high temperature hot water circuit pre-heats the hot water supply scheme. The system is operated for 24 hours continuously throughout the whole year. The capacity of gas engine is 160kW, and the generation efficiency is 28.7%, the heat recovery efficiency is 47.7%

As we all know, power generation unit is the most important part of DER system, not only because power generation unit is related to power production and waste heat recovery, but also because the power generation unit is more complex than other units, usually including fuel supply, combustion system, generator, cooling water, lubricating parts and other subsystems. The power generation units of DER in KSRP include the gas engine and fuel cell. More inside information of the two generators are presented as followings.

Gas engine

The gas engine of the DER system (also called cogeneration system) in KSRP was installed by *Yanmar Co. Ltd.* in 2001. The institution format is a 4 Cycle water-cooled gas engine. The institution name is 6LAALG-DT. The gas engine combustion system uses the spark-ignition to power the engine. The city gas is used to support the fuel consumption, for this engine the best fuel is the No. 13A city gas fuel. The starting model of the gas engine is an electrical start-up by the starter motor. The cooling system for the gas engine, the clear water is used to cool the cylinder jacket part, lubricating oil and air cooler. In the piston part, the lubricating oil is used to cool this part. The turning part uses the turning bar. The institution total quality is 1950 kg.

The gas engine includes the power generation unit, cooling water unit, heat recovery unit and auxiliaries. The power generation unit includes the power unit body appearance, engine oil of power unit, cooling water power unit in the gas engine inside, power machine bearings and generator unit, charging device, ventilation fan. The cooling water unit includes cooling tower circulation pump, cooler cooling water pump. The heat recovery unit includes the cooler for heat exchangers, waste water pump, surplus heat for exchanger, expansion tank (waste water), and heat exchange unit boiler flue gas. And the Auxiliaries include ventilation and air condition for heat room.

Fig.3-5 is a simplified process flow diagram for gas engine. The gas engine produce power by use the city gas, and the waste water is sent to the heat exchanger to supply the high temperature water to the heat recovery unit (heating exchanger, absorption chiller cooling or heating or hot water heat exchanger), then the return water is sent to condenser for cooling and the water is cycled to gas engine.

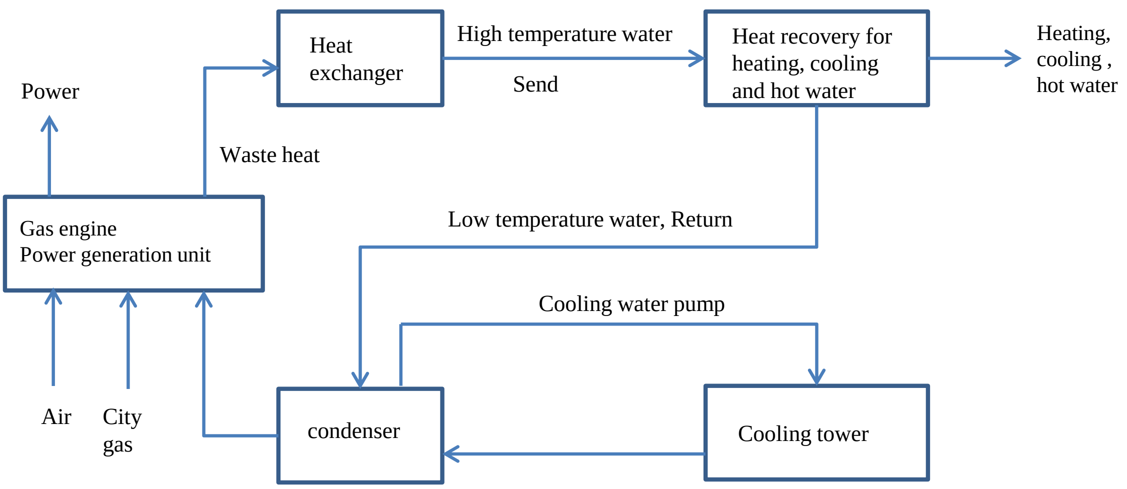
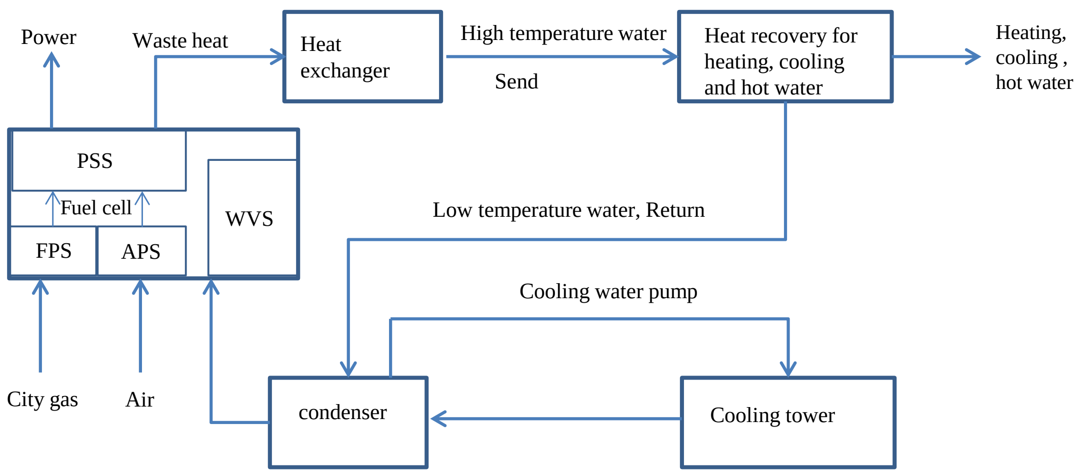


Fig.3-5 A simplified process flow diagram for gas engine

Fuel cell

The fuel cell, which has the 200kW capacity, was used to supply the electricity for the DES system in the KSRP. Toshiba Company installed the fuel cell in 2001. The fuel cell uses the city gas as the energy source. Fuel cell is a complicated energy generation system; it includes power section system (PSS), fuel processing system (FPS), air processing system (APS), thermal management system (TMS), water treatment system (WTS), nitrogen purge system (NPS), and cabinet ventilation system (CVS). The power section system is the part, which is occurring electrochemical reaction use the H2 from fuel processing system and the air from the air processing system. The by-products of electrochemical reaction include water and heat. The water of by-products will be removed through the fuel emission and air emission from the cell stack assembly (CSA). The heat of the by-products will be removed through the thermal management system send to cabinet ventilation system to cool by cooling water.



PSS: power section system; FPS: fuel processing system; APS: air processing system; WVS: water vapor separator.

Fig.3-6 A simplified process flow diagram for fuel cell

The main apparatus of the fuel cell is composed of fuel-modified apparatus, Composite reactor, and water vapor separator and so on. Fig.3-6 is a simplified process flow diagram for fuel cell. The fuel cell produces power by use the city gas, at the first, the city gas is changed to H2 throw the fuel processing system. And the air will be clear and changed by air processing system, then the H2 and the changed air is sent to the power section system to produce the electricity. And the waste heat will be sending to heat exchanger to supply the high temperature water heat recovery unit. And return low temperature water is recycled to condenser. Then it will be sent back to fuel cell.

3.2.3. Previous Studies of DER System in KSRP

The DER in KSRP has been running 15 years ago, so it is a good study object for the application of DER system for a university campus. Now, it has closed to design lifecycle. There are so many literatures about the DER system in KSPR have been published, it can provide a reference for this research.

The DER system in KSRP has been introduced and the running situation during 2002 has been analyzed by Ruan et al in 2005 [5]. The results show that the on-site generating electricity equipment provided 51.2%of the total electricity demand, including fuel cell with 34.5%, gas engine with 13.4%, and PV system with 3.3%. The fuel can run with higher power generation efficiency 8572 hours, about 30.8%. And the gas engine can run with higher power generation efficiency only 4281 hours, about 24.5%. The heat recovery efficiency of the fuel cell was lower, but the heat exchanger and absorption chiller can utilize the recovery heat. It is different with fuel cell; the heat recovery efficiency of gas engine was higher, but the recovery equipment can utilize only 70% recovery heats. The distributed energy system in KSRP achieved 56% primary energy utilization efficiency, 10.9%, saving energy ratio and 1.32% CO_2 emissions.

The comparison, evaluation on running situation of heat resource system with the year of the DER system in KSPR was analyzed by the Ruan and Gao et al [6]. The power generation production and heat recovery data from June 2001 to December 2003 total 2-year half has been collected and analyzed to evaluate the running situation of the DES. The power supply for the electricity demand every month, the fuel cell provide 30%, gas engine provide 12%, PV provide 3%, power from city grid is 55%. The average power generation efficiency of fuel cell is about 31%, and the average power generation efficiency of gas engine is 25%. The primary energy utilization efficiency of fuel cell was between 30% and 65%, and the he primary energy utilization efficiency of gas engine was between 20% and 70%; the average primary energy utilization efficiency during one year is more than 50%.

Optimization of a district energy system at KSRP using HEATMAP was investigated to find the difference to not use by Ruan and Gao [7]. The optimization results presented that the primary energy utilization efficiency can arrive 59% through using the HEATMAP; it increased about 9% compared with the system before. It can reduce the energy consumption more than 8945GJ for one year. It can reduce the CO_2 emissions from 1.3% to 6.9%.

Ren et al analyzed the feasibility of adopting biomass energy in Kitakyushu Science and Research Park in 2008 [8]. The economic, environmental and energy saving of distributed energy system had been analyzed and compared with the CHP system and conventional system. The results presented that the environment and energy saving of biomass energy system is better than the CHP system and conventional system, but the economy of biomass energy is bad.

The economic optimization model for operation of distributed energy system and a case study of Kitakyushu Science and research Park in Japan was analyzed by Yang et al in 2007 [9]. They analyzed the effects of fuel price and equipment efficiency on the operation time, running costs and energy saving. The increase of electricity price and decrease of gas price will increase the attractiveness of distributed energy resource. And the result shows that the best operation hours for gas engine are 4132 hours for one year during the current price of city gas and electric. If the electricity price is increasing and the city gas price is reduced, it is better for the distributed energy system competition in the market. The operation times of distributed energy system have affected for environmental and energy saving of power generation system. According to the load function of the system, energy-saving and environmental improvement will have a maximum value at its optimal operating time.

Running situation of system due to the change of power/gas cost and equipment efficiency was analyzed by Gao, Yang and Ruan in 2005 [10]. the beat economic operation status was simulated and analyzed by the E-GAME model, in order to find the best operation status of a distributed energy system. The result shows that if the most energy generation efficiency is 80%, and never changed. The case with 50% electricity generation efficiency and 30% heat recovery efficiency was saving energy than the case with 30% electricity generation efficiency and 50% heat recovery efficiency.

Field study of the operation situation during 2007 and evaluation over the years of distributed energy system in Kitakyushu Science and Research Park was investigated and evaluated by Su et al in 2009 [11]. The power supply for the electricity demand, the fuel cell provides 27.59%, gas engine provides 8.24%, PV provide 2.35%, power from city grid is 61.65%. The power generation unit both the fuel cell and gas engine did not up to the design power generation efficiency. The power generation efficiency of the fuel cell was around 30%, and tend to fall slowly; and the power generation efficiency of gas engine was up to the 23% during the 90% power generation times. The design efficiency is 28.7%, it was 5.7% lower than the design value. The heat recovery efficiency of gas engine was higher; it was more than 30% during the 90% of total power generation times. The heat recovery efficiency of the fuel cell was about 15%, all of the recovery heats from fuel cell can be utilized by the system.

The evaluation of district energy system at Kitakyushu Science and Research Park over the years (2001-2007) was studied by Su et al 2009 [12]. The power generation data and the city gas consumption and the heat recovery data was collected and analyzed to evaluate the distributed power generation system. From the 2003, the power generation efficiency of the fuel cell was around the 30%. And the power generation efficiency of gas engine was increased slowly, end of around 26%. From the 2006, it began the interim period stoppage. It began to buy the electrical power from the city grid. The waste heat recovery efficiency of gas engine was about 60%, and the waste heat recovery of the fuel cell was about 12-20%. Those all lower than the catalogue value (gas engine: 47.7%; fuel cell: 40%).

Situation of utilization of distributed energy system in Kitakyushu Science and Research Park in 2009 was analyzed by Shi et al in 2011 [13]. The result shows that the power supply for the electricity demand, the fuel cell provides 21.49%, gas engine provides 7.4%, PV provide 2.21%, and power from city grid is 68.99% in 2009. The power generation efficiency of the fuel cell was around 30%, it was 10% lower than design efficiency; and the power generation efficiency of gas engine was around the 26%, it near the design value.

The review shows that most of literatures are focused on the optimization for the operational strategy of DES, or focus on the new design for the system, such as to put into new equipment like HEATMAP. The other literatures were attentive to the environmental benefit, saving energy and evaluation of the distributed energy system at Kitakyushu Science and Research Park.

3.3. Investigation on the Management and Maintenance Strategy of DER system in KSRP

3.3.1. The Equipment Management and Maintenance of Whole System

In order to analysis and optimization of the DER system, the Maintenance Strategy of DER system in KSRP are investigated and introduced in this chapter. Generally, the management of equipment is divided into two parts, equipment management and equipment operation and maintenance (O&M).

According to the record of the equipment management of Kitakyushu Science and Research Park, the management contents include the integrated management, operation management, office/business management and environmental & health management. The details are investigated and shown in Table 3-3.

Table 3-3 The details of equipment management in KSRP

Type of equipment management	**Management details**
Integrated management	a) Supervise all operations and perform smooth operations by communicating and coordinating with cleaning companies, security agents and other outsourcing companies. b) Opinions from a professional position on the planning and implementation of repair plans etc. c) Advice and do the documentation on facility maintenance. d) Responding to inquiries about equipment, etc. e) Assistance for planning and training of firefighting and disaster prevention plans. f) Control of each outsourcing company, etc. in an emergency.
Operation management	a) Driving operation, monitoring, recording, communication, report (creation of daily report, daily report, monthly report, report etc.) b) Creation and implementation of operation plans. c) Implementation of energy saving measures. d) Conduct daily and monthly, conduct regular inspections and make records. e) Daily cleaning of machine room etc. and arrangement and storage of tools, fixtures etc.
Office/business management	a) Metering of various meters such as electricity, water supply, air conditioning, grasping the amount of energy used and making of materials about them. b) Management of consumables, etc.

	c) Various communication to FAIS. d) Assistance with change of the rules in the hall and the rules of use. e) Support such as business plan which accounts for FAIS, balance plan, business report and financial statements f) Public relations assistance such as posters and banners. g) Assistance such as guidance of visitor and inspection correspondence. h) Creation and implementation of maintenance plans. i) Communication, coordination, advice, working witness and check with specialized maintenance companies in KSRP. j) Creation of equipment-related external data。 k) Notifications to government offices, etc. l) Emergency response. m) Other matters necessary for preparation of materials required by C and maintenance of facilities.
Environmental & health management	a) Development of maintenance management plan. b) General supervision of the maintenance operation plan. c) Conduct of measurement or inspection about maintenance management in environmental hygiene and result evaluation. d) Implementation and evaluation of various surveys required for maintenance and management of environmental health.

According to the records of equipment operation and maintenance in KSRP, the equipment O&M are including the routine maintenance, inspection and maintenance (include the scheduled maintenance and the planning maintenance). Some maintenance and inspections required by law are called statutory maintenance. This part is also performed during scheduled maintenance. According to the inspection results, some components need to be repaired or replaced within a certain time, and this part is within the scope of planned maintenance. The relationship of routine maintenance, scheduled maintenance and planning maintenance is shown in Fig.3-7. Therefore, the routine maintenance and scheduled maintenance can be seen as the time-based maintenance (TBM), and the planning maintenance can be seen as the condition-based maintenance (CBM). When the equipment is found to have deterioration or potential failure risk in routine maintenance and scheduled maintenance, the manager will carry out planned maintenance according to the level of deterioration or failure risk. The details of equipment maintenance in KSRP are shown in Table 3-4.

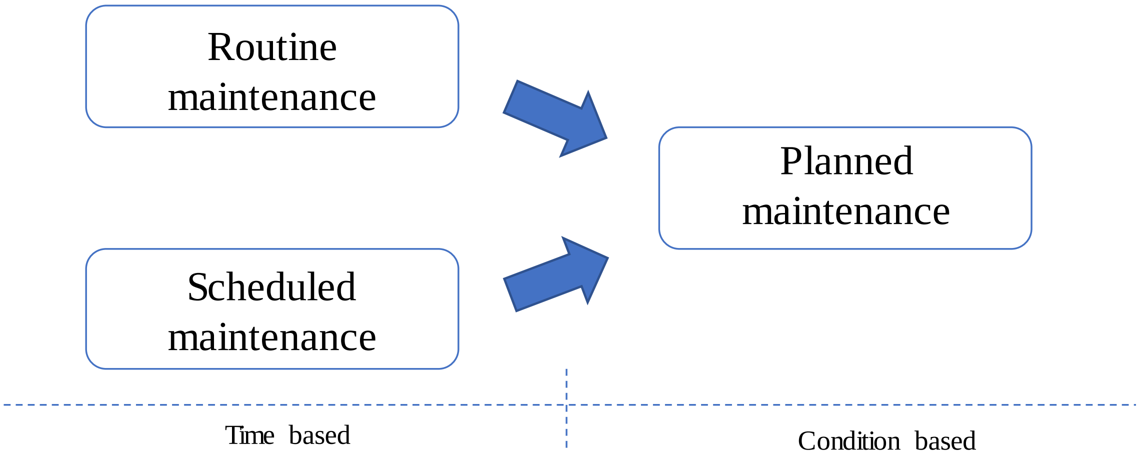


Fig.3-7 The relationship of routine maintenance, scheduled maintenance and planning maintenance

Table 3-4 The details of equipment maintenance in KSRP

Type of equipment maintenance	**Maintenance details**
Routine maintenance	a) Patrol inspection, adjustment, record. b) Detection of failures and abnormal points (tubes, water leaks, abnormal sounds, etc.) c) Support for maintenance work and other related work. d) Management of various records, storage and periodic reporting. e) Management of equipment and materials required for operation management. f) Emergency response (fire, blackout, water outage and other disasters) g) Other matters necessary for equipment operation management.
Scheduled maintenance	Maintenance is performed with schedule according to the manufacturer or professional managers' recommendations.
Planned maintenance	Maintenance is performed based on the results of routine maintenance and scheduled maintenance. The planning of maintenance includes the time, materials, labors and so on.
Corrective maintenance	The corrective maintenance will be performed when the failures are occurred. If a minor failure occurs, maintenance may be delayed and a planned maintenance will be performed. If the failure is severe, emergency maintenance may be required.

The FMEA method has been introduced in chapter 2.3.2. According to the FMEA method, the function block diagram can be drawn as the Fig.3-16. As shown in Fig.3-16, the function of DER system can be divided into four sub-system, power generation sub-system, heat utilization sub-system, cooling water sub-system and auxiliary devices. The devices of power generation sub-system include the gas engine, fuel cell and PV. However, the power generation of PV is not stabilization, and the maintenance of PV is not complex, maybe only inspection can be done by managers. Therefore, the PV generation units only perform the general maintenance. The devices of heat utilization sub-system include the waste heat exchangers, gas-fired absorption chiller (one for waste heat, two for the city gas-fired) and an auxiliary boiler. The cooling water sub-system is an important part of DER system, it supplies all the cooler water for every generation, heat exchanger etc. units. For instance, cooling tower 1 for gas engine, cooling tower 2 for fuel cell, cooling tower 3 for absorption chillers. It also has some auxiliary devices, like city gas meter, hot water tank, pumps etc.

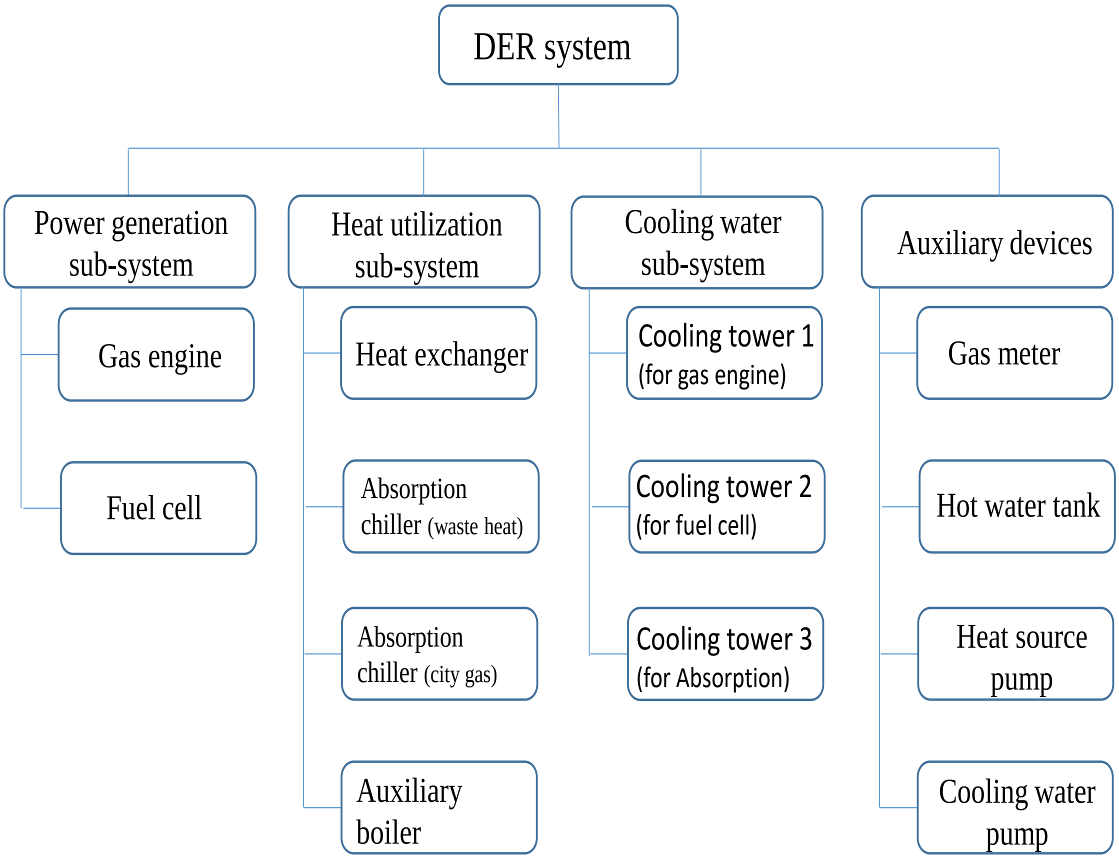


Fig.3-8 Functional Equipment block diagram of DER system in KSRP

According to the equipment management and maintenance record, the DER system was classified based on the important level of maintenance. The main equipment of the DER system is the gas engine and fuel cell, and the important level of other equipment is lower. Therefore, the maintenance strategies are introduced as the follows.

3.3.2. The Equipment Maintenance of Power Generation Units

1. Gas engine

The maintenance of gas engine was classified into routine maintenance and scheduled maintenance. In order to show the routine maintenance some data are investigated. The investigation contents are listed in the Table 3-5. We can get the main information of the gas engine, the internal structure of gas engine and failure position description from the manual of the gas engine; the data of 1000 hours inspection record and failure reason review were recorded in gas engine inspection and maintenance work report (from the July 2001 to March 2015); from the construction completion certificate of gas engine and construction plan statement of gas engine, the data of failure's repair record, failure reason review, maintenance description and failure's reasons description can be gotten.

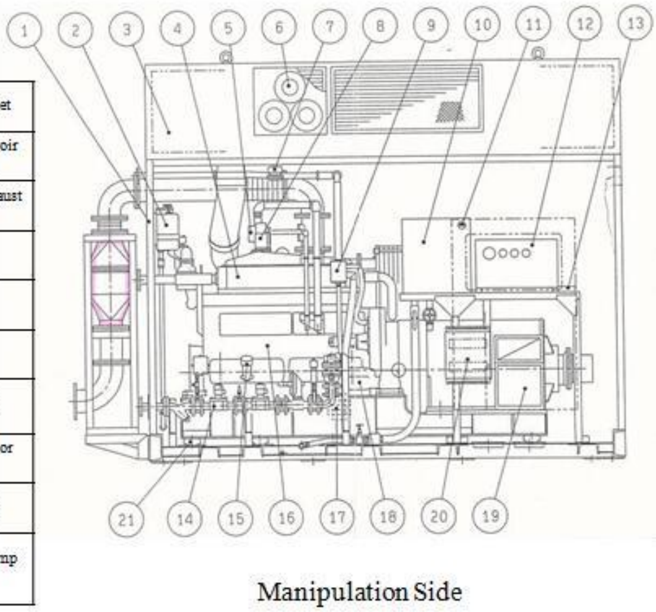
Table 3-5 The investigation contents of gas engine

No.	Content	Details
1	Manual of the gas engine	Information of gas engine; Internal structure of Gas Engine; Failure position description.
2	Gas engine inspection and maintenance work report (from the July 2001 to March 2015)	Data of 1000 hours inspection record; Failure reason review.
3	Construction completion certificate of gas engine	Data of failure's repair record; Failure reason review, maintenance description.
4	Construction plan statement of gas engine	Operation instruction of gas engine; Maintenance and repairing methods; Failure's reasons description.

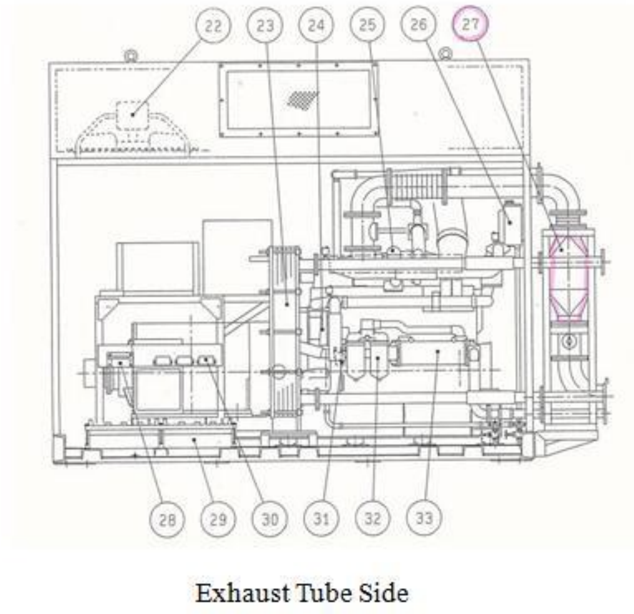
Gas engine is a complex system, it contains a variety of components. Gas engine also is the main equipment for a DER system.

Fig.3-9 is the internal structure of the gas engine. The figure of gas engine was investigation from the *Manual of the gas engine*. It has been introduced from the manipulation side and exhaust tube side. There are 33 components that are shown here. These components are sorted by the Manual of the gas engine, it is a classification of the perspective of development design.

1	Soundproof bonnet
2	Jacket water reservoir tank
3	Air supply and exhaust duct
4	Air cooler
5	Gas mixer
6	Air filter
7	Gas detector
8	Electronic governor actuator
9	Mist separator
10	Lubricating oil sump tank



11	Lubricating oil sump tank refueling port
12	Instrument panel
13	DC voltage converter
14	Gas valve unit
15	Lubricating oil refueling port
16	Gas engine
17	Drain tank
18	Sel-motor
19	Three phase AC brushless generator
20	Engine terminal block
21	Rubber vibration isolator



22	ventilating fan
23	water-water heat exchanger
24	Jacket water pump
25	supercharger
26	Jacket water pressure tank
27	three-way catalyst
28	battery switch
29	battery
30	protective relay
31	Jacket water protective heater
32	lubricating oil filter
33	lubricating oil cooler

Fig.3-9 Internal structure of gas engine

1) Routine maintenance of gas engine

The details of routine maintenance of gas engine were shown in Table 3-6. In the daily maintenance of the main equipment, not only for the inspection and maintenance of the components of the main equipment, but also for the inspection and maintenance of the related equipment of the main equipment. As shown in Table 3-6, when the gas engine performs the routine maintenance, the related equipment like cooling water tower circulation pump, cooler cooling water pump, waste water pump, heat exchanger units are also be performed the routine maintenance. it because that the related equipment is also importance for the gas engine operation.

Table 3-6 The details of routine maintenance of gas engine

Unit	Inspection points	Items
Power generation of gas engine	Power unit body appearance	Noise, odor, vibration, dirt, damaged
	Engine oil of power unit	Pressure, temperature,
	Cooling water power unit	temperature, water level
	Power machine bearings and generator unit stator	temperature
	Charging device	Gas engine control panel、Battery liquid level
	ventilation fan	electric currents
	Boiler control panel	Lamps, toggle switch status, abnormal display, damper
Cooling water of gas engine	Cooling tower circulation pump	electric current, pressure, flow, noise, odor, vibration, dirt, damaged
	Cooler cooling water pump	electric current, pressure, flow, noise, odor, vibration, dirt, damaged
Heat recovery unit of gas engine	Cooler for heat exchangers	Cooling water temperature (cooler circulation, cooling tower circulation)
	Waste water pump	electric current, pressure, flow, noise, odor, vibration, dirt, damaged
	Surplus heat for exchanger	Cooling water temperature and discharge water temperature
	Expansion tank (waste water)	Pressure
	Heat exchange unit boiler flue gas	Waste hot water temperature
Auxiliaries	Ventilation	Ventilation inlet and outlet temperature and humidity
	Air condition for heat room	Fan coil unit operating conditions, cold water source pressure, valve opening and closing conditions, noise, vibration, dirt, damage, leakage etc.

2) Scheduled maintenance of gas engine

The scheduled maintenance of gas engine is performed based on the time. There are three types of basic maintenance: 1000 hours maintenance, Determination of smoke emission and Generator panel inspection. Fig.3-10 shows the relationship of all the types of basic inspection.

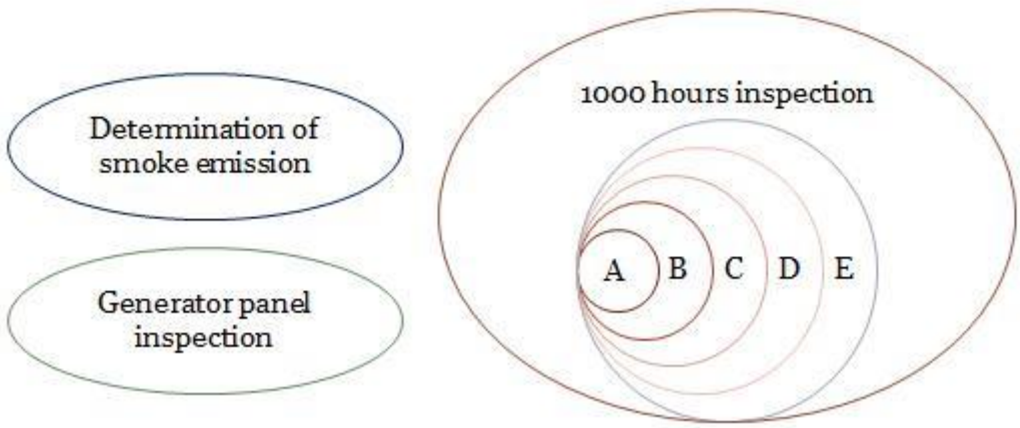


Fig.3-10 The relationship of each maintenance types of gas engine

As shown in Table3-7, for the 1000 hours inspection, it is the basic and common inspection of gas engine during its operation. As it is described by its name, the 1000 hours inspection would be held when the gas engine was operated per 1000 hours. The 1000 hours inspection means to do the inspection on all the safety devices, the environment of the component and the replacement of some component. Different types of inspection have to deal with different kinds of the components or parts of the gas engine. And the distinction among them is the operation hours. For the A type inspection, it will be held when the gas engine was operated per 1000 hours, and the contents include the inspection of all the safety devices, the environment of the component, the replacement of the lubricants, with the oil pan will also be replaced per 1000 hours. For the B type inspection, it will be held when the gas engine was operated per 2000 hours, but the contents include all the contents of A type inspection, and also include the internal inspection of various counters, distributor inspection and the exchange of ignition (according to the Gas engine inspection and maintenance work report 2002, the lubricants replacement of A type inspection was changed into the B type inspection.) For the C type inspection, it will be held when he gas engine was operated per 4000 hours, while the contents include all the contents of B type inspection, and also include the inspection of gas support unit, the inspection of plug cord, the inspection of mist tube, the cleaning of the intake filter and the inspection of the function of the protection device. The D type inspection will be held per 8000 hours, and the contents include all the contents of C type inspection, and also include the inspection of regulator and frame arrester, the inspection of exhaust gas heat exchanger, the distributor driving inspection, the magnet inspection, the cooling water pump inspection, management of cooling water and so on. The E type inspection is the largest scale inspection. It will be held per 16000 hours, and include all the contents of D type, also include the inspection, cleaning of heat exchanger decomposition, mixer and diaphragm exchange, the inspection and cleaning of cylinder liner and water cooler decomposition, lubricants pump, lubricants cooler inspection, crank inspection and measuring and so on.

Table 3-7 The maintenance contents of different maintenance types

Type	Time Interval	Content	Remark
A Type	Per 1000 Hours	□ Inspection of all the safety devices □ The environment of the component □ The replacement of lubricants	□Oil pan: Per 1000 Hours □With Sub tank: Per 2000 Hours
B Type	Per 2000 Hours	□A type content □Internal inspection of various counters □Distributor inspection □Exchange of ignition	Include A Type Inspection
C Type	Per 4000 Hours	□B Type content □Inspection of gas support unit □Inspection of Plug cord □Inspection of mist tube □Clean the intake filter □Inspect the function of the protection device	Include A and B Type Inspection
D Type	Per 8000 Hours	□C Type content □Inspection of Regulator and Frame arrester □Inspection of Exhaust gas heat exchanger □Distributor driving inspection □Magnet inspection □Cooling water pump inspection □Management of cooling water □And so on	Include A, B and C Type Inspection
E Type	Per 16000 Hours	□D Type content □Heat exchanger decomposition, inspection, cleaning □Mixer, diaphragm exchange □Cylinder liner and water cooler decomposition, inspection, cleaning, lubricants pump, lubricants cooler inspection □Crank inspection and measuring □And so on	Include A, B, C and D Type Inspection

2. Fuel cell

It is same to the gas engine; the fuel cell is also a complex system. The maintenance of fuel cell was classified into routine maintenance and scheduled maintenance. In order to show the routine maintenance some data are investigated.

1) Routine maintenance of fuel cell

Table 3-8 shows the objects and contents of the fuel cell inspection. The inspection points include power supply unit of fuel cell, electric transformers edition, nitrogen gas supply system, wastewater pump, waste water unit, hot water pump 1, hot water preheating heat exchanger, hot water pump 2, heat exchanger for space heating, hot water pump 2, heat exchanger for space heating, RH-1 waste water (operation for fuel cell), RH-2 waste water (operation for gas engine), gas measurement and gas detection alarm. The inspection items of power supply unit include electric current, generating capacity and voltage. The inspection items of electric transformers edition include the temperature and the abnormal information of equipment. The inspection items of nitrogen gas supply system include a series pressure, B series pressure, intermediate pressure, outlet pressure, console input pressure, CRT data. The inspection items of waste water pump include electric current, pressure, noise, and odor, and vibration, dirt, damaged. The inspection items of waste water unit console output pressure, input temperature, output temperature. The inspection items of hot water pump 1 include electric current, pressure, noise, and odor, and vibration, dirt, damaged. The inspection items of hot water preheating heat exchanger include input temperature and pressure, output temperature and pressure. The hot water pump 2 and heat exchanger for space heating only used for space heating. The inspection items of hot water pump 2 include electric current, pressure, noise, and odor, and vibration, dirt, damaged. The inspection items of heat exchanger for space heating include the water flow, input temperature and output temperature. The RH-1 waste water unit and the RH-2 waste water unit only used for space cooling. The RH-1 waste water unit is used when the fuel cell is operated. The RH-2 waste water unit is used when the gas engine is operated. The water flow was recorded for RH-1 and RH-2 waste water unit. The inspection items of gas measurement include gas pressure and gas flow. The inspection items of gas detection alarm include power indicator light, concentration, and abnormal status, alarm of equipment.

2) Scheduled maintenance of fuel cell

The scheduled maintenance of fuel cell is performed by the manufacturer, and fuel cell maintenance cycles are longer than gas engine maintenance cycles. Maintenance is performed once a year. However, some components still need to be replaced regularly. For example, resin parts need to be replaced every three months.

Table 3-8 The details of routine maintenance of fuel cell

Unit	**Inspection points**	**Items**
Power generation unit	Power supply unit	Electric current, generating capacity, voltage
	Electric transformers edition	Temperature
	Nitrogen gas supply system	A series pressure, B series pressure, Intermediate pressure, Outlet pressure, Console input pressure, CRT data
	Waste water pump	Electric current, Pressure, Noise, odor, vibration, dirt, damaged
	Waste water unit	Console output pressure, input temperature, output temperature.
	Hot water pump 1	Electric current, Pressure, Noise, odor, vibration, dirt, damaged
	Hot water preheating heat exchanger	Input temperature and pressure, output temperature and pressure.
Space heating unit	Hot water pump 2.	Electric current, Pressure, Noise, odor, vibration, dirt, damaged
	Heat exchanger for space heating (Hot water and waste water)	Water flow, input and output temperature.
Space cooling unit	RH-1 waste water (Operation for fuel cell)	Water flow rate
	RH-2 waste water (Operation for gas engine)	Water flow rate
City gas unit	Gas measurement	Pressure, gas flow
	Gas detection alarm	Power indicator light, concentration, abnormal status and alarm of equipment.

3.3.3. The Equipment Maintenance of Heat Utilization and Auxiliary Equipment

According to the investigation of gas engine and full cell, the routine maintenance of heat utilization and auxiliary equipment will be performed when the routine maintenance of gas engine and fuel cell are performing. Therefore, this chapter only introduce the scheduled maintenance of heat utilization and auxiliary equipment. The details of heat utilization and auxiliary equipment are shown in the Table 3-9. The equipment includes the pump, cooling tower, expanded tank, boiler and absorption chiller.

Table 3-9 The details of heat utilization and auxiliary equipment

Equipment types	**Equipment**	**Numbers**
Pump	First C&H pump (5.5kW)	1
	First C&H pump (15 kW)	2
	Second C&H pump (30kW)	5
	Cooling water pump (26kW)	1
	Cooling water pump (55kW)	2
	Second Hot water pump (3.7kW)	1
Cooling tower	Cooling tower for absorption chiller	3
	Cooling tower for gas engine	1
	Cooling tower for fuel cell	1
Expanded tank	Expanded tank for air condition	1
	Expanded tank for air condition for hot water supply	1
Boiler	Boiler	1
Absorption chiller	Absorption chiller (No.210)	1
	Absorption chiller (No.630)	2

For different kinds of equipment, Maintenance policies vary greatly difference based on difference function and the characteristics of the equipment itself. The obvious difference is the maintenance period. Therefore, the maintenance period and maintenance items are investigated for the heat utilization and auxiliary equipment.

Table 3-10 The details of scheduled maintenance of heat utilization and auxiliary equipment

Equipment	Items of scheduled maintenance	Maintenance period
Pump	Confirm and adjust pump pressure and working condition. Inspect the pump for abnormality and unpleasant odor.	One week
	Check for oil and water leakage. Sweep the pump parts and fill the oil. Check whether the pump body has deformation, loss, corrosion and deterioration. Verify the supply voltage and current. Confirm the pump inlet and outlet pressure.	One month
	Inspect fixed metal parts for deterioration and fixed screws. Check the shockproof material and brake. Confirm the pump bearing deterioration.	Six months
	Check the lubricating oil.	One year
Cooling tower	Inspection around cooling tower body. Tank inspection. Blower inspection. Sprinkling pump inspection. Check the antifreeze device. Operation adjustment. Check the quality of cooling water.	One month
	Inspect the blower blade for damage and corrosion. Repair and inspect the corrosion and deterioration of inside the cooling tank.	Three months
	Check the deterioration and subsidence of cooling water base. Detect the damage and deformation of the water dispersing device. Test for containment devices, suppressors and heat exchangers. Check the corrosion condition of the water tank. Inspect the rotary device of the blower.	Six months
	Confirm the fan sprinkler pump motor device. Cleaning and disinfection of sink equipment. Confirm and clean the dirt, sand and foreign matter in the sink. Inspection and exchange of damaged and aged parts. Confirmation and correction of motor running direction.	One year

Expanded tank	Confirm base screws and secure metal parts. Inspect the pipes for corrosion, deterioration, damage, etc.	One mouth
	Damage and peeling of insulation material. Damage and corrosion of the body. Check for leaks. Confirm cover for wear, corrosion, damage, etc. Make sure there is no leakage of pressure gauge. Confirm whether there is any damage to pressure gauge, thermometer, etc. Confirm the condition of auxiliary pipe and pump.	One year
Boiler	The maintenance is performed two times per year; if it needs the emergency maintenance, the emergency maintenance will be performed. Burner unit: pilot burner disassembly and cleaning; cleaning and adjustment of the ignition electrode rod; inspection of fire detector etc. Vacuum unit: inspect the exhaust device etc. Combustion unit: gas pressure, exhaust gas concentration, temperature, etc. Control unit: confirm the operation of each machine and confirm the safety device etc.	Six months
Absorption chiller	Absorption refrigerator is divided into cooling period and heating period. Therefore, maintenance occurs mainly around the time of cooling and heating. The maintenance includes vacuum confirmation, confirm the vacuum degree, confirm the electrical system, check the control function, check the microcomputer controller parameters, check the inverter set value, check the gas leak, check combustion relation, inspect the absorbent etc.	4 times per year

As mentioned above, the maintenance strategy of the main equipment for the academic research of the distributed urban energy system in Kitakyushu Science and Research Park is described. The main equipment to be maintained are fuel cells and gas engines. The maintenance frequency of the Heat Utilization and Auxiliary Equipment is relatively low. However, in DER systems, the impact of failure is different for each equipment, and how to identify the level of equipment in maintenance requires more analysis of the impact and cost of failure under this maintenance strategy.

3.4. The Operation Status of DER System in KSRP

The gas engine and fuel cell are the main equipment for the operation of DER system, a health and availability operation status are the ultimate goal of maintenance. Therefore, the operation status should be investigated based on the maintenance strategies of the DER system in KSRP. The operational status of fuel cell and gas engine are analyzed as the followings.

3.4.1. Analysis on the Operation Status of Gas Engine

1. Classification of operation status of gas engine

The gas engine of DES in KSRP was operated from 8 o'clock to 22 o'clock. It was stopped on Sunday and holiday, from the 2005, it was stopped in spring and autumn where the cooling space and heating space has been need not. In order to show the operation status, clearly, and better for the data analysis in this research, we classify the operation status by different standards. The classification standards include operation or stoppage, abnormal status (both of stoppage and operation), stoppage classification, abnormal operation classification. The Table 3-11 is the classification of operation status for gas engine.

Table 3-11 Classification of operation status for gas engine

	Classification 1	Classification 2	Status of gas engine
Gas engine operation status	Stoppage	Schedule stoppage	Stoppage
		Interim period stoppage	Stoppage
		Inspection and maintenance	Stoppage
		Failure	Stoppage
		Low load	Stoppage
		Others	Stoppage
	Operation	Inspection and maintenance	Temporary stoppage
		Failure	Temporary stoppage/ Operation with minor failure
		Low load	Operation half day
		Others	Temporary stoppage
			Operates all day

The first classification of operation status is the operation or stoppage. The operation means that the gas engine has been operated to provide power; maybe it stopped because of so reason (failure, maintenance or others) and cannot operate all day. Both of operate all day and cannot operate all day was recorded as operation. The stoppage means that gas engine was not used to provide the power; it includes the schedule stoppage and stoppage because of inspection, maintenance, and failure and so on.

As shown in Table 3-11, in this classification, the stoppage and abnormal status include normal stoppage, abnormal stoppage and abnormal operation. The normal stoppage includes the schedule stoppage and stoppage on interim period. The schedule stoppage includes Sunday and holiday, the gas engine will be stopped on schedule stoppage days. The stoppage on interim period means that the gas engine stopped in the spring and autumn when the buildings need not the space cooling and heating. The abnormal stoppage includes inspection, maintenance, failure, stoppage because of low load, and others. The abnormal operation means that the gas engine has some problem, but it also can operate. The status of abnormal operation includes inspection, maintenance, minor failure, temporary stoppage and others.

Table 3-12 is classed of inspection, maintenance and failure. The classification of inspection and maintenance includes inspection per 1000 hours, casual inspection, maintenance, standard measurement inspection and others. The standard measurement means that to measure the electrical insulation or the NOx-, NO, NO_2, SOx and so on. The others include the supply to tour of students, guidance and so on.

The classification of failure includes power generation unit, heat recovery unit, cooling water unit and auxiliaries of gas engine. Actually, it was classified according to the position classification.

Table 3-12 Classification of inspection, maintenance and failure for gas engine

Items	Classification
Inspection and maintenance	Inspection per 1000 hours
	Casual inspection
	Maintenance
	Standard measurement
	Others
Failure	Power generation unit
	Cooling water unit
	Heat recovery unit
	Auxiliaries

2. Analysis of operation status of gas engine

1) Operation or stoppage analysis

The inspection data of the gas engine is from July 2001 to February 2016, nearly 15 years data. Table3-13 is the summary of survey of gas engine. The data for one year is from the April of this year for the March of next year. One year has 365 or 366 days. The gas engine is operated from 8 o'clock to 22 o'clock, total 14 hours every day. The first year is from the July 2001 to March 2002, totally 265days. The last year data is from April 2015 to February 2016, totaling 335 days.

Table 3-13 shows the data of classification include both the Classification 1 and Classification 2 (as shown in table 3-11). Every class includes all of the operation status, for example, the failures in this table it means both failures of abnormal stoppage and abnormal operation are seen as the failure of the equipment. Some failures lead to the equipment cannot run; it belongs to abnormal stop. Some failures are minor failures; it made the equipment, temporary stoppage or operation with minor failure; it belongs to abnormal stoppage.

Table 3-13 Summary of survey of gas engine

Year	**Days of the year**	**Operation days**	**Stoppage days**	**Schedule stoppage**	**Interim period**	**Inspection and**	**Failures**	**Low load**	**Others**
2001	265*1	201	64	46	0	13	20	6	4
2002	365	273	92	70	0	18	1	3	3
2003	366	299	67	55	0	12	16	1	0
2004	365	315	50	31	0	18	15	1	3
2005	365	278	87	66	0	8	10	0	4
2006	365	241	124	57	49	9	6	0	6
2007	366	240	126	59	58	6	6	1	4
2008	365	222	143	51	72	16	2	0	4
2009	365	236	129	57	66	10	5	0	2
2010	365	251	114	55	48	10	8	0	0
2011	366	238	128	52	40	12	28	0	0
2012	365	249	116	54	50	9	12	0	3
2013	365	238	127	57	56	14	2	0	1
2014	365	259	106	65	32	8	2	0	1
2015	335*2	221	114	52	53	6	3	0	2

One-year data is from the April to March of the next year. *1 the first year is from July, 2001. *2 the last year is end of February, 2016.

Others mean support tour or no record.etc.

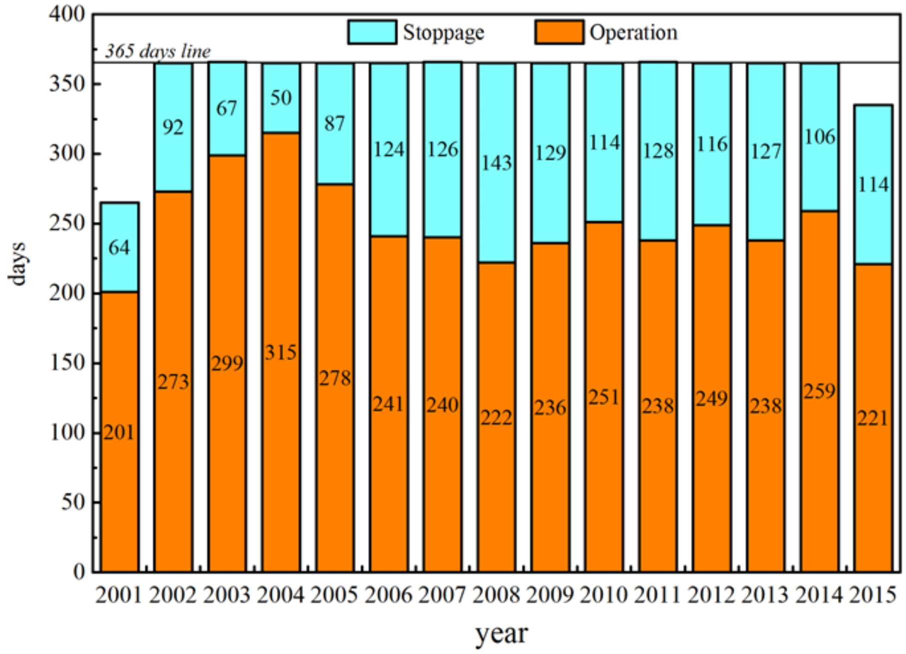


Fig.3-11 Operation status during 15 years of gas engine

Operational status during 15 years of gas engine is presented in Fig.3-11. The sum of every year is 365 or 366 days. The first year and the last year data are not enough, it can be ignored. From 2002 to 2014, in the began few years, the operation days are higher than after years, because of it did not have the interim period before 2006. The most operation days occurred in 2004, the number of operating days is 315. The lower operation days occurred in 2008, the number operation days are 222. The number of operating days was in the range of 220 to 260 from to 2006 to 2014. The rate of operation during one year was in the range of 60.2% to 71.2%.

2) Stoppage and abnormal status analysis

Classification of total stoppage and abnormal status of the gas engine is presented in Fig.3-12. Fig.3-12 (a) and Fig.3-12 (b) shows the schedule stoppage and interim period, respectively; it was belonging to the normal stoppage classification. From the Fig.3-12 (a) we can find that the most of the schedule stoppage days were in the range of 50 to 70 days. The lowest number of schedule stoppage days occurs in 2004. It only has 31 days; the record of inspection table shows that the gas engine was operating on Sunday. Especially, all of Sunday in June, July, August and September were operated. Maybe because of the high temperature in summer 2004. Fig.3-12 (b) shows that the interim period stoppage was begun in 2006; the longest interim period was occurred in 2008, the stoppage days are 72, The interim period stoppage was occurred between the space heating period and space cooling period in spring or autumn every year. The length of interim period, mainly depends on the heating and cooling load of campus or the temperature of the weather.

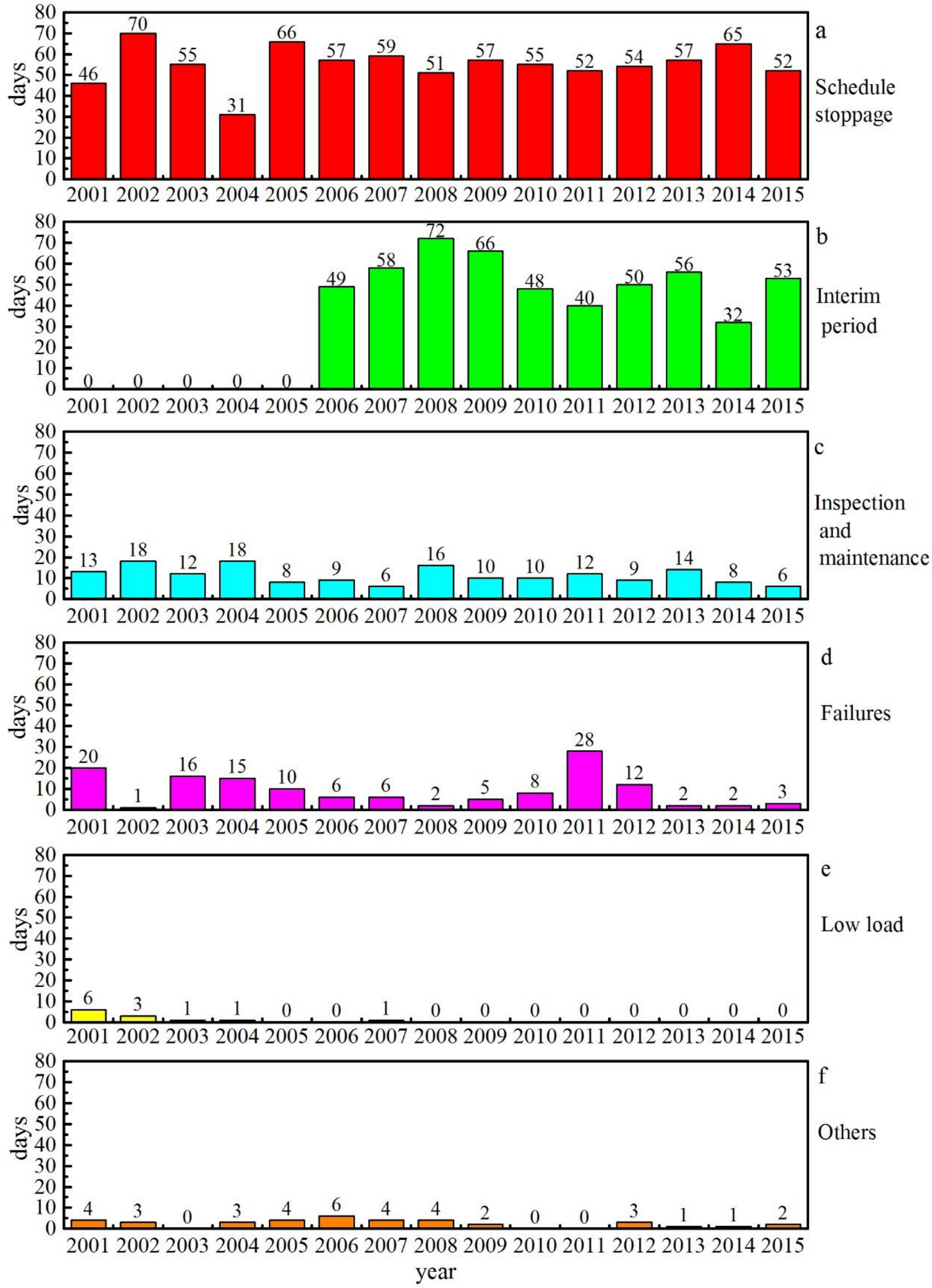


Fig.3-12 Classification of total stoppage of gas engine

Fig.3-12 (c) shows the inspection and maintenance status during 15 years; Fig.3-12 (d) shows the failure status during 15 years; Fig.3-12 (e) shows the stoppage due to the low energy load status during 15years; Fig.3-12 (f) shows the stoppage or temporary stoppage of others status during 15 years. The

4 figures belong to the abnormal stoppage and abnormal operation status. From the Fig.3-12 (c) we can find that the longer inspection and maintenance days were occurred in 2002, 2004, 2008 and 2013. That is because it did the overhaul in 2002 and 2008, respectively. In 2004, it the inspection of 16000 hours did 7 days. In 2013, the inspection of 48000 hours did 10 days, it was very longer than others, so it has long stoppage in 2013. Fig.3-12 (d) shows that the failures was happening in every year. The most failure days were in 2001 and 2011. That is because the minor failure was occurred in2001, it was not repaired more than 10 days; because it is a minor failure, so it also is able to operate. It had a long stoppage time because of the failure in 2011. Besides that, there are 4 years failures more than 10days, it was in 2003, 2004, 2005 and 2012. Fig.3-12 (e) present the stoppage because of low load was occurred in began the year, especially in 2001 and 2002. Due to adopt the interim period stoppage after 2005, so it almost did not stop because of low load. Fig.3-12 (f) shows that the stoppage of others was occurred often, but it was very short days. The reason includes a student tour in energy center, no record, other construction in the energy center and so on.

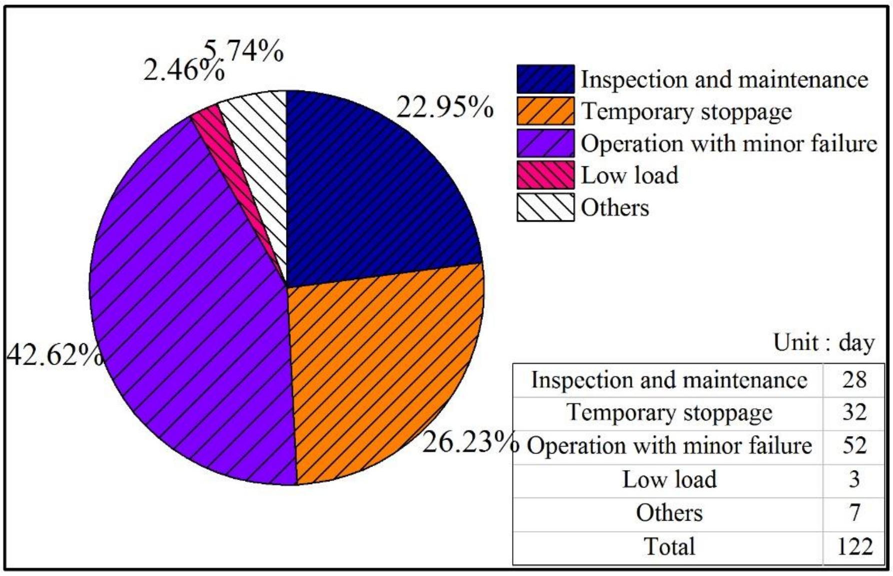


Fig.3-13 Classification of abnormal operation of gas engine in total 15 years

Fig.3-13 is the classification of abnormal operation of gas engine in total 15 years. Abnormal operation includes inspection and maintenance, temporary stoppage, operation with minor failure, low load and others. The total abnormal operation days are 122 days during all of 15 years. The highest abnormal operation is an operation with minor failure, it is nearly 42.62% of total abnormal operation, 52 days. The second higher abnormal operation is temporary stoppage, it is nearly 26.23% of total abnormal operation, it is 32 days. The inspection and maintenance are nearly 22.95% of total abnormal operation, it is 28 days. The others are nearly 5.74% of total abnormal operation, it is 7 days. The low load is nearly 2.46% of total abnormal operation, it is 3 days. Results indicate that the maintenance of the gas engine are not very quickly, or the maintenance is not making adequate preparation.

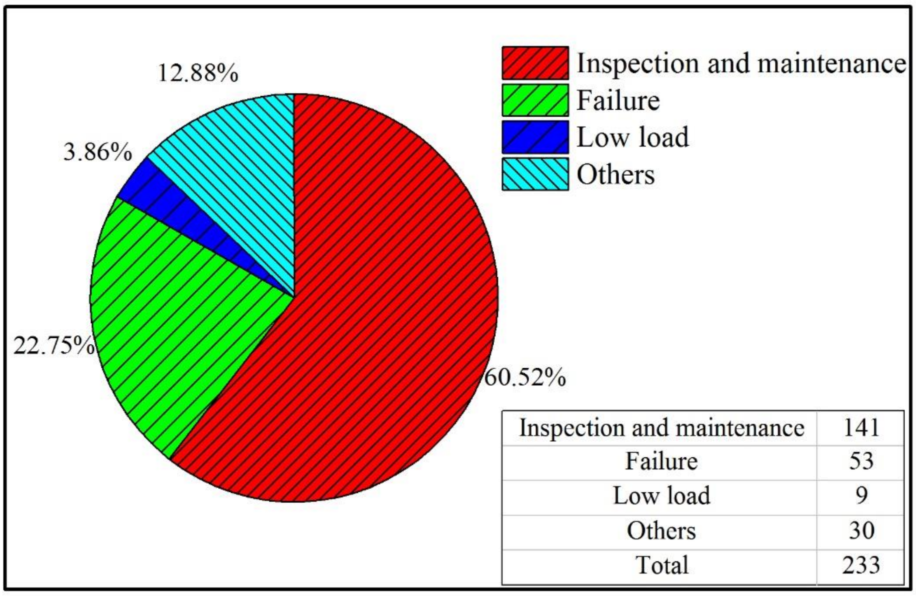


Fig.3-14 Classification of abnormal stoppage of gas engine in total 15 years

Fig.3-14 is the classification of abnormal stoppage of gas engine in total 15 years. Abnormal stoppage includes the inspection and maintenance, failures, Low load and others. The total abnormal stoppage days are 233 days during all of 15 years. The highest abnormal stoppage is inspection and maintenance, it is nearly 60.52% of total abnormal stoppage, 141 days. The failure of abnormal operation is nearly 22.75%, it is 53days. The Others of abnormal operation is 12.88% of total abnormal stoppage, it is 30 days during all of 15 years. The low load of abnormal stoppage is 3.86% of total abnormal stoppage, it is 9 days all of 15 years. It means that the inspection and maintenance is the main reason lead to the gas engine stoppage. Beside that, the failure also has an important effect of abnormal stoppage.

3) Classification of inspection and maintenance analysis

Classification of inspection and maintenance of the gas engine is presented in Fig.3-15. Fig.3-15 (a) shows the status of insertion are 1000 hours; Fig, 3-15 (b) shows the status of casual inspection; Fig.3-15 (c) shows the maintenance of this classification; Fig.3-15 (d) shows the standard measurement of this classification. To compare the Fig.3-15 (a) to (e), it is noticeable that the main classification of inspection and maintenance is inspection per 1000 hours. And the casual inspection is higher than inspection per 1000 hours in 2000 and 2008, because of it did the overhaul in these two years. And in 2009 and 2010, it inspected the gas valve, so it's higher than inspection per 1000 hours. The record of maintenance is very low, because the maintenance has been finished with the inspection per 1000 hours and casual inspection.

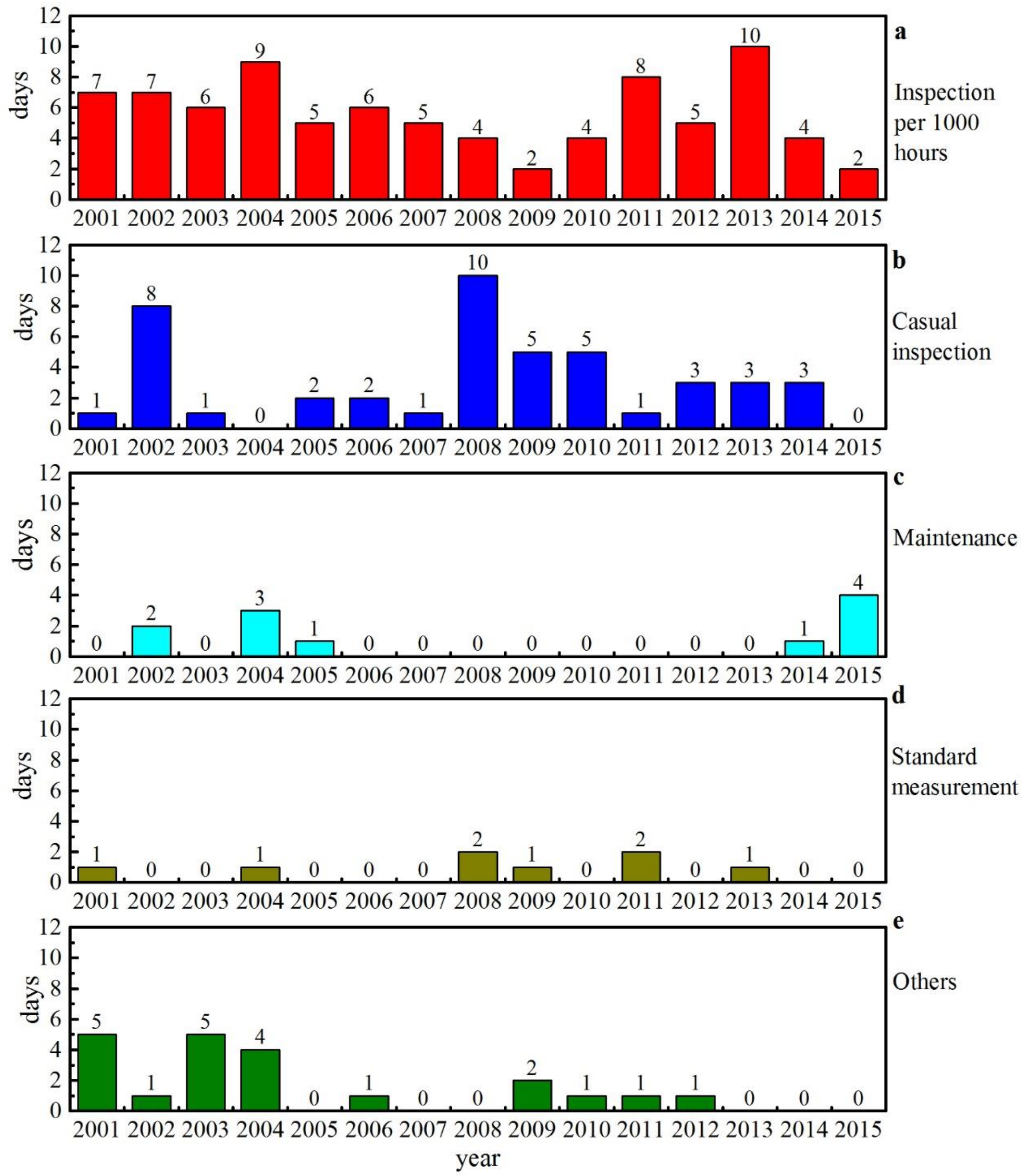


Fig.3-15 Classification of inspection and maintenance of gas engine

4) Classification of failure analysis

Classification of the failures of the gas engine is shown in Fig.3-16. The failures were classified by the different unit of the gas engine system. Fig.3-16 (a) shows the failures of power generation unit of gas engine; Fig.3-16 (b) shows the failures of cooling water engine of gas engine system; Fig.3-16 (c) shows the failures of heat recovery unit of gas engine system; Fig.3-16 (d) shows the failure of auxiliaries of gas engine system. The figure shows that power generation unit was often occurred the failures. Especially in 2011, because of the gas engine failures was kept 24 days. But it did not occur the failures in 2002 and 2008, maybe the overhaul in the two years is better. To compare the Fig.3-16 (b) and (c), result indicates that the cooling water unit was more likely to occur failure than heat recovery unit. The auxiliary unit failure was often occurred, especially in 2001, it has 15 days, it's because that the minor failure has not been repaired in time.

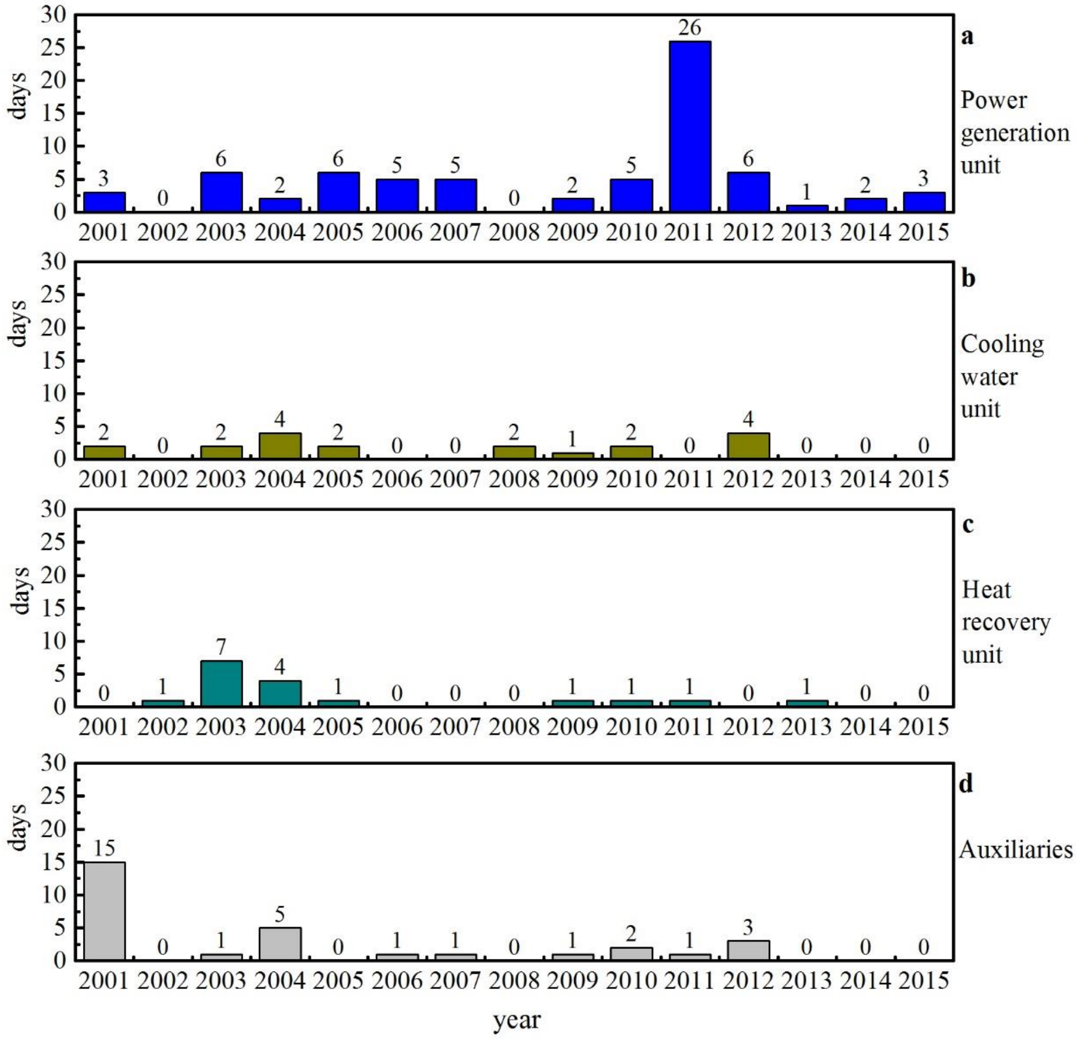


Fig.3-16 Classification of failures of gas engine

3.4.2. Analysis on the Operation Status of Fuel Cell

1. Classification of operation status of gas engine

The fuel cell of Kitakyushu Science and Research Park was operating all days of all over the year.

The fuel cell was operated from June 2001 to September 2011. In order to show the operation status clearly, the operation status was classified as annual inspection, casual inspection, maintenance and failure. The classification of operation status for fuel cell is present in Table 3-14. There are two classifications for the fuel cell as the following.

The classification 1 includes stoppage and operation. There are there generating capacity of gas engine for the operation, 125kW capacity, 150kW capacity and 200kW capacity. The different capacity means that the energy load is low or the fuel cell has some failures cannot provide the enough capacity.

As shown in Table 3-14, the classification 2 includes annual inspection, casual inspection, maintenance and failure. The annual inspection means that the fuel cell was inspected once of every year, at that time, the fuel cell should be stopped. Besides that, the fuel cell was stoppage or temporary stoppage when it was doing the casual inspection for some reasons. And the fuel cell was stoppage or temporary stoppage when it was doing maintenance. In addition, the fuel cell was stoppage or temporary stoppage when it was faulted. When the fuel cell was casual inspection, maintenance and failure with operation, it was called abnormal operation.

Table 3-14 Classification of operation status for fuel cell

	Classification1	Classification 2	Status of fuel cell
Fuel cell operation status	Stoppage	Annual inspection	Stoppage
		Casual inspection	Stoppage
		Maintenance	Stoppage
		Failure	Stoppage
	Operation (200kW,150kW,125kW)	Casual inspection	Temporary stoppage
		Maintenance	Temporary stoppage
		Failure	Temporary stoppage
			Operation all day

2. Analysis of operation status of fuel cell

1) Stoppage and operation analysis

Operational status during 15 years of gas engine is presented in Fig.3-17. The fuel cell was operated from 2001 to 2011. The fuel cell only operated 304 days in the first year and operated 241 days in the last year. So, the data of first year and the last year can be ignored. The power generation production includes 125kW, 150kW, and 200kW when the fuel cell was operated. The result indicated that the stoppage days of fuel cell are very few; the longest stoppage time occurred in 2005. In the first few years, the fuel cell was operated by 200kW production, but from 2005, the 150kW operation time had begun. From 2008, the operational production of fuel cell was lower than before; and the 125kW operational production was occurring. The total power generation operation was reducing year by year.

Fig.3-17 Operation status during 11 years of fuel cell

2) Stoppage and abnormal operation status analysis

The classification of operational status of fuel cells is presented in Fig.3-18. Fig.3-18 (a) is the operational status of annual inspection during 11years. The annual inspection was occurred take 3 to 6 days in the February or March every year. The Fig.3-18 (b) is the operational status of casual inspection during 11years; the Fig.3-18 (c) is the operational status of maintenance during 11 years. Compared the Fig.3-18 (c) and the Fig.3-18 (d), the casual inspection and maintenance days are longer than other years. That means the stoppage days are higher than other years. The failure status of fuel cell in presenting in Fig.3-18 (d). The Result of Fig.3-18 (d) indicates that the failure has occurred in 2009 was more than other years. The failure has occurred 8 days in 2011, after that the fuel cell was stopped.

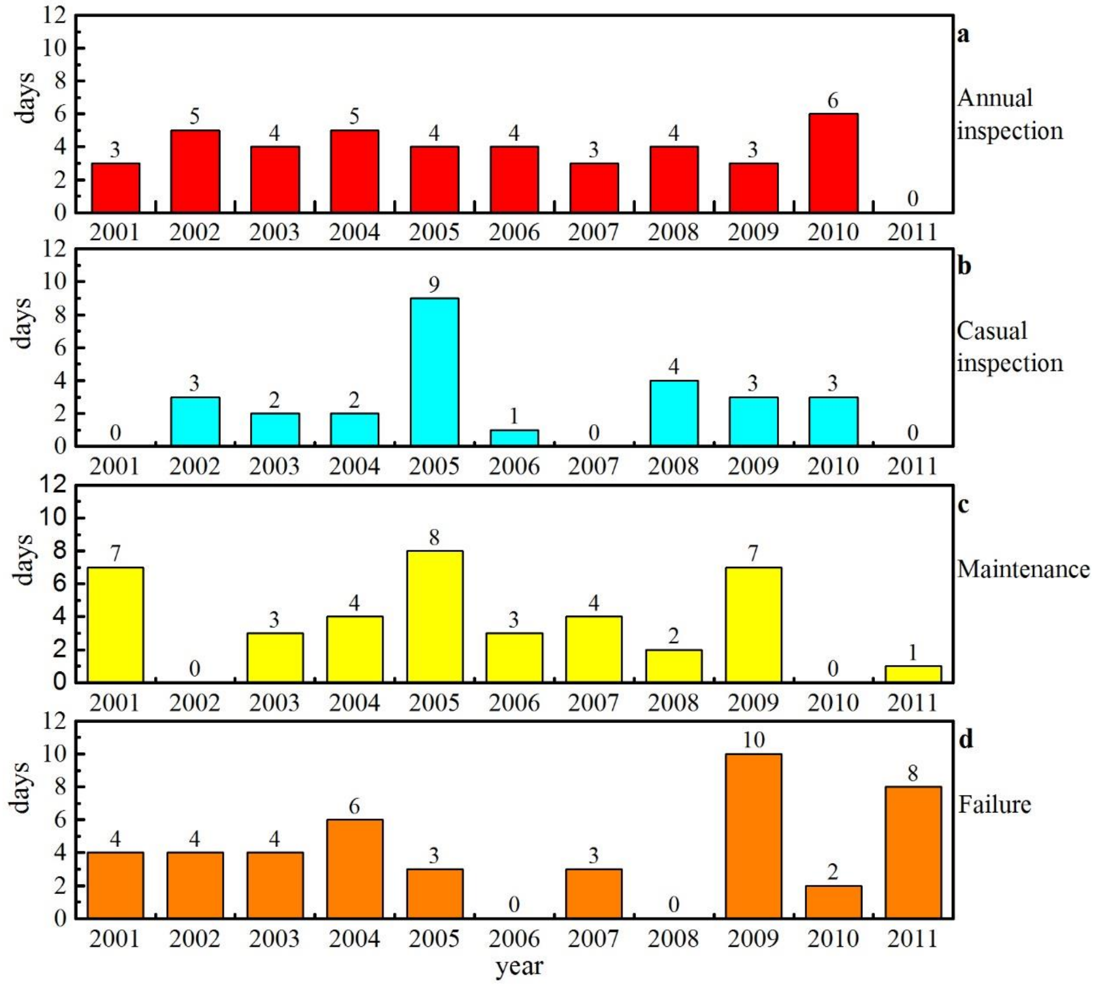
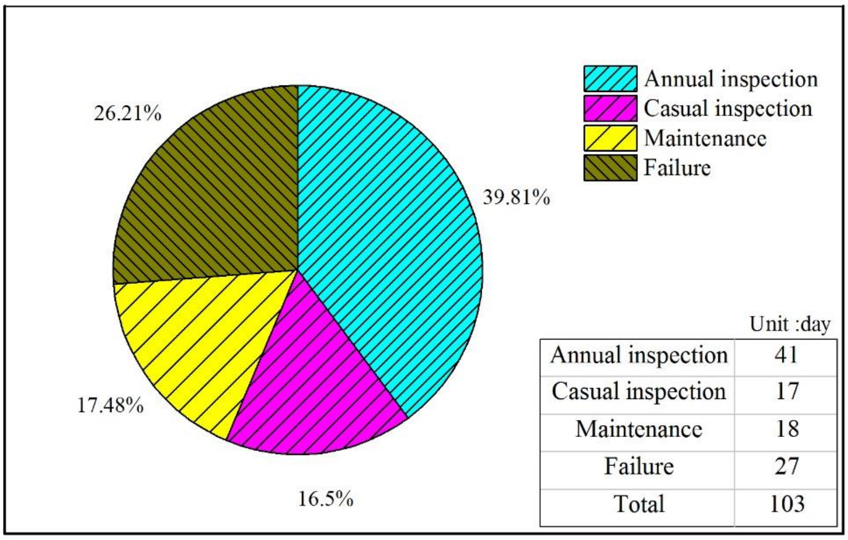


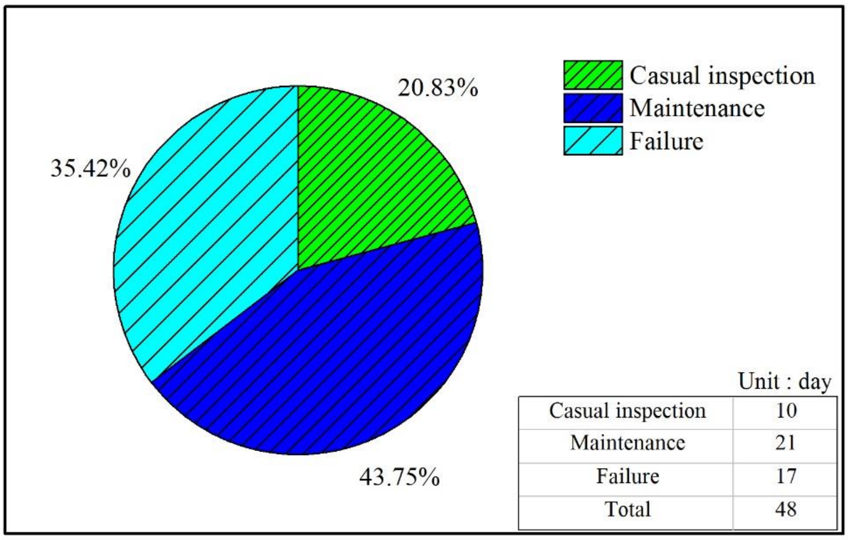
Fig.3-18 Classification of operation status for fuel cell

Fig.3-19 is the classification of the stoppage status of fuel cell in total 11years. The figure shows that the annual inspection is the main reason lead to the stoppage of fuel cell, the total days are 41 days during 11 years, nearly 29.81%. Failure is the second reason lead to stoppage of fuel cell, the total days is 27 days, nearly 26.21%. The maintenance was occurred total 18 days, nearly 17.48%. The casual inspection was occurred total 17 days, nearly 16.5%. The result is noticeable that the annual inspection is the main stoppage reason in the stoppage status. And most of the maintenance was finished in the annual inspection time.



Annual inspection	41
Casual inspection	17
Maintenance	18
Failure	27
Total	103

Fig.3-19 Classification of abnormal stoppage of fuel cell in total 11 years



Casual inspection	10
Maintenance	21
Failure	17
Total	48

Fig.3-20 Classification of abnormal operation of fuel cell in total 11 years

The Fig.3-20 is the classification of abnormal operation of fuel cell in total 11years. There are three classifications for the abnormal operation. It includes the casual inspection, maintenance and failure. The difference with stoppage is the annual inspection as the normal stoppage. The figure shows that the main stoppage is the maintenance. It means that the fuel cell was operated by maintenance; the failure, which was repaired, is the minor failure, it's little affects the operation of fuel cell. And the operation with failure is 17 days, nearly 35.42%. The casual inspection is 10 days, nearly 20.83%.

3.5. Analysis of the Failure of DER System in KSRP

The component replacement is the main action for the system maintenance. The cycle and frequency of component replacement can reflect the degree of system maintenance and the reliability of components. For the DER system in KSRP, the gas engine system is operated more than 15years, and the main maintenance schedule and actions are performed by the managers and profession Operation and Maintenance (O&M) engineers. However, the maintenance of fuel is performed by the manufacturer, and the operation of fuel cell was stopped in 2011. Therefore, this chapter analyze the gas engine replacement and failure data for analysis.

As introduced in chapter 3.3.2, the gas engine is performed the inspection (routine maintenance) per 1000 operation hours. There are five maintenance types, A, B C, D, E. According to the inspection data, there are 20 main components are selected and analyzed in this research. The main components of gas engine system are shown in Fig.3-21. The data is calculated from the July 2001 to March 2015.

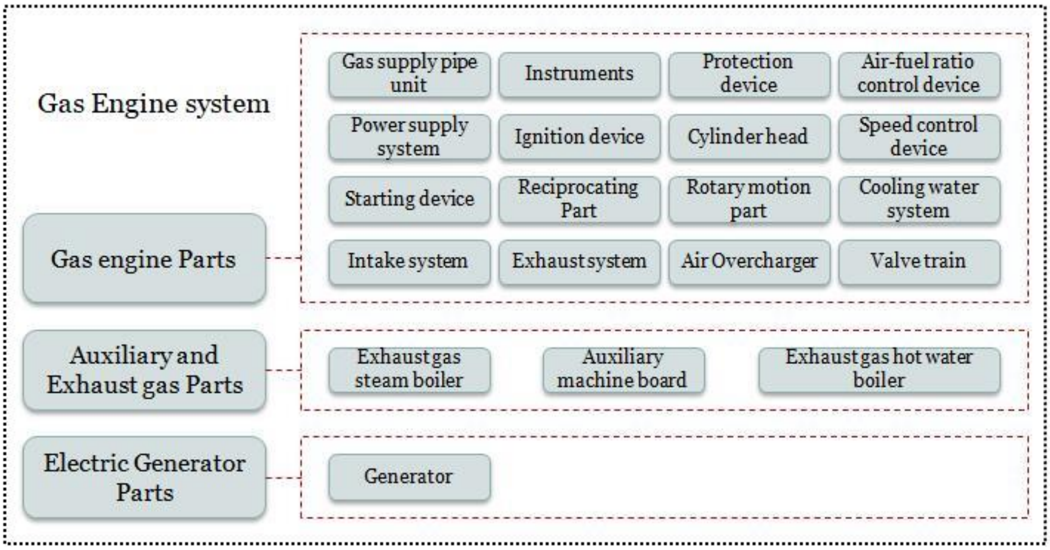


Fig.3-21 The main components of the gas engine system

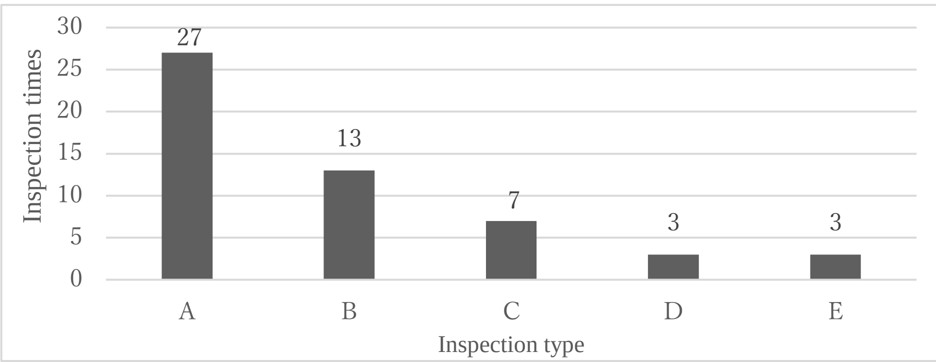


Fig.3-22 Total inspection times of each type 1000 hours

The Fig.3-22 present the total times of each type 1000 hours inspection of gas engine. The figures show that the inspection times of A is 27, actually, the inspection contents of A are performed 53 times, because each other 4 types inspection content contain the A types inspection contents. Therefore, the inspection contents of B type are performed 26times; the inspection contents of C types are performed 13 times; the inspection contents of D types are performed 6 times, and the inspection contents of E types are performed 3 times.

Table 3-15 Total cumulative replacement times of each component

Component	Gas supply pipe unit	Instruments	Protection device	Air-fuel ratio control device	Starting device
Total times	2	0	1	5	1
Component	Power supply system	Ignition device	Cylinder head	Speed control device	Reciprocating part
Total times	13	47	8	3	6
Component	Rotary motion part	Cooling water system	Intake system	Exhaust system	Air exchanger
Total times	48	14	4	2	6
Component	Valve train	Exhaust gas steam boiler	Auxiliary machine board	Exhaust gas hot water boiler	Generator
Total times	0	0	0	0	2

The total cumulative replacement times of each component is shown in Table 3-15. The result shows that the three main components of auxiliary and exhaust gas parts did not replacement in the past 14 years, those include Exhaust gas steam boiler, Auxiliary machine board and Exhaust gas hot water boiler. And the electrical generator part, the generator is replaced 2times. There are two components of engine part are not replaced, the Instruments and Valve train. And the Protection device and starting device are replaced 1 time. The Gas supply pipe unit, Exhaust system are replaced 2 times. Speed control device is replaced 3 times, Intake system is replaced 4 times. Air-fuel ratio control device is replaced 5 times. Reciprocating part and Air exchanger are replaced 6 times. The Power supply system and Cooling water system are replaced more than 10 times. And the Ignition device and Rotary motion part are replaced about 53 times. Ignition device and Rotary motion part belong to an inspection. And the total inspection times of A type were 53 times. That is to say, the replacement rate of Ignition device and Rotary motion part are 88.6% and 90%. The results show that the engine part has the high-level wear and tear. In particular, the engine startup and operating devices. More failure modes, failure cause and failure effect of DER system in SDRP will be presented in Chapter 4.

The failure rate and MTTR of the main components of DER system in KSRP is presented in Table

3-16. The failure data are investigated from the 2002 to 2010.

Failure rate is the frequency which a component or a system fails during a period, expressed in failures per unit of time. It can be calculated as the follows:

$$failure\ rate\ = \frac{failure\ numbers}{total\ operation\ time}$$

MTTR can be calculated as the follows:

$$MTTR\ = \frac{total\ repair\ time}{repair\ times}$$

Table 3-16 The failure rate, MTTR of main components of DER system in KSRP

Main Components	**Failure rate (Failure/ day)**	**MTTR (days)**
Fuel Cell	0.002982	2.0
Cooling tower for fuel cell	0.001210	1.0
Cooling pump for fuel cell	0.001534	1.0
Gas engine	0.008037	1.4
Cooling tower for gas engine	0.001143	1.0
Cooling pump for gas engine	0.001534	1.0
Heat recovery steam generator for fuel cell	0.001217	1.5
Heat recovery steam generator for gas engine	0.001217	1.5
Absorption chiller	0.005265	2.0
Auxiliary boiler	0.000930	1.0
Heat exchanger	0.000846	1.0

3.6. Analysis of the Maintenance Cost of DER System in KSRP

Maintenance cost analysis of DER system is performed based on the real data. The DER system of KSRP was operating since June 2000, the fuel cell was stopped on May 2011, and the gas engine was stopped at the end of 2017. In order to compare the maintenance cost of different devices, the data were calculated from April 2001 to March 2011, total 10 years data.

As introduced earlier, maintenance action includes Preventive Maintenance (PM) and (Corrective Maintenance) CM. PM actions were performed to keep the reliability of the component or system at a certain level, for instance, the inspection-based time or the overhaul-based time. In the inspection action of PM, some components will be repaired and replaced in order to keep the level, the cost of the repair and replacement of the inspection time is belonging to PM cost. CM actions are performed after a failure occurs to fix a component or system failure.

In the DER system of KSRP, 5 main devices were investigated and analyzed, they include the power generation units: gas engine, fuel cell, and the waste heat utilization and heat generation units: absorption chiller, the cooling units: all of the cooling tower of this system, and the translation power units: all of the pumps of this system. According to the investigation, the details of maintenance cost was classified into Component cost, Labor cost, overhead expenses and Subsidiary material cost.

The PM and CM cost of the main equipment of DER system in KSRP are shown in Fig.3-23. The figure shows that the maintenance cost of fuel cell is highest during the five equipment. The second higher is the maintenance cost of absorption chiller. And the maintenance gas engine is the third of the total maintenance cost. If the number of absorption chillers is considered to be three, the average maintenance cost of one is less than that of a gas engine. Although the PM cost of fuel cell is higher, but the CM cost is lower than each equipment in the DER system. Therefore, the high PM cost can reduce the incidence of failure. On the contrary, other equipment have the lower PM cost, but the CM cost are higher. The CM cost of gas engine accounts for 11.5% of the total maintenance cost. The CM cost of fuel cell accounts for 1.3% of the total maintenance cost. And the CM cost of absorption chiller account for 13.4%. However, the CM cost of the cooling tower and pump are higher than the PM cost. That because the most CM of cooling tower and pump is replacing the components or the whole pump, therefore, the CM cost is higher than PM cost.

The PM cost of the power generators (gas engine and fuel cell) of DER system in KSRP is shown in Fig.3-24. This figure presented the comparison of fuel cell and gas engine. Dur to the two power generators are performing different maintenance strategies, the PM costs are different. The fuel cell is performed the maintenance per year. The PM cost about 800 ten thousand to 935 then thousand. The annual maintenance cost varies little. However, the PM cost of gas engine are different of each year. The low PM cost of one year is around the 200 ten thousand, but the highest PM cost of one year is around 650 ten thousand. It is because that the gas engine has the different Preventive Maintenance types (A, B, C, D, E). The cost will be increased with the maintenance types from A to E.

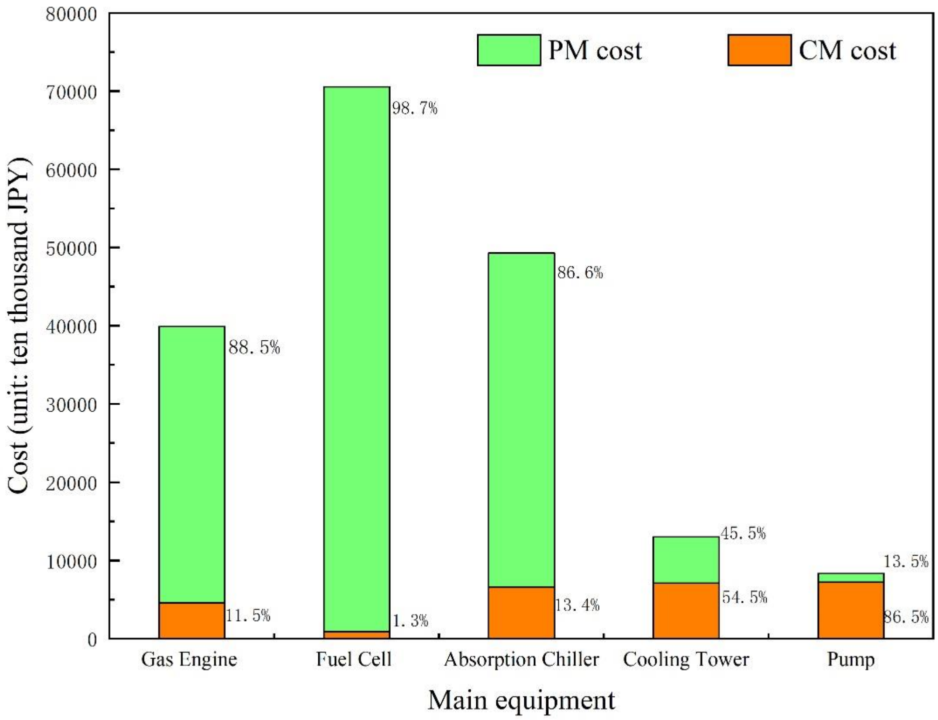


Fig.3-23 The PM and CM cost of the main equipment of DER system in KSRP

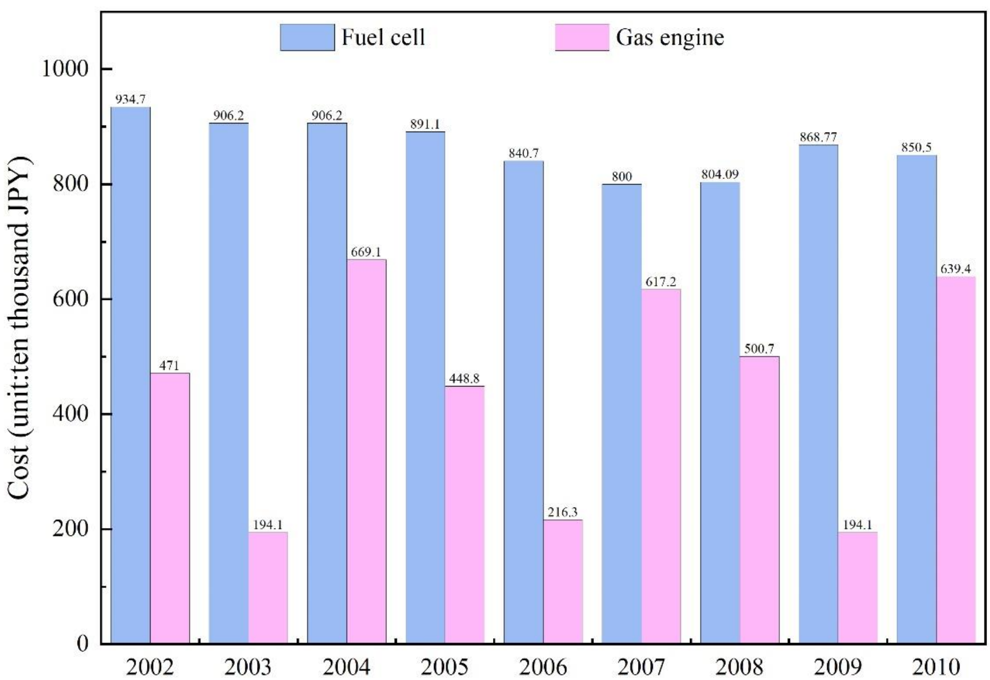


Fig.3-24 The PM cost of the power generators (gas engine and fuel cell) of DER system in KSRP

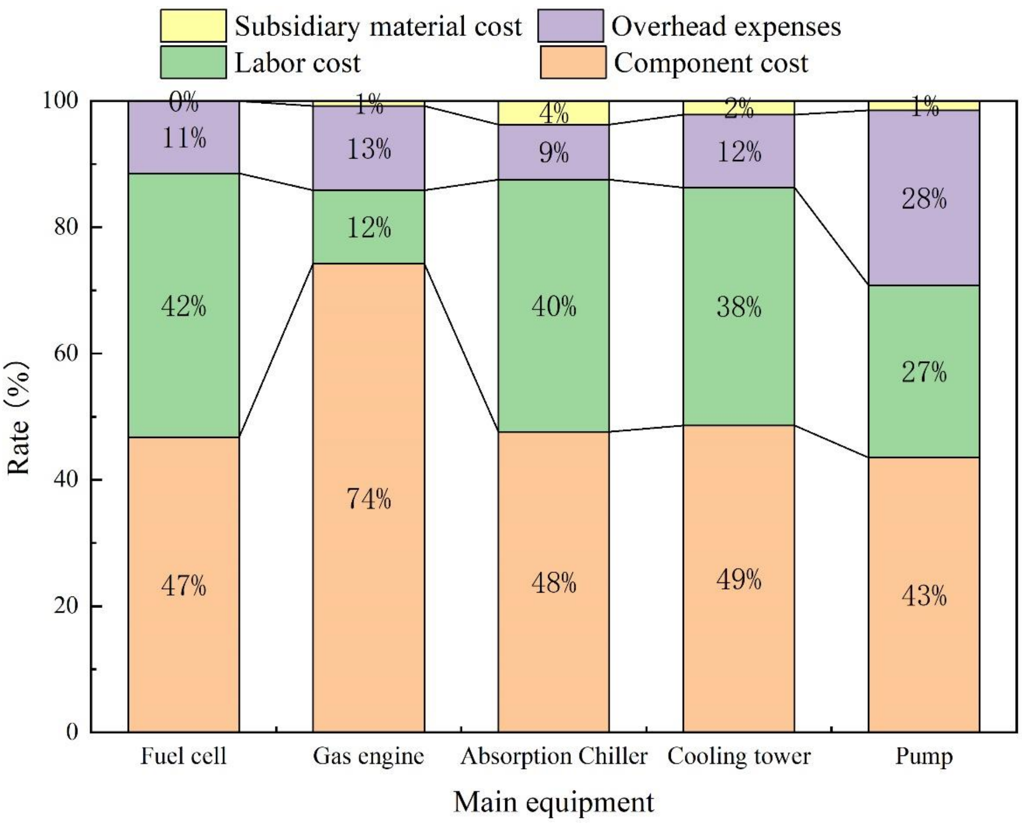


Fig.3-25 Proportion of CM cost for difference devices (Sum of 10 years)

The total CM actions' records during the investigation were 48 events for repair or replacement. The proportion of CM cost during the classification for the 5 devices was shown in Fig.3-25. It also appears from Fig.3-25 that generally the proportion of component cost of the device is about half of the total CM cost, but the gas engine more than 70%; that because the gas engine has the largest number of components and a high failure rate. The Overhead expenses of pump are higher than other devices, and the labor expenses are lower than other devices. Because the pump repair and replace time is short. The PM cost and CM cost are compared in Fig.4 and Fig.5. The PM cost of fuel cell is highest in the 5 devices, but the CM cost is lower than others.

3.7. Effect Analysis of Maintenance on Generation Efficiency of DER system in KSRP

The main purpose of the DER system is to supply the energy to meet the user's demand, especially the electrical demand. Therefore, the power generation efficiency of the DER system is the main index to assess the system performance of the DER system.

As presented above, the gas engine and fuel cell have the difference maintenance strategies, to understand how the maintenance actions to affect the power generation efficiency may can help the maintainers and managers to improve the maintenance on the engineering practice. Therefore, this chapter will analyze the relationship between maintenance actions and power generation efficiency, and determine the maintenance behavior that affects power generation efficiency.

The scheduled maintenance of gas engine is performed per 1000 hours, it includes five types; A type is performed per 1000 hours. B type is performed per 2000 hours, C type is performed per 4000 hours, D type is performed per 8000 hours, B type is performed per 16000 hours. The scheduled maintenance of fuel cell is performed one time per year. The analysis of the maintenance on generation efficiency are presented as the follows.

3.7.1. Effect Analysis of Maintenance on gas engine

The power generation data are investigated from 2001 to 2010. Until end of 2010 the gas engine was operated about 40,000 hours. During the ten 40,000 hours, the A type maintenance was performed 20 times, B type maintenance was performed 10times, C type maintenance was performed 6 times, D type maintenance was performed 2 times, and E type maintenance was performed 2times.Therefore, the power generation efficiency of different maintenance types is analyzed in this chapter.

In order to avoid the influence of other maintenance or repair actions, we selected the generation efficiency of 10 days before and after maintenance actions for analysis, and no maintenance action occurred in these 10 days.

1. A type maintenance of gas engine

The total A type maintenance had performed 20 time, but only 7 times are satisfied the analysis requirement. The data of the A type maintenance and the power generation efficiency changed results are shown in Table 3-17. The maintenance actions of A type maintenance are occurred in gas engine part. The components include Ignition device, Rotary motion part and Power supply system. the result show that the effect of A types is irregularly. The highest change is 0.9997% after 11000 maintenance, the maintenance action is only exchanging the spark plug of ignition device. When the Element exchange for Strainer of Rotary motion part are performed, the efficiency of gas engine only up a little. Compared of the 25000 hours, 27000 hours, 27000horus, 33000 hours maintenance actions, we can find that supply the lubricating oil may lead the power generation efficiency will down a little.

Table 3-17 The maintenance actions and power generation efficiency changed result of A type maintenance of gas engine.

Hours	**Inspection Type**	**Major classification**	**Minor classification**	**Inspection Part**	**Maintenance action**	**Result**
11000	A	Gas engine Part	Ignition device	Spark plug	Total exchange	0.997% up
15000	A	Gas engine Part	Ignition device	Spark plug	Total exchange	0.039% up
			Rotary motion part	Strainer	Element exchange	
23000	A	Gas engine Part	Power supply system	Battery	Electrolyte supply	0.023% down
			Ignition device	Spark plug	Total exchange	
			Rotary motion part	lubricating oil	40L supply	
				Strainer	Element exchange	
25000	A	Gas engine Part	Power supply system	Battery	Electrolyte supply	0.15% up
			Ignition device	Spark plug	Total exchange	
			Rotary motion part	lubricating oil	12L supply	
				Strainer	Element exchange	
27000	A	Gas engine Part	Ignition device	Spark plug	Total exchange	0.226% down
			Rotary motion part	lubricating oil	15L supply	
				Strainer	Element exchange	
33000	A	Gas engine Part	Ignition device	Spark plug	Total exchange	0.415% down
			Rotary motion part	lubricating oil	12L supply	
				Strainer	Element exchange	
35000	A	Gas engine Part	Ignition device	Spark plug	Total exchange	0.188% up
			Rotary motion part	Strainer	Element exchange	

The average power generation efficiency of A type maintenance on 23,000 hours is shown in Fig.3-25. We can find that the power generation are changed a little, the change is irregularly.

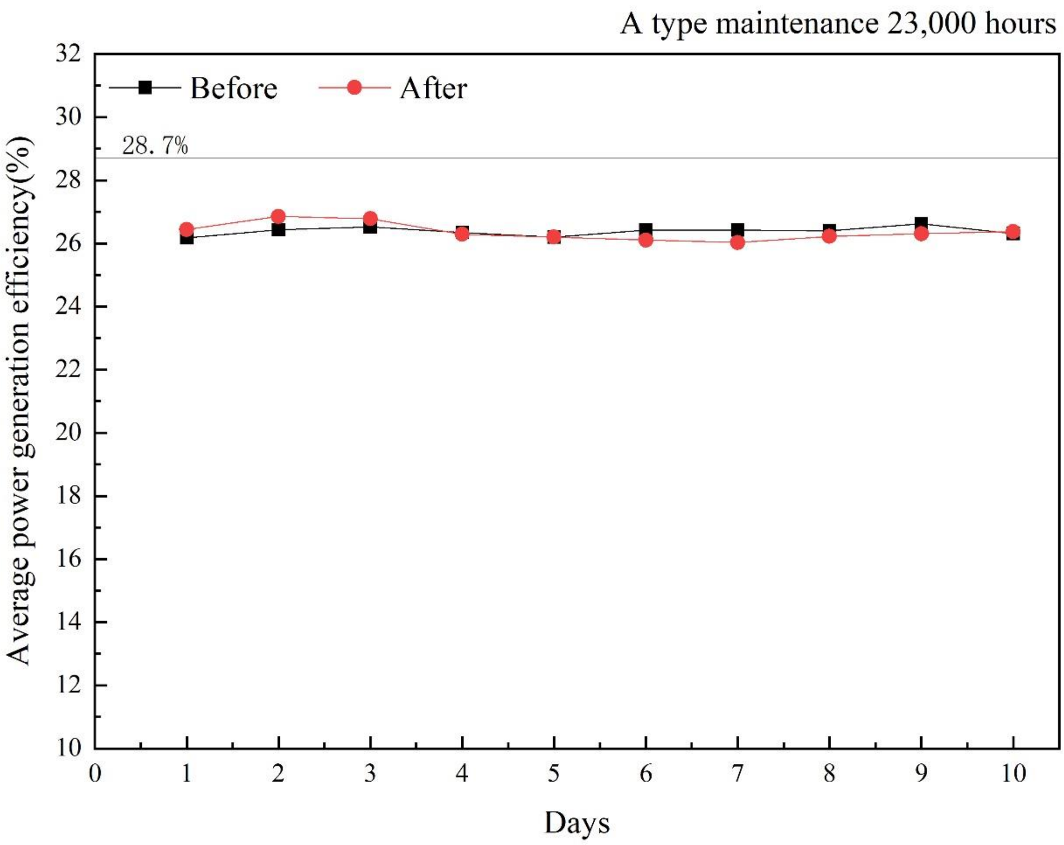


Fig.3-26 Average power generation efficiency of A type maintenance on 23,000 hours

Table 3-18 The maintenance actions and power generation efficiency changed result of B type maintenance of gas engine.

Hours	**Inspection Type**	**Major classification**	**Minor classification**	**Inspection Part**	**Maintenance action**	**Result**
2000	B	Gas engine Part	Ignition device	Spark plug	Total exchange	0.239% up
			Rotary motion part	lubricating oil	Total exchange	
				Strainer	Element exchange	
30000	B	Gas engine Part	Power supply system	Battery	Exchange	0.561% down
			Ignition device	Spark plug	Total exchange	
			Rotary motion part	lubricating oil	Total exchange	
				Strainer	Element exchange	

2.B type maintenance of gas engine

The total B type maintenance are performed 10 times, but only 2 times are satisfied the analysis requirement. And the maintenance actions and power generation efficiency changed result of B type maintenance of gas engine is shown in Table 3-18. The result show that the is irregularly.

3.C type maintenance of gas engine

The total C type maintenance are performed 6 times, but only 3 times are satisfied the analysis requirement. The maintenance actions and power generation efficiency changed result of C type maintenance of gas engine are shown in Table 3-19. In the 4,000 hours C type maintenance actions are only changed on the A type maintenance contents. But the 28,000 hours C type maintenance actions not only the A type maintenance contents, but also maintain the Ignition device Plug cord and Cylinder head Intake valve･Exhaust valve. It makes the power generation efficiency improve 0.832%.

Table 3-19 The maintenance actions and power generation efficiency changed result of C type maintenance of gas engine.

<table>
<tr><th>Hours</th><th>Inspection Type</th><th>Major classification</th><th>Minor classification</th><th>Inspection Part</th><th>Maintenance action</th><th>Result</th></tr>
<tr><td rowspan="3">4000</td><td rowspan="3">C</td><td rowspan="3">Gas engine Part</td><td>Ignition device</td><td>Spark plug</td><td>Total exchange</td><td rowspan="3">0.078% up</td></tr>
<tr><td rowspan="2">Rotary motion part</td><td>lubricating oil</td><td>Total exchange</td></tr>
<tr><td>Strainer</td><td>Element exchange</td></tr>
<tr><td rowspan="4">12000</td><td rowspan="4">C</td><td rowspan="4">Gas engine Part</td><td>Ignition device</td><td>Spark plug</td><td>Total exchange</td><td rowspan="4">0.583% down</td></tr>
<tr><td rowspan="2">Rotary motion part</td><td>lubricating oil</td><td>Total exchange</td></tr>
<tr><td>Strainer</td><td>Element exchange</td></tr>
<tr><td>Power supply system</td><td>Battery</td><td>Electrolyte supply</td></tr>
<tr><td rowspan="6">28000</td><td rowspan="6">C</td><td rowspan="6">Gas engine Part</td><td rowspan="2">Ignition device</td><td>Spark plug</td><td>Total exchange</td><td rowspan="6">0.832% up</td></tr>
<tr><td>Plug cord</td><td>Terminal seal exchange, NO.2 CYL exchange</td></tr>
<tr><td rowspan="2">Cylinder head</td><td rowspan="2">Intake valve･Exhaust valve</td><td>Exchange</td></tr>
<tr><td>Valve seat exchange</td></tr>
<tr><td rowspan="2">Rotary motion part</td><td>lubricating oil</td><td>Total exchange</td></tr>
<tr><td>Strainer</td><td>Element exchange</td></tr>
</table>

Table 3-20 The maintenance actions and power generation efficiency changed result of D type maintenance of gas engine.

Hours	Inspection Type	Major classification	Minor classification	Inspection Part	Maintenance action	Result
8000	D	Gas engine Part	Ignition device	Spark plug	Total exchange	0.253% up
				Plug cord	Total exchange	
			Reciprocating Part	Piston	Piston ring exchange	
			Cooling water system	Cooling water pump	Mechanical seal exchange	
				Temperature control valve	Exchange	
			Rotary motion part	Lubricating oil	Total exchange	
				Lubricating oil Strainer	Element exchange	
			Air Overcharge	Overcharge	Bearing exchange	
			NOX control device	O2 Sensor	Exchange	
24000	D	Gas engine Part	Ignition device	Spark plug	Total exchange	0.456% up
				Plug cord	No.6-cylinder exchange	
			Governor	Mixer	Diaphragm exchange	
			Reciprocating Part	Piston	Piston and ring exchange	
				Connecting rod	No.1・No.6 exchange	
				Cylinder liner	No.6 exchange	
			Cooling water system	Cooling water pump	Bearing exchange	
					Mechanical seal exchange	
			Rotary motion part	lubricating oil	Total exchange	
				Strainer	Element exchange	
				Cooler	O ring exchange	
			Exhaust system	Flue	Exhaust bellows exchange	
			Air Overcharge	Overcharge	Bearing exchange	
			Other	Cooling water	Exchange	

4.D type maintenance of gas engine

The total D type maintenance are performed 2 times, and satisfied the analysis requirement. The maintenance actions and power generation efficiency changed result of D type maintenance of gas engine is shown in Table 3-20. The power generation efficiency after maintenance actions are improve 0.253% and 0.456% in 8,000 hours and 24,000 hours D type maintenance respectively. The difference maintenance actions with C type maintenance is that the Cooling water system, Rotary motion part cooler, Air Overcharge and Exhaust system are included in the maintenance actions.

5.E type maintenance of gas engine

The total E type maintenance are performed 2 times, and satisfied the analysis requirement. The maintenance actions and power generation efficiency changed result of E type maintenance of gas engine is shown in Table 3-21. The power generation efficiency after E type maintenance action are improved 1.784% and 2.741% in the 16,000 hours and 32,000 hours E type maintenance. The E type maintenance are performed more maintenance actions for the gas engine. The most different with D type maintenance is the crankshaft was maintained. In addition, the related pumps are maintained in the E type maintenance, such as Cooling water pump, Jacket water pump, Hot water pump. And the Gas supply system are also maintained in this E type maintenance.

Table 3-21 The maintenance actions and power generation efficiency changed result of E type maintenance of gas engine.

Hours	**Inspection Type**	**Major classification**	**Minor classification**	**Inspection Part**	**Maintenance action**	**Result**
16000	E	Gas engine Part	Ignition device	Magnet Pulsar Igniter	Oil seal Exchange	1.784% up
				Spark plug	Total exchange	
			Cylinder head	Ignition sleeve	Exchange	
			Reciprocating Part	Piston	Piston ring exchange	
				Connecting rod	Exchange	
				Cylinder liner	Exchange	
			Crankshaft	Crankshaft metal part	Exchange	
			Cooling water system	Cooling water pump	Bearing·Mechanical seal exchange	
				Temperature control valve	Exchange	
			Rotary motion part	lubricating oil	Total exchange	
				Strainer	Element exchange	
				Cooler	O ring exchange	
			Air Overcharge	Overcharge	Bearing exchange	
				Air cooler	Exchange	

Hours	Inspection Type	Major classification	Minor classification	Inspection Part	Maintenance action	Result
32000	E	Gas engine Part	Gas supply pipe unit	Gas regulator	Diaphragm exchange	2.741% up
			Air-fuel ratio control device	O2 Sensor	Exchange	
			Ignition device	Pulsar	Driving part exchange	
				Igniter	Exchange	
				Spark plug	Total exchange	
				Plug cord	Total exchange	
			Cylinder head	Plug sleeve	O ring and packing exchange	
				Intake valve・Exhaust valve	Total exchange	
			Speed control device	Throttle valve	Rod end bearing exchange	
			Reciprocating Part	Piston	Piston ring exchange	
				Connecting rod	Exchange	
				Cylinder liner	Exchange	
			Rotary motion part	Crankshaft metal part	Exchange	
				lubricating oil	Total exchange	
				lubricating oil pump	Exchange	
				Strainer	Element exchange	
				Cooler	O ring exchange	
			Cooling water system	Cooling water tank	Gauge exchange	
				Cooling water	Total exchange	
				Cooler water pump	Bearing ・ mechanical seal exchange	
				Jacket water pump		
				Hot water pump		
			Gas supply system	Venturi mixer	Diaphragm exchange	
				Rubber fitting	Exchange	
				Air cleaner	Filter element exchange	
			Exhaust system	Exhaust manifold	Packing exchange	
			Air Overcharge	overcharge	Bearing exchange	
				Air cooler	Exchange	

The comparison of average power generation efficiency between D type maintenance and E type maintenance is shown in Fig.3-26 and Fig.3-27. The results show that the power generation efficiency of the E type maintenance is lower than D type maintenance. That is because with the extension of operating time, equipment appears deterioration, so the generation efficiency is reduced.

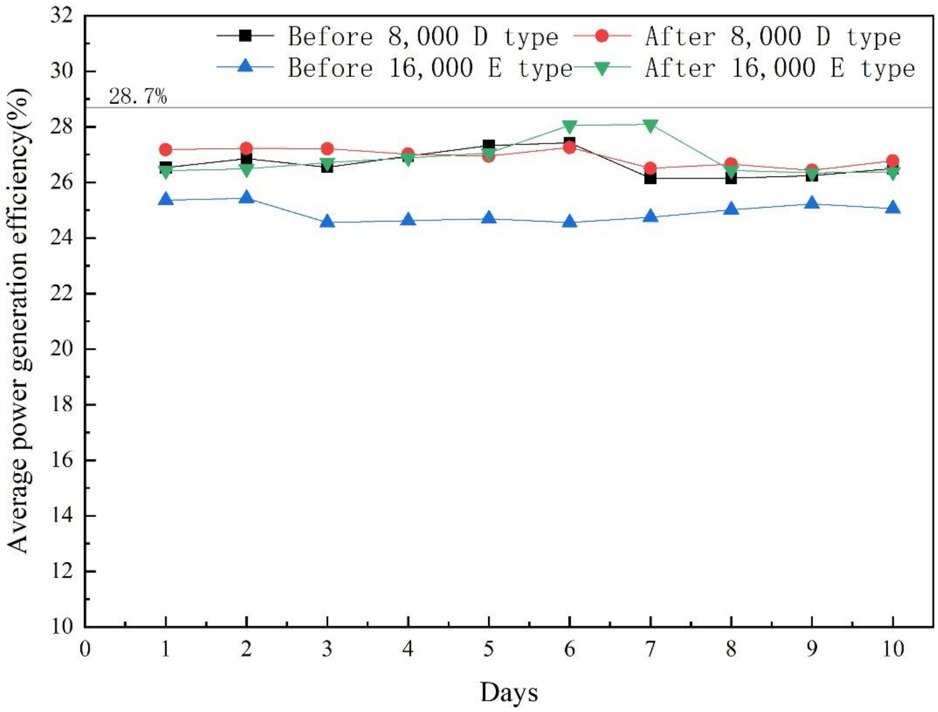


Fig.3-27 Comparison of average power generation efficiency between 8,000 hours D type maintenance and 16,000 hours E type maintenance

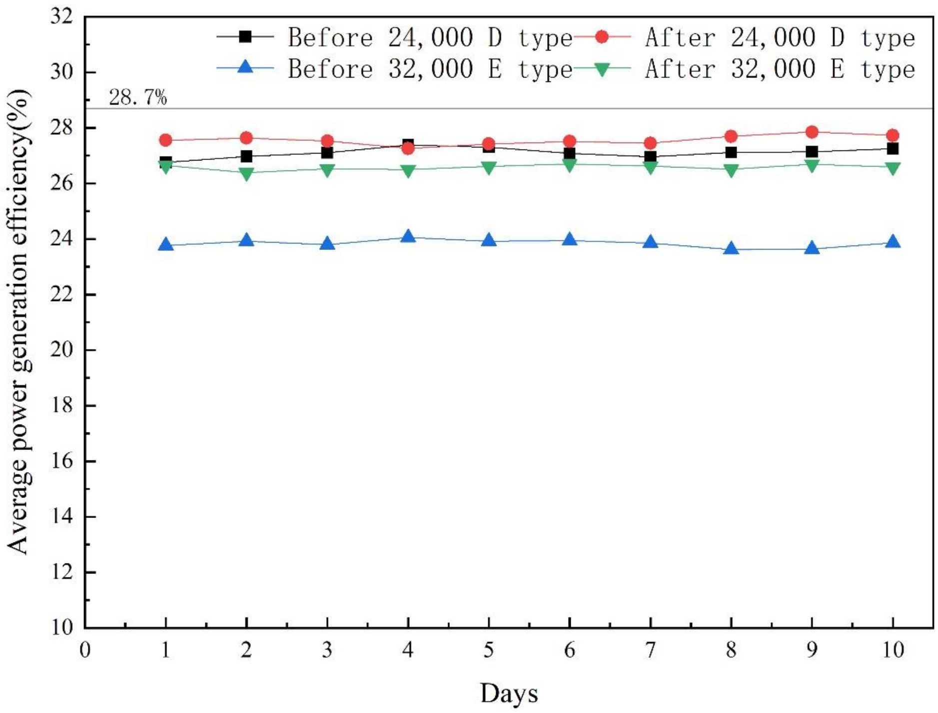


Fig.3-28 Comparison of average power generation efficiency between 24,000 hours D type maintenance and 32,000 hours E type maintenance

The max power generation efficiency of gas engine in different period was shown in Fig.3-28. The result shows that the summer power generation efficiency of gas engine was higher than the winter power generation efficiency. The design efficiency of gas engine is 28.7%, compared the three-life period, only the efficiency in useful life can up to the grade. And the result presents that the early life power generation efficiency of gas engine was higher than begin to wear out life power generation efficiency of a gas engine and the early life power generation efficiency of gas engine. The white space of the line means that the gas engine was stopped. This figure shows that the best efficiency of gas engine was occurred in the useful life.

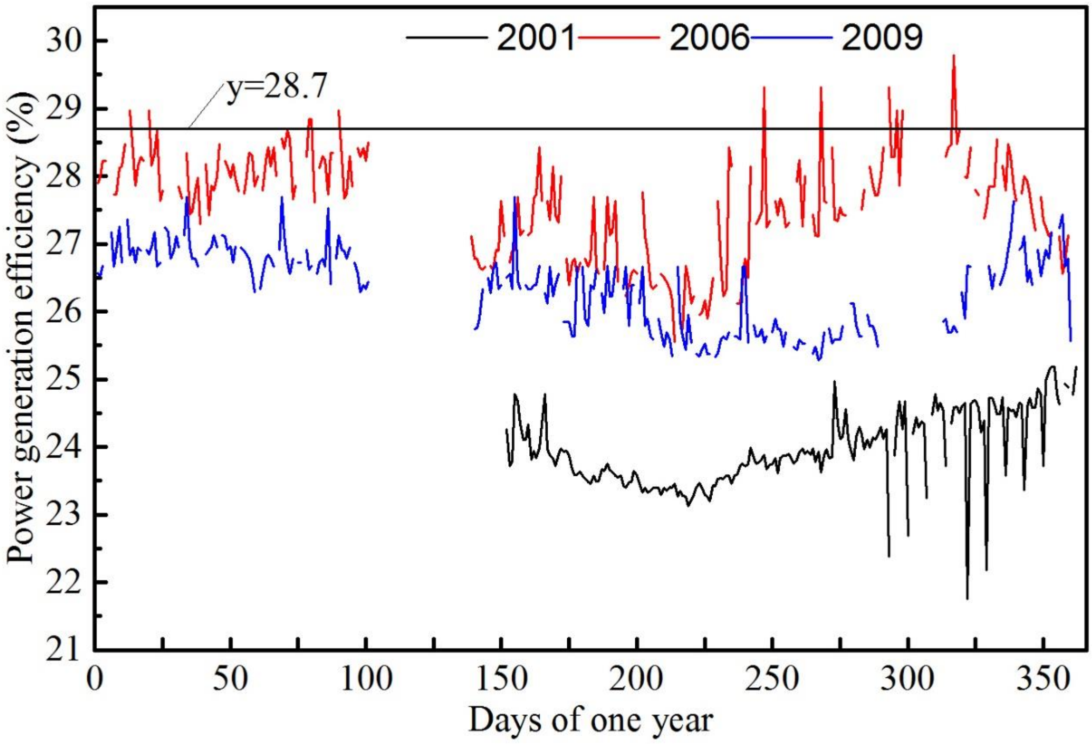


Fig.3-29 Max power generation efficiency of gas engine in 2001, 2006 and 2009

3.7.2. Effect Analysis of Maintenance on fuel cell

The fuel cell operates from 2001 and end of the 2011. After the annual maintenance of 2010, the fuel cell is stopped. Therefore, only 9times maintenance are satisfied the analysis requirement. The e maintenance actions and power generation efficiency changed result of annual maintenance of fuel cell is shown in Table 3-22. The result shows that the maintenance actions can ensure that the generation efficiency is maintained at a certain level, but it is difficult to improve the generation efficiency. In addition, we can find that the efficiency of fuel cells does not change much with the increase of operating time.

Table 3-22 The maintenance actions and power generation efficiency changed result of annual maintenance of fuel cell

Maintenance actions	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**
Motorized valve electromagnetic brake	○	○	○	○		○	○	○	○
PMP450/451 Replacement parts	○	○	○	○	○	○			
PMP830 Overhaul		○	○		○				
PSV500/800 Overhaul	○				○				
Gas detector inspection test gas	○	○	○	○	○	○	○	○	○
Detector inspection test gas	○	○	○	○	○	○			
HEX920 Steam cleaning baking soda	○	○	○	○	○	○	○	○	○
HEX920 Gasket	○	○	○	○	○	○	○	○	○
ORG400 (Activated carbon)	○	○	○	○		○			
ORG450 (Activated carbon)							○	○	○
DMN400 (Ion exchange resin)	○	○	○	○		○			
DMN450 (Ion exchange resin)							○	○	○
FIL100	○	○	○	○	○	○	○	○	○
FIL150	○	○	○	○	○	○	○	○	○
DMN440 Ion exchange resin	○	○	○	○	○	○	○	○	○
DMN440 O-ring	○	○	○	○	○	○	○	○	○
CV500 Maintenance kit	○	○	○	○	○	○	○	○	○
CV500 Gasket	○	○	○	○	○	○	○	○	○
FIL401 Gasket	○	○	○	○	○	○	○	○	○
FIL830 Gasket	○	○	○	○	○	○	○	○	○
Second-order filter	○	○	○	○	○	○	○	○	○
Inverter cooling fan	○	○	○	○		○			
Ejector replacement parts			○	○		○			
UPS			○	○		○	○		
Glycol					○	○	○	○	
Anticorrosive material	○	○	○	○		○	○	○	
General consumables	○	○	○	○	○	○	○	○	○
PMP400 Overhaul	○								
Power controller air conditioner maintenance	○								
Value of efficiency changed (%)	-0.364	0.528	0.249	0.672	0.327	0.141	0.372	0.888	0.108

3.8. Summary

This chapter investigates the maintenance management strategies, system operational status, the replacement and failures, the maintenance cost, and maintenance effect for the power generation efficiency.

The maintenance management of the DER system has been introduced, the maintenance management strategies of each equipment are different, For the power generation units, gas engine and fuel cell, the maintenance is getting more attention, the maintenance of a gas engine is performed by the professional company, the maintenance of fuel cell are performed by the manufacturer. The other equipment is performed by the managers. Maintenance of power generation equipment is more important than other equipment. The routine maintenance, scheduled maintenance, planned maintenance and corrective maintenance are applied to the DER system in KSRP.

The operation status and failure status are analyzed in this chapter. For the gas engine system, the most of the failures were occurring in engine part of gas engine. With the output power are more and more low, form 200kW to 125kW. And the frequency of failures is increasing with the time increased. The failure rate and MTTTR of the main component in the DER system are presented in this chapter.

In the DER system of KSRP, maintenance cost of 5 main devices was investigated and analyzed, the gas engine, fuel cell, absorption chiller, cooling tower and pump. The maintenance cost of fuel cell is highest during the five equipment. The second highest is the maintenance cost of absorption chiller. PM cost of fuel cell is higher, but the CM cost is lower than each equipment in the DER system. Therefore, the high PM cost can reduce the incidence of failure.

According to the investigation, the details of maintenance cost was classified into Component cost, Labor cost, overhead expenses and Subsidiary material cost. The proportion of component cost of the device is about half of the total CM cost, but the gas engine more than 70%; that because the gas engine has the largest number of components and a high failure rate.

According to the power generation efficiency of power generation equipment, we can find that the power generation efficiency will be decreasing with the time increasing. And Maintenance can significantly improve equipment performance. In particular, the system to a greater degree of maintenance. So, maintenance management is very important in the operation of distributed energy system. However, maintenance costs are high, and reasonable allocation of maintenance resources and funds is an important research point in maintenance management.

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Chapter 4. Maintenance Optimization of the DER System Based on the FMEA Method

4.1. Introduction

Failure modes and effects analysis (FMEA) were one of the first highly structured and systematic techniques for reliability and maintenance analysis. It is a systematic method for analysis and ranking the risks associated with various products or processes, failure modes, prioritizing them for remedial action, acting on the highest ranked items, reevaluating those items and returning to the prioritization step in a continuous loop until marginal returns set in.

As mentioned above, The DER system in KSRP is mainly divided into two parts, gas engine sub-system and fuel cell sub-system. In addition to the main power generation equipment, there are multiple heat utilization and auxiliary equipment are included in the main power generation equipment system. Therefore, there are many components in the gas engine sub-system and fuel cell sub-system. Each component has the reliability during difference maintenance strategy. When a component is failing, it may be led to the failure of a part or the whole system. Therefore, one of the ways to improve system reliability is to find the weakest components in the system and carry out a higher level of maintenance. However, for different components, there are different failure reasons and failure modes. Therefore, the analysis of the cause, mode and consequences of component failure can provide reference and basis for reliable maintenance.

In this chapter, the reliability centered maintenance (RCM) applied here to the DER system in KSRP uses an FMEA method which allows the processing of each individual analysis of a system's components. This analysis identifies the various possible failure modes which affect each component, along with the failure causes and the failure consequences, both the gas engine and fuel cell sub-system. Generally, the maintenance and operation of equipment will be based on the advice of designers and manufacturers, but are not knowledgeable in the operation of equipment. In this investigation and analysis, we consider the opinions of technicians who are performing the maintenance and management.

The risk priority number (RPN) is evaluated for the maintenance optimization of DER system. According to the RPN data, the maintenance strategy and actions can be optimized for the future maintenance.

This chapter is organized as the following. In Chapter 4.2 the FMEA methods and the research following are introduced, and the risk priority number (RPN) is discussed. The maintenance optimization analysis of gas engine sub-system is presented in Chapter 4.3. And the maintenance optimization analysis of gas engine sub-system is presented in Chapter 4.4. The Chapter 4.5 is the summary.

4.2. Analysis Method and Research Flow

The reliability of a complex system depends on the reliability of its components and how the components are connected throughout the system. Many reliability methods have been developed to assess the reliability of complex systems, such as fault tree analysis (FTA) method, failure mode and effect analysis (FMEA) method, reliability, maintenance block diagram, Bayesian network model, Markov chain and Monte Carlo simulation etc. Some methods have been introduced in Chapter 2.

The method has mentioned was designed to model the operation of the system to determine its reliability characteristics. Each method has its advantages and disadvantages and has been widely analyzed in the scientific literature. The advantages and disadvantages have been introduced, and the compression of FTA, FMEA and FMECA has been presented. FTA method may not find the all possible initiating failures and cannot analyze the more complex system. The FMECA method can give us more details of the system's component reliability, however, it needs to investigate a large number of trivial cases, but for a complex DER system, it may not have a lot of actual case data to be analyzed.

This method does not allow the evaluation of reliability functions of complex systems, but allows for the identification and analysis of all system failures, assesses their importance in system reliability, and then focuses on maintenance practices and their impact on system reliability. In addition, FMEA allows for the processing of uncertainties due to the complexity of the system and the fuzziness of human judgment[1]. The FMEA method uses real data from equipment during operation to analyze the relevant faults of components, so there is no theoretical causality. The effectiveness of the FMEA method comes from the practice-based approach, which allows the selection of cost-effective actions to the correct maintenance plan.

The FMEA method is widely used to predict failure modes of products. This method links the failure mode of the product with the failure impact and evaluates the importance of the failure mode. For a complex system, FMEA techniques can be used for component and subcomponent failure modes. FMEA is mainly used for analysis of individual components and provides references to designers, operators and customers to improve maintenance methods and reduce direct and indirect losses. This method is mainly used in product development, manufacturing, quality control and maintenance phase analysis.

The FMEA method adopts the risk priority number (RPN) to evaluate and optimize the failure of component by analyzing the failure modes, causes and effects of the failure. The steps of FMEA method can be written as the follows:

Step 1: review the system's components details, such as the requirement, maintenance data, system function, component's function, failure events etc.

Step 2: break down the structure of equipment or system, and draw the reliability equipment block diagram. The equipment block diagram for a complex system is shown in Fig.4-1.

Step 3: determine the failure mode, failure cause and failure effect of the components. The effect of failure can relate to a part, a sub-system and whole system.

Step 4: calculate the risk priority number (RPN), the severity (S), Occurrence (O) and Detection (D) for each failure mode.

Step 5: perform the FMEA process to assess the reliability and maintenance.

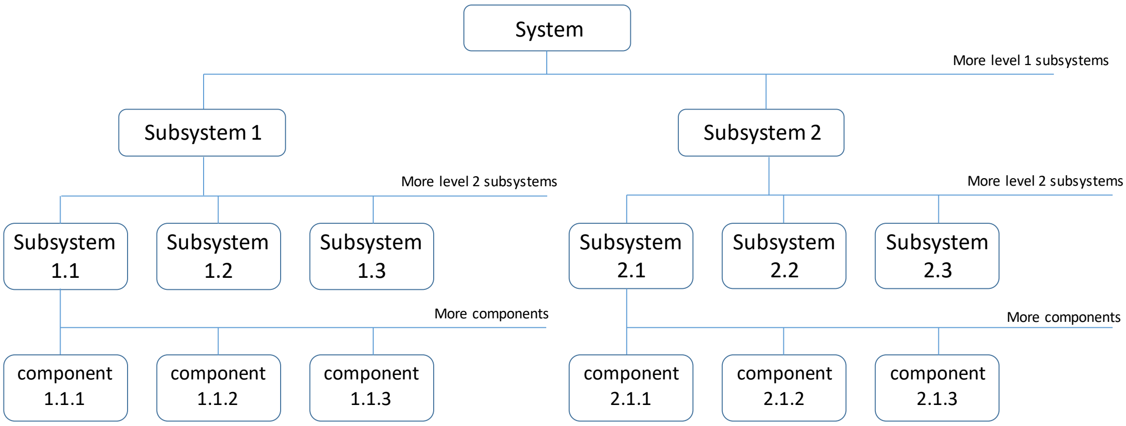

Fig.4-1 Equipment block diagram for a complex system

The FMEA process for DER system in KSRP is shown in Fig.4-2. The FMEA process is applied to assess the importance level of the component. After performed the FMEA assessment, a team review will be applied for the maintenance strategy. The members for the team can include the engineers, operators, manufacturers, designers, managers and maintainers etc. Through professional maintenance knowledge, equipment knowledge, maintenance experience and management experience, put forward improvement strategy for equipment maintenance strategy and evaluate new RPN.

There are three factors are used to calculate the RPN, include severity, Occurrence and detection. Severity (S), occurrence (O), and detection (D) factors are rated separately using numerical scales, usually ranging from 1 to 10 [2].

The details of the three factors can be descripted as the follows [3]:

- Severity (S): Result generated from failure.
- Occurrence (O): Opportunity or probability of a failure.
- Detection (D): Opportunity for an unidentified failure because of the difficulty in detection.

The RPN can be expressed as:

$$RPN = S \times O \times D \tag{4-1}$$

The evaluation rank is based on a scale of 1–10, with the corresponding description from the Mauro Villarini et al. [1], Kapil Dev Sharma et al. [4], Jichuan Kang [5] and the investigation in KSRP. The rank of Severity (S), occurrence (O), and detection (D) is shown in Table 4-1, Table 4-2 and Table 4-3, respectively. As a consequence of the scale indicators, the RPN values are ranked between 1 and

1000. The Effect of different RPN level is divided into four levels, includes No effect (RPN 1-10), Duty unfulfilled (11-100), Failing an important mission (101-250), Abandonment of duties (251-1000).

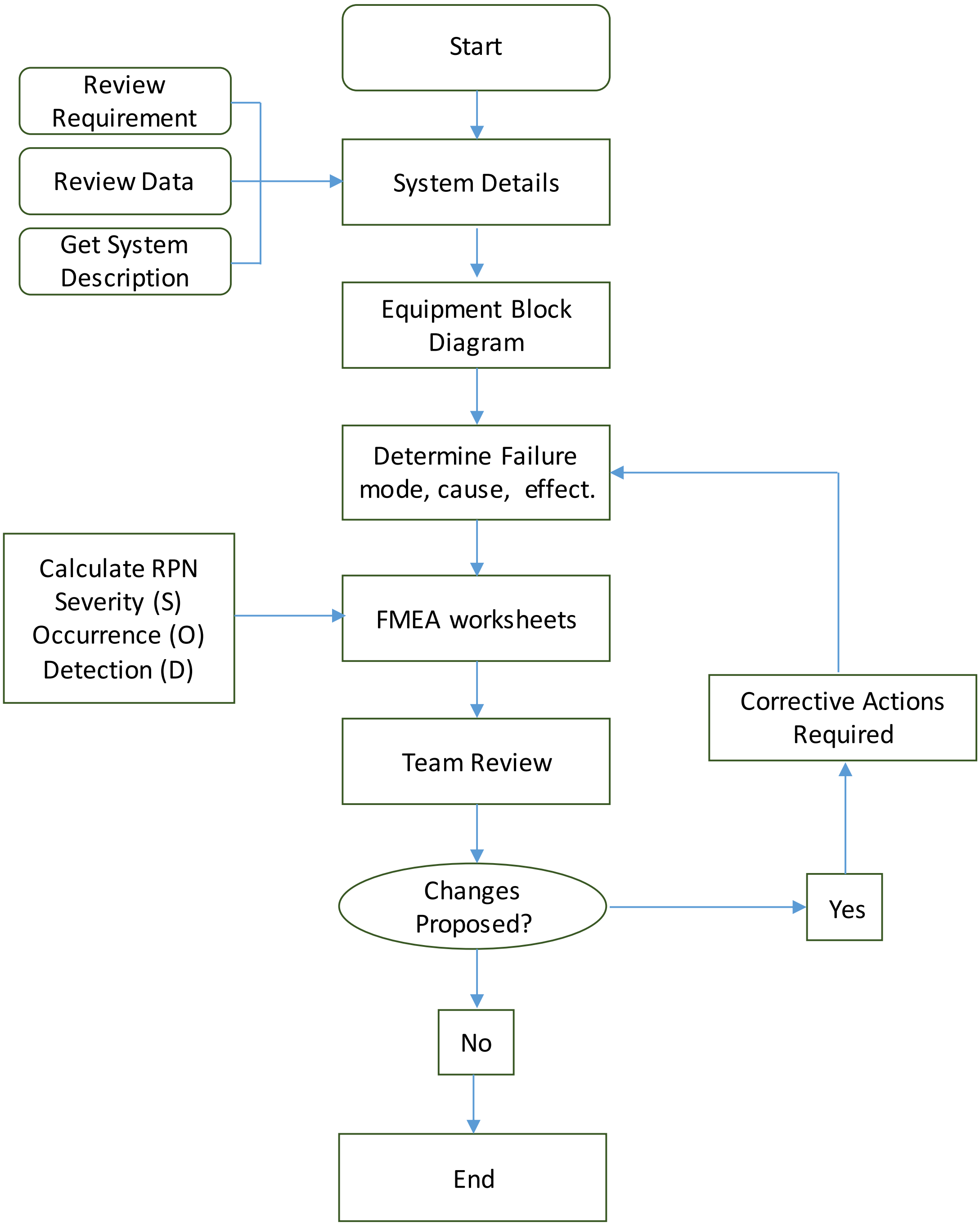

Fig.4-2 The FMEA process for DER system

Table 4-1 Severity rating scale for FMEA

Rank of severity	**Description**
1–2	Failure is of such minor nature that the operator will probably not detect the failure.
3–5	Failure will result in slight deterioration of part or system performance.
6–7	Failure will result in operator dissatisfaction and/or deterioration of part or system performance.
8–9	Failure will result in high degree of operator dissatisfaction and cause non-functionality of system.
10	Failure will result in major operator dissatisfaction or major damage.

Table 4-2 Occurrence rating scale for FMEA

Rank of occurrence	**Description**
1	An unlikely probability of occurrence: probability of occurrence＜0.001
2–3	A remote probability of occurrence: 0.001＜probability of occurrence＜0.01
4–6	An occasional probability of occurrence: 0.10＜probability of occurrence＜ 0.10
7–9	An occasional probability of occurrence: 0.10＜probability of occurrence＜ 0.20
10	A high probability of occurrence: 0.20＜probability of occurrence

Table 4-3 Detection rating scale for FMEA

Rank of detection	**Description**
1–2	Very high probability that the defect will be detected.
3–4	High probability that the defect will be detected.
5–7	Moderate probability that the defect will be detected.
8–9	Low probability that the defect will be detected.
10	Very low (or zero) probability that the defect will be detected.

Table 4-4 Effect of different RPN level.

Level	RPN	Effect
I	1～10	No effect.
II	10～100	Duty unfulfilled.
III	100～250	Failing an important mission.
IV	250～1000	Abandonment of duties.

In this analysis, we invite some maintenance managers and workers to form a maintenance review team. Maintenance data and strategies for fuel cell sub-systems and gas engine sub-systems of DER system in KSRP are discussed in an interview. The members of the maintenance review team are shown in Table 4-5. The numbers of our research group who participate in the seminars is 3 students.

The interview is divided into two stages. In the first stage, the causes and results of each failure mode and corresponding maintenance measures are given. In the second phase, S, O, and D of the maintenance plan are determined after the maintenance level is improved.

We obtained responses to preliminary interviews with maintenance managers and workers on this selected set of items, using indexes S, O and D to determine the value of RPN and the size of the most critical events. And the maintenance advice from manufacturers and designers refer to the equipment's maintenance instruction and other data that we can collect them from past records.

Based on the FMEA process of DER system which has presented at mention. The maintenance analysis and optimization of DER system in KSRP are performed in next Chapter 4.3 and Chapter 4.4.

Table 4-5 The members of the maintenance review team

Qualification	Numbers	Experience
Asset manager	1	More than 5 years asset management in KSRP
Technician	2	Good profile with more than 10 years of experience on system management and maintenance of DER system in KSRP.
Maintenance engineers	4	At least 5 years' experience in DER system management and maintenance.

4.3. Reliability and Maintenance Optimization of Gas Engine

4.3.1. Basis Data of Gas Engine

In order to analyze the failure modes and effects of gas engine of DES in KSRP, this study was collected the failures data from the energy center of Kitakyushu Science and Research Park. The details of failures data source were shown in Table 4-6.

Table 4-6 Details of basis data source of gas engine sub-system

No.	Data	Details
1	Inspection table of gas engine (from the July 2001 to March 2015)	Data of failures; Preliminary estimate of the failure's reason; Failure position description.
2	Construction completion certificate of gas engine (from the July 2001 to March 2015)	Data of failure's repair record; Failure reason review; Maintenance description.
3	Gas engine yearly report (from the July 2001 to March 2015)	Report of inspection, maintenance and repair during one year. Failure's position and repair details.
4	Construction plan statement of gas engine	Operation instruction of gas engine; Maintenance and repairing methods; Failure's reasons description.

Total four kinds of data files are used to collect and analyze the failures of gas engine. It includes Inspection table of gas engine, Construction completion certificate of gas engine, Gas engine yearly report, and Construction plan state of gas engine. The analysis range is from the July 2001 to March 2015, total 15 years' data. Content of inspection table of gas engine includes the data information of failures, preliminary estimate of the failure's reason, and failure position description. Content of construction completion certificate of gas engine includes Data of failure's repair record, failure reason review, maintenance description. Content of Gas Engine yearly report includes inspection, maintenance and repair information during one year. Content of Construction plan state of gas engine includes Operation instruction of gas engine, maintenance and repairing methods, failure's reasons description.

4.3.2. Equipment Block Diagram of Gas Engine

Gas engine of DER system is a complex system; it includes the gas supply system, engine system, power generator, system related devices. Equipment block diagram is easily used to show the components and equipment of the system. The equipment block diagram of gas engine sub-system is shown in Fig.4-3.

Each device contains multiple components; for instance, the gas supply system includes the gas supply pipe unit, meter unit, protective device. The gas supply pipe unit is made up of the filter, gas regulator, solenoid value. The meter unit is made up of pressure gauge, thermometer and other instruments, each component is performed difference functions in this system.

The engine system includes the waste heat control device, starter device, electricity supply unit, ignition device, cylinder head unit, valve gear, speed control device, reciprocating unit and related parts, rotary unit, lubricating oil unit, heat utilization, cooling water system, air supply system, exhaust system, superchargers system.

The power generator only has one device, the generator. This device includes stator, bearing, excitation machine, rotor, inside and outsider of the board, wirings, circuit breaker, appliances.

And the related devices of this system, include the complementary, exhaust gas steam boiler and exhaust gas hot water boiler. The complementary device includes inside and outside the board, wirings, appliances. The exhaust gas steam boiler includes gauge glass, electrode holder, electrode rod, strainer relationship component, water pipe outside, water supply pump, safety value, check valve, vacuum break value, instruments etc. The exhaust gas hot water boiler includes safety valve, body and instruments.

We can find that there are 3 devices are included in gas supply system; there are 15 devices are included in engine system; there are 1 device is included in power generator; there are 3 devices are included in system related devices. The numbers of total components are 94. Each component has its function.

Main advantage of the division of systems into subsystems and part systems is to identify remarkable failure modes, causes and their effects on systems. Thus, equipment block diagram is easily used to show how the different components of the system interact with another component to verify the critical path.

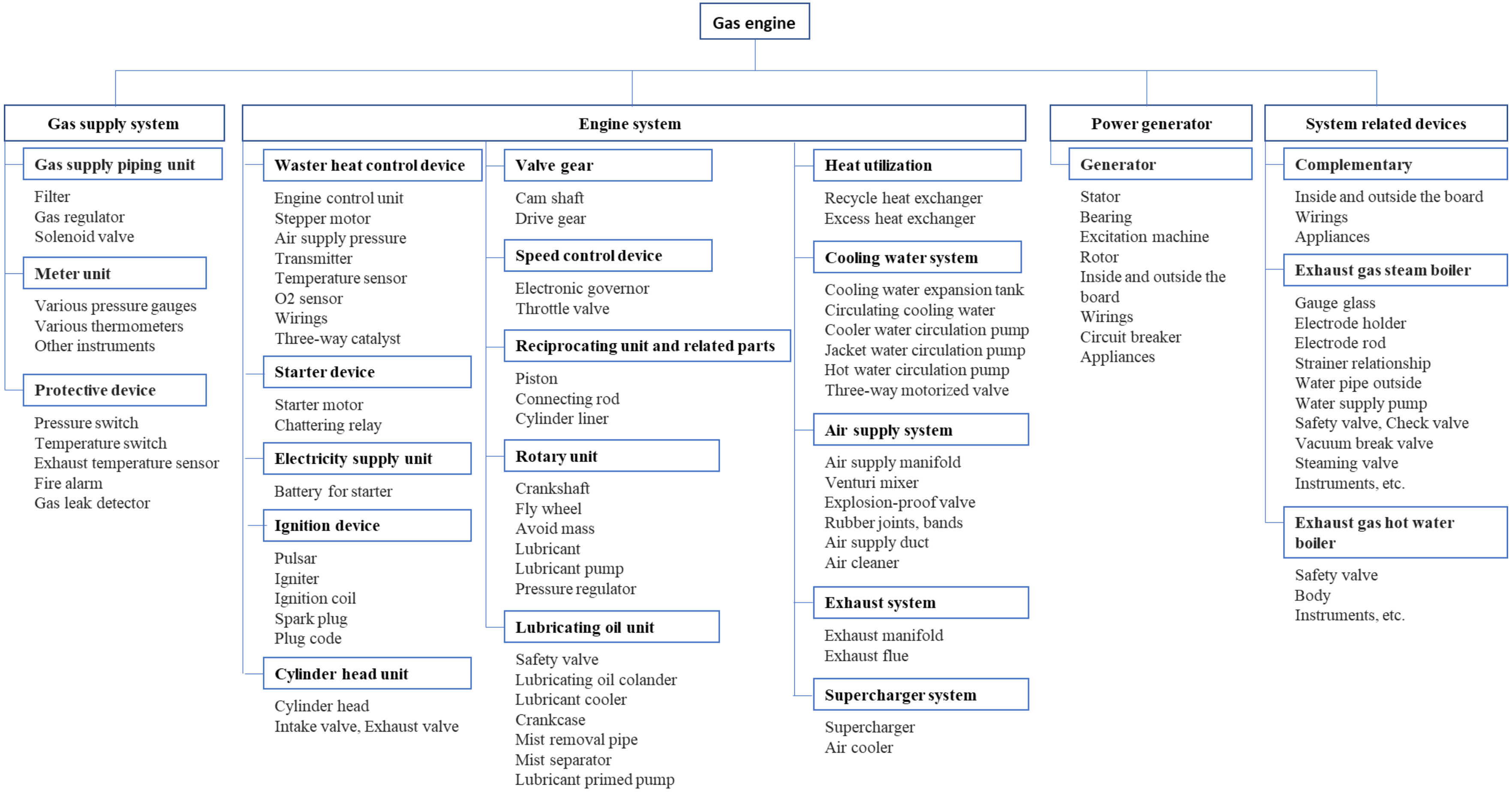

Fig.4-3 The equipment blocks diagram of gas engine sub-system

4.3.3. Failure Modes of Gas Engine

The failure modes of gas engine sub-system are reviewed in Table 4-7. There are total 41 component modes in the gas engine sub-system are calculated. The Table 4-7 shows that one component may include multiple failure modes: such as the battery for starter includes three failure modes battery failure, battery voltage drop and no direct-current power supply. In the Supercharger system, the supercharger includes two failure modes: high temperature and deformation. The component failures are investigated based on the real data of the gas engine system, maybe, there are some failure modes exist, but those failure modes are not actually occurring or observed in the real data, perhaps, those hidden failure modes are maintained under the current maintenance strategy.

Table 4-7 Details of failure modes of the main components of gas engine

Subsystem	Device	Component	Failure mode	No.
Gas supply system	Gas supply piping unit	Gas line	Gas leak	1
		Valve unit	Manual valve failure	2
		Plumbing	Fuel supply shortage	3
		Gas source valve	Pressure gauge defect	4
		Filter	Shutoff valve failure	5
		Gas regulator	Outlet pressure shortage	6
		Solenoid valve	Gas lack	7
Engine system	Starter device	Starter motor	Out-of-operation	8
	Electricity supply unit	Battery for starter	Battery failure	9
			Voltage drop	10
			No direct-current power supply	11
	Ignition device	Pulsar	Failure	12
		Igniter	Ignition failed	13
		Spark plug	Poor ignition	14
	Cylinder head unit	Cylinder head	Valve and valve seat failure	15
		Intake valve, Exhaust valve	Sucking, exhaust valve head defect	16
	Valve gear	Cam shaft	Faulty fuel gas shutoff valve	17
	Speed control device	Electronic governor	Unstable signal pressure	18
		Governor linkage	Malfunction	19
	Reciprocating unit and related parts	Piston	Piston bad	20
		Cylinder liner	Failure	21
	Rotary unit	Crankshaft	Unstable signal pressure	22
	Lubricating oil unit	Lubricating oil colander	Clogging	23

Subsystem	Device	Component	Failure mode	No.
		Lubricant cooler	Viscosity defect	24
		Crankcase	Lubricating oil temperature high	25
		Mist removal pipe	Pressure regulating valve defect	26
		Mist separator	Obstruction	27
		Lubricant primed pump	Lack	28
	Heat utilization	Excess heat exchanger	Capacity shortage	29
	Cooling water system	Cooling water expansion tank	Lack of cooling water	30
		Circulating cooling water	Cooling water pump capacity shortage	31
		Cooler water circulation pump	High temperature cooler water	32
		Jacket water circulation pump	Lack of cooling water	33
		Packing	Water leak	34
		Cooling tower	Strainer clogging	35
	Supercharger system	Supercharger	High temperature	36
			Deformation	37
		Air cooler	Fuel supply pressure drop	38
Power generator	Generator	Rotor	Failure	39
		Wirings	Stop short	40
System related devices	Complementary	Wirings	Shutoff valve failure	41

4.3.4. FMEA Worksheets and Team Review for Gas Engine

The FMEA worksheets are performed by the review team, the current maintenance strategy is evaluated by the severity (S), Occurrence (O) and Detection (D), and the RPN is shown in Table 4-8. The results of show that there are 8 components RPN are more than 100, but did not more than 250. That means those 8 components are on the Level III, Failing an important mission. The other 32 component modes are more than 10 and less than 100. It means that those components are on the levelII, Duty unfulfilled. According to the reviewers’ discussion and recommendations, new maintenance actions are proposed and new possible RPN are calculated. This provides the possibility to improve system reliability through system maintenance strategy.

Table 4-8 The RPN results of FMEA process for gas engine

No	Components	Failure mode	Failure cause	Failure effect	Current maintenance strategy	S	O	D	RPN	New proposed maintenance strategy	S	O	D	New RPN
1	Gas line	Gas leak	Air is in the fuel gas system	Although the engine rotates according to the start command, the rotation does not rise, the engine starts but stops immediately	Perform bleeding according to air removal	8	2	4	64	Increase the number of examinations	8	2	3	48
2	Valve unit	Manual valve failure	Fuel gas has not arrived	Although the engine rotates according to the start command, the rotation does not rise	Open manual valve	6	2	4	48	Exchange regularly	6	2	3	36
3	Plumbing	Fuel supply shortage	Fuel system failure	Engine power reduction	Increase piping size	3	2	5	30	Test piping size	3	2	3	18
4	Gas source valve	Pressure gauge defect	Fuel gas has not arrived	Although the engine rotates according to the start command, the rotation does not rise	Pass through the main source or gas	7	3	3	63	Increase the number of examinations	7	3	2	42
5	Filter	Shutoff valve failure	Gas shutoff valve or wiring degradation	Although the engine rotates according to the start command, the rotation does not rise	Correction of wiring, disassembly of gas shutoff valve or exchange	6	3	5	90	Increase the number of examinations	6	3	3	54
6	Gas regulator	Outlet pressure shortage	Fuel gas has not arrived	Although the engine rotates according to the start command, the rotation does not rise.	Adjust the regulator outlet to the specified pressure	7	4	5	140	Test piping size and pressure	7	4	3	84
7	Solenoid valve	Gas lack	Valve loosed	Mixture ratio of fuel gas and air is inappropriate; Unsafe operation.	strengthening valve or changed.	6	3	6	108	Increase the number of inspection and detection	6	3	3	54

No	Components	Failure mode	Failure cause	Failure effect	Current maintenance strategy	S	O	D	RPN	New proposed maintenance strategy	S	O	D	New RPN
8	Starter motor	Out-of-operation	Degradation	Engine does not rotate by start command	Replacement	7	2	7	98	Exchange regularly	7	2	7	98
9	Battery for starter	Battery failure	The signal from the magnetic pickup is weak or not at all	The actuator of the governor does not operate at all	Pick up exchange	8	4	3	96	Increase the number of examinations	8	4	2	64
10	Battery for starter	Voltage drop	Lack	Engine does not rotate by start command	Replace the battery and recharge	6	4	2	48	Increase the number of examinations	6	4	2	48
11	Battery for starter	No direct-current power supply	Battery bad	The actuator of the governor does not operate at all	Battery charging or replacement	8	5	4	160	Increase the number of replacements	8	3	4	96
12	Pulsar	Failure	Ignition timing failure	Knocking	Rotate the pulsar body, adjust at the specified time	6	2	3	36	Exchange thermostat	6	2	3	36
13	Igniter	Ignition failed	Electrode damaged	Cannot start.	Replacement of electrode	6	7	3	126	Increase the number of inspections	6	4	3	72
14	Spark plug	Poor ignition	Wear and tear	Cannot start, Abrupt stop, output reduction, rotation does not rise.	Replacement of spark plug	6	9	3	162	Increase the number of inspections	6	2	2	24
15	Cylinder head	Valve and valve seat failure	Intake, exhaust valve head skimmer inappropriate, seat contact failure	Engine power reduction	Valve and valve seat alignment	4	2	4	32	Turn off the switch	4	2	2	16
16	Intake valve, Exhaust valve	Sucking, exhaust valve head defect	Intake, exhaust valve head skimmer inappropriate, seat contact failure	Engine power reduction	Adjust to specified value of intake valve head	5	3	5	75	cleaning	5	3	5	75

No	Components	Failure mode	Failure cause	Failure effect	Current maintenance strategy	S	O	D	RPN	New proposed maintenance strategy	S	O	D	New RPN
					and exhaust valve head skimmer									
17	Cam shaft	Faulty fuel gas shutoff valve	Burnout	The engine suddenly stops	Replacement of the coil	8	3	3	72	Regular cleaning	8	3	2	48
18	Electronic governor	Unstable signal pressure	Degradation	The governor's actuator does not operate at all (the actuator is in the fuel shutoff position)	Actuator replacement	8	2	6	96	Increase the number of examinations	8	2	3	48
19	Governor linkage	Malfunction	Poor connection of governor linkage	Idling malfunction	Linkage operation adjustment	4	4	3	48	Check and clearance	4	4	3	48
20	Piston	Piston bad	Wear and sticking of piston ring	Engine power reduction	Replacement of Piston	3	3	6	54	Increase the number of examinations	3	3	4	36
21	Cylinder liner	Failure	Wear of cylinder liner	Engine power reduction	Replace	3	2	5	30	Downtime check	3	2	3	18
22	Crankshaft	Unstable signal pressure	Oil seal bad	Lubricant leaks	Exchange of oil seal	7	2	5	70	Increase the number of examinations	7	2	4	56
23	Lubricating oil colander	Clogging	Clogging of lubricating oil sieve	The lubricating oil pressure becomes less than the specified value	Replacement	7	8	3	168	Increase the number of examinations	7	3	2	42
24	Lubricant cooler	Viscosity defect	leak or temperature is too high	The lubricating oil pressure becomes less than the specified value	Change the lubricating oil	6	5	4	120	Increase the number of examinations	4	2	4	32
25	Crankcase	Lubricating oil	Water shortage	The lubricating oil pressure becomes less than the specified value	Keep cooling water temperature low, increase the	3	2	5	30	Properly lower the lubricant to	3	2	3	18

No	Components	Failure mode	Failure cause	Failure effect	Current maintenance strategy	S	O	D	RPN	New proposed maintenance strategy	S	O	D	New RPN
		temperature high			amount of cooling water					the machine temperature				
26	Mist removal pipe	Pressure regulating valve defect	Degradation	The lubricating oil pressure becomes less than the specified value	Replacement	6	2	7	84	Increase the number of examinations	6	2	4	48
27	Mist separator	Obstruction	Clogged mist pipe	Lubricant leaks	Change piping route	6	2	6	72	Exchange regularly	6	2	5	60
28	Lubricant primed pump	Lack	Lack	The lubricating oil pressure becomes less than the specified value	Replenishment	3	5	5	75	Increase the number of examinations	3	3	3	27
29	Excess heat exchanger	Capacity shortage	Heat dissipation system defect	Overheat	Select capacity of heat exchanger	3	3	8	72	Timely cleaning	3	3	5	45
30	Cooling water expansion tank	Lack of cooling water	Air is contained in cooling water piping	Engine overheat	Thorough air bleed	5	4	5	100	Increase the number of examinations of air	5	3	4	60
31	Circulating cooling water	Cooling water pump capacity shortage	Lack of cooling water	Engine overheat	Appropriate add cooling water pump capacity	4	4	5	80	Test piping size and degradation level	4	4	5	80
32	Cooler water circulation pump	High temperature cooler water	Insufficient cooling water during the pump degradation	Engine power reduction, knocking.	Clean pump or increase the flow	7	3	4	84	Inspection regularly	7	3	4	84
33	Jacket water circulation pump	Lack of cooling water	Cooling water piping system resistance too large	Engine overheat	Reselect cooling water pump capacity, correct piping route, size	4	4	4	64	Increase the number of examinations, Timely cooling	4	4	3	48

No	Components	Failure mode	Failure cause	Failure effect	Current maintenance strategy	S	O	D	RPN	New proposed maintenance strategy	S	O	D	New RPN
34	Packing	Water leak	Junction part packing failure or bolt looseness	Overheat	Perform bolt retightening, packing exchange	7	3	4	84	Increase the number of examinations	7	2	3	42
35	Cooling tower	Strainer clogging	Dust and fallen leaves mixed in the cooling tower	gas Engine overheat	Coolant water discontinuation, and clean cooling tower	4	2	5	40	To confirm in advance	4	2	4	32
36	Supercharger	High temperature	Intercooler cooling water temperature is high	Engine power reduction	Decrease coolant inlet temperature of intercooler	3	4	6	72	Increase the number of examinations	3	4	4	48
37	Supercharger	Deformation	Clogging of intake filter	Engine power reduction	Intake air filter replacement; intake air filter reinforcement treatment	4	3	5	60	Confirm increase in inspiratory resistance and eliminate	4	3	3	36
38	Air cooler	Fuel supply pressure drop	Fuel system failure	Engine power reduction	Increase supply pressure after consultation with gas company	4	3	6	72	Increase the number of examinations	4	3	4	48
39	Rotor	Failure	Unstable signal pressure	Lubricant leaks	Exchange of oil seal	7	2	5	70	Increase the number of examinations	7	2	4	56
40	Wirings	Stop short	Burnout, cutting	The engine suddenly stops	Cable, fuse replacement	8	3	3	72	Increase the number of examinations	8	3	2	48
41	Wirings	Shutoff valve failure	Wiring failure	The engine starts but stops right away	Modify wiring and sequence	8	4	3	96	Increase the number of examinations	8	4	3	96

The most remarkable failure mode generated by the whole gas engine system analysis had a 168 RPN. The failure mode of gas engine with an RPN higher than 100 is shown in Fig.4-4. The PRN more than 100 failure modes include Lubricating oil colander- Clogging, Spark plug -Poor ignition, Battery for starter- No direct-current power supply, Gas regulator -Outlet pressure shortage, Igniter-Ignition failed, Lubricant Cooler-Viscosity defect, Solenoid valve -Gas lack, Cooling water expansion tank-Lack of cooling water. For the top 8 failure modes, 6 failure modes are from the engine system, and 2 from the gas supply system. And the lubricating oil unit needs more attention.

The new proposed maintenance strategy includes increasing the number of examinations, increase the number of inspections, test piping size and pressure, exchange / replacement regularly, timely cleaning, check and clearance, to confirm in advance, etc. Through discussion and evaluation, the new proposed maintenance strategy can effectively reduce the risk of component.

The proportion of failure modes in each subsystem of gas engine is shown in Fig.4-5. The figure shows that most of failure will be occurred in the engine system of gas engine, and the proportion is 75.61%. The second part is the gas supply system, the proportion of failure modes is 17.07%. The third part is power generator unit, the proportion of failure modes is 4.88%. And the proportion of system related device failure modes is 2.44%. Therefore, the failure mode of engine system should be given more attention.

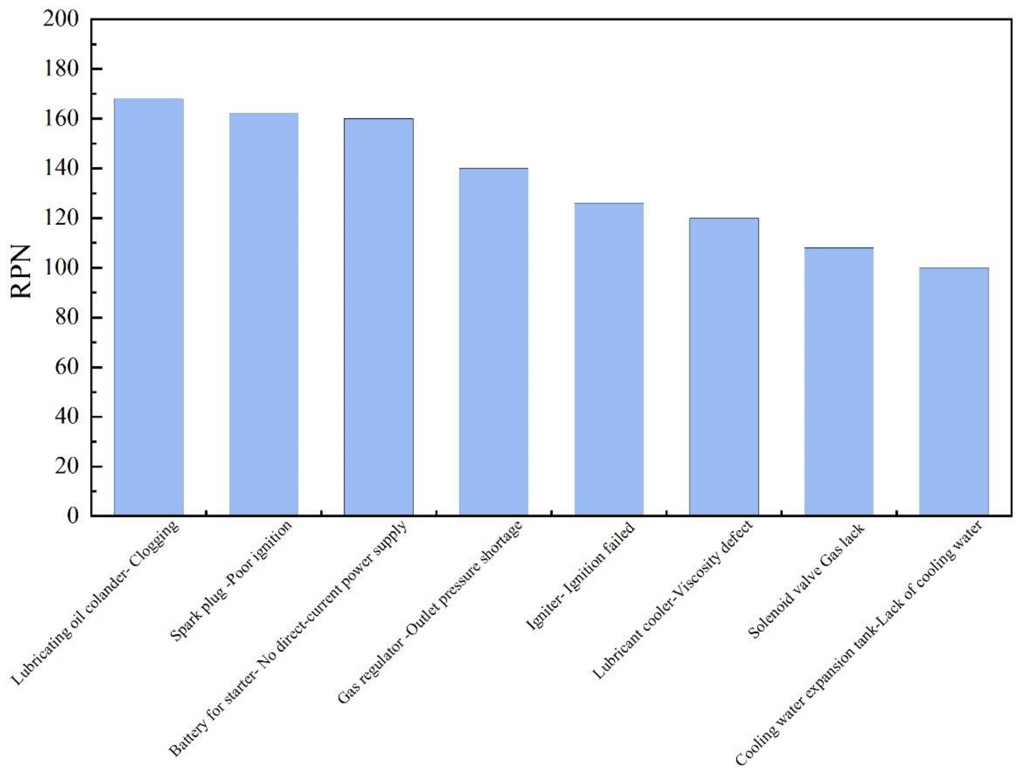

Fig.4-4 Failure mode of gas engine with an RPN higher than 100

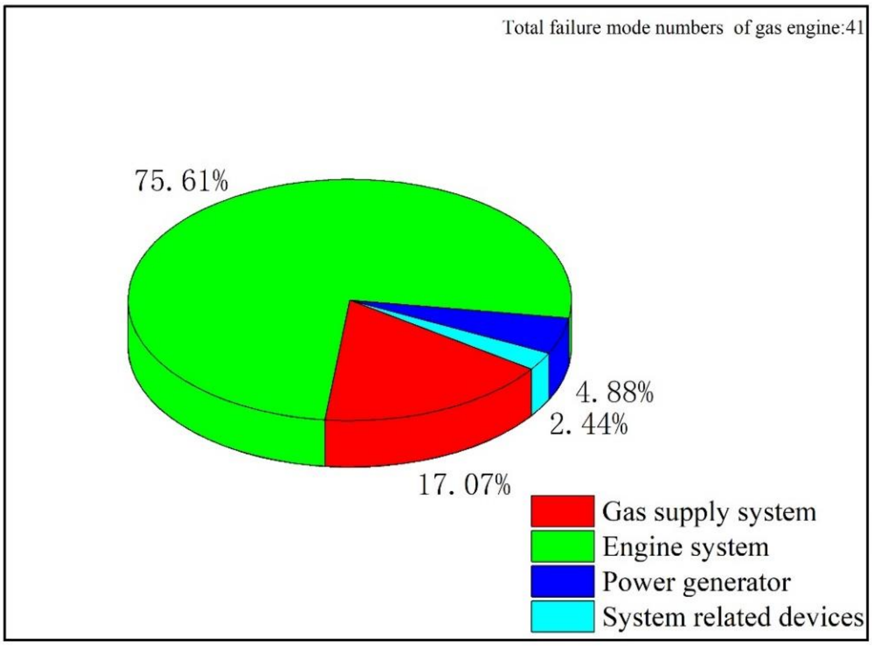

Fig.4-5 The proportion of failure modes in each subsystem of gas engine

4.3.5. Evaluation of the Maintenance Actions within the Gas Engine Maintenance Plan

According to the result of team review, the fault modes are sorted according to the RPN value under the current maintenance strategy. The RPN results of FMEA process of gas engine are shown in Fig.4-6. The rate of RPN decrement was calculated and presented. The results show that most of RPN can be reduced, only a few failure modes cannot be changed, such as No.8, No.41, No.32, No.31, No.16, No.10, No.19 and No.12. The RPN value changes differently in different maintenance modes. The most reducing failure mode is No.14, the rate of No.14 failure mode is 85.2%. The No.14 failure mode is Spark Plug-Poor ignition, the spark plug is an important component of engine system of gas engine. It relates with the start of the gas engine, if the failure mode is occurred, the gas engine will not be started, abrupt stop or output reduction, or rotation does not rise. The second failure mode with a large reduction is the No.23 failure mode. Meanwhile, No.23 is the failure mode with the highest RPN value, the rate of No.23 failure mode is 75%. The No.23 failure mode is Lubricating oil colander Clogging. Lubricating oil colander is an important component of engine system, it relates with the gas engine operation. If the No.23 failure mode occurred, the gas engine lubricating oil pressure becomes less than the specified value, and the engine will be stopped. The third failure mode with a large reduction is the No.28, Lubricant primed pump lacking. It also related to the lubricating system. The total failure modes of the Lubricating oil unit are 6 modes. Some rate of failure mode RPN decrement also have very high reduction, but the RPN is less than 100.

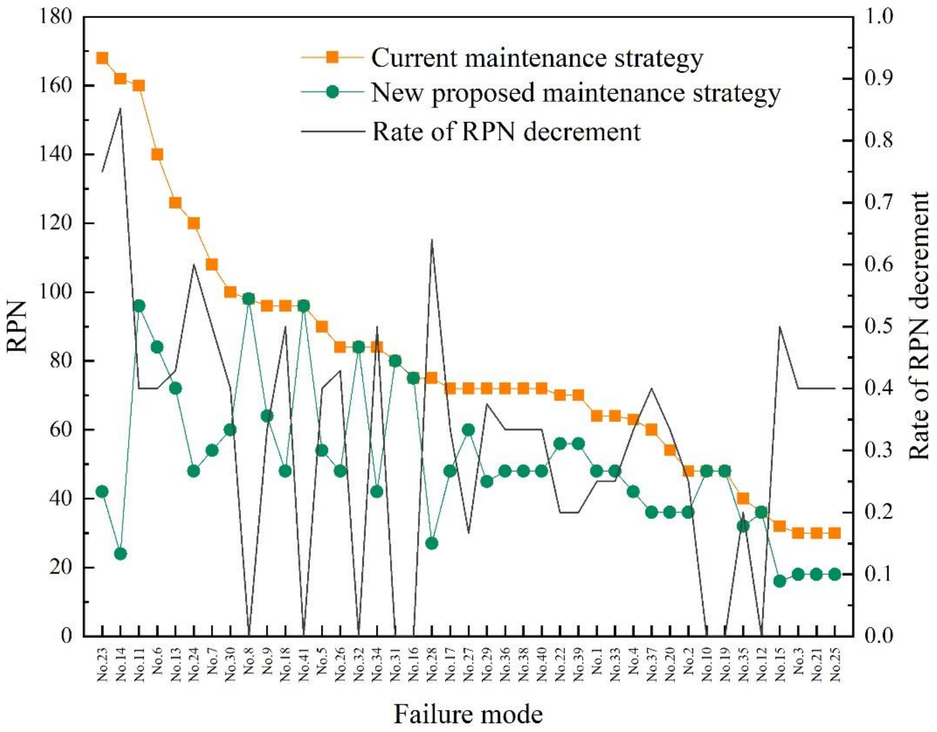

Fig.4-6 The RPN results of FMEA process of gas engine

The trends of the three indexes (Severity, Occurrence and Detection), before and after the new proposed maintenance strategy are shown in Fig.4-7, Fig.4-8 and Fig.4-9, respectively. The results show that the Detection Index are highly correlated with the consulted objects. The Severity Index of the failure modes is not changed under the new proposed maintenance strategies. It means that the Severity Index almost unaffected by the new proposed maintenance strategies. A few of Occurrence Index can be reduced by the new proposed maintenance strategies. But most of Occurrence Index cannot be reduced. The largest Occurrence Index reducing is No.14, park plug-poor ignition.

The proportion of new proposed maintenance strategy is shown in Fig.10. The new proposed maintenance strategies include Increase the number of inspections, Increase the number of replacements, Increase the number of examinations, Exchange regularly, Test piping size and Timely cleaning. The highest of proportion of new proposed maintenance strategy is Increase the number of inspections, it can help the maintainers and engineers to improve the reliability of system.

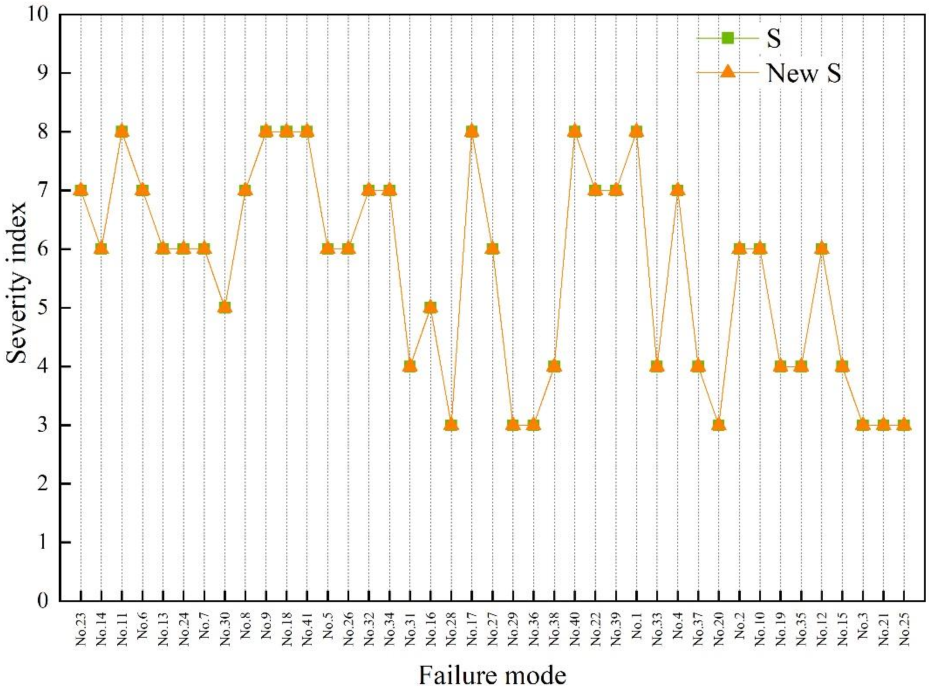

Fig.4-7 The S index modification with corrective actions

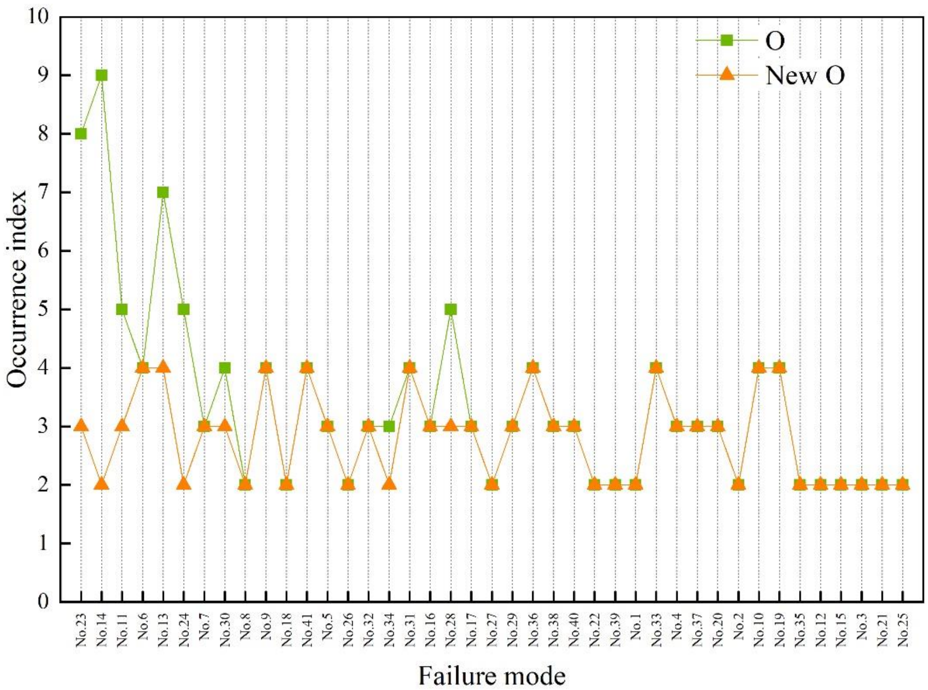

Fig.4-8 The O index modification with corrective actions

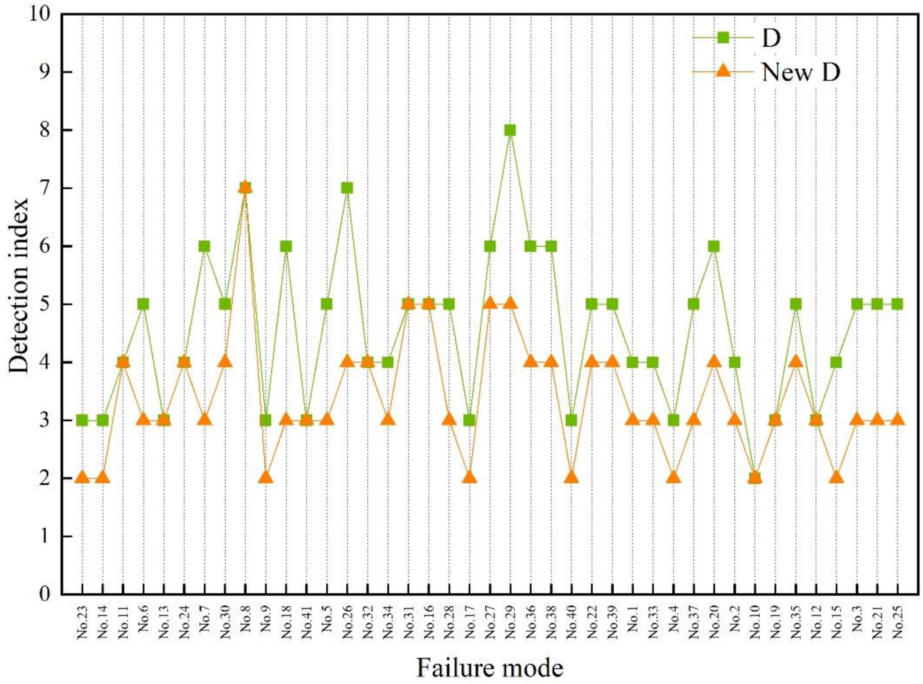

Fig.4-9 The D index modification with corrective actions for gas engine

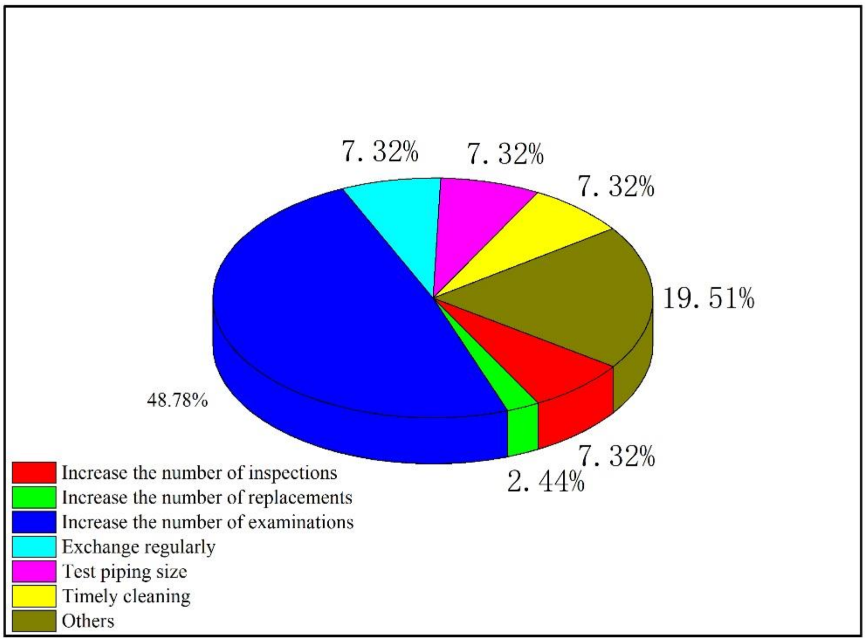

Fig.4-10 The proportion of new proposed maintenance strategy for gas engine

4.4. Reliability and Maintenance Optimization of Fuel Cell

4.4.1. Basis Data of Fuel Cell

In order to analyze the failure rate of fuel cell of DER in KSRP, this study was collected the failures data from the energy center of Kitakyushu Science and Research Park. The details of failures data source are shown in Table 4-9.

Table 4-9 Details of basis data source of fuel cell sub-system

No.	Item	Details
1	Inspection table of fuel cell (2001 to 2011)	Data of failures; Preliminary estimate of the failure's reason; Failure position description.
2	Construction completion certificate of fuel cell (2001 to 2011)	Data of failure's repair record; Failure reason review; Maintenance description.
3	Fuel cell yearly report (2001 to 2011)	Report of inspection, maintenance and repair during one year. Failure's position and repair details.
4	Construction plan statement of fuel cell	Operation instruction of fuel cell; Maintenance and repairing methods; Failure's reasons description.

Total four kinds of data files used to collect and analyze the failures of fuel cell. It includes Inspection table of fuel cell, Construction completion certificate of gas fuel cell, Fuel cell yearly report, and Construction plan statement of fuel cell. The analysis range is from 2001 to 2011, total ten year's data. Content of inspection table of fuel cell includes the data information of failures, preliminary estimate of the failure's reason, and failure position description. Content of construction completion certificate of fuel cell includes Data of failure's repair record, failure reason review, maintenance description. Content of Fuel cell yearly report includes inspection, maintenance and repair information during one year. Content of Construction plan statement of fuel cell includes Operation instruction of gas engine, maintenance and repairing methods, failure's reasons description.

4.4.2. Equipment Block Diagram of Fuel Cell

Fuel cell in the DER system is a complex system; it includes the power section system, fuel processing system, air processing system, water vapor system, and Auxiliary system. Equipment block diagram is easily used to show how the different parts of the fuel cell system. The equipment block diagram of fuel cell sub-system is shown in Fig.4-11.

According to the function of gas-used fuel cell, the fuel processing system and air processing system is the important devices for fuel treatment and air treatment. The fuel processing system includes three devices: fuel system, reformer and instrumentation. The reformer includes Frame sensor 030, Igniter, Thermocouple 012 and Heat exchanger 910. The instrumentation parts only have one component, Force switch. The air processing system only has the filter, but it includes two types, one is Filter 100, another is Filter 150.

The power section system includes for devices: rotator, primary system steam system, cell body and power conditioning subsystem. The rotator includes several types pumps, Pump 400, Pump 450, Pump 451, Pump 830; two types fan, Fan 165 and Fan 800; and Blower 100. The primary system steam system includes 7 components. The cell body includes 4 components; and the power conditioning subsystem includes two components, main circuit and protection function.

Water vapor system includes two main devices: Water recovery / treatment system and Secondary system. The main components include heat exchanger 920, settling tank, degas tower, water tank, filters, Ion exchange resin tower and activated carbon filter. The secondary system includes secondary water, steam separator, secondary cooling water, filter and cooling module.

The comprehensive and auxiliary system includes 5 devices, comprehensive equipment, incidental equipment, Security equipment, Uninterruptible power supply devices and Electrical conditioning system (ECS).

The equipment block diagram of fuel cell sub-system is easily to help us to understand the relationship of each components. The components of the fuel cell system are less than the components of gas engine.

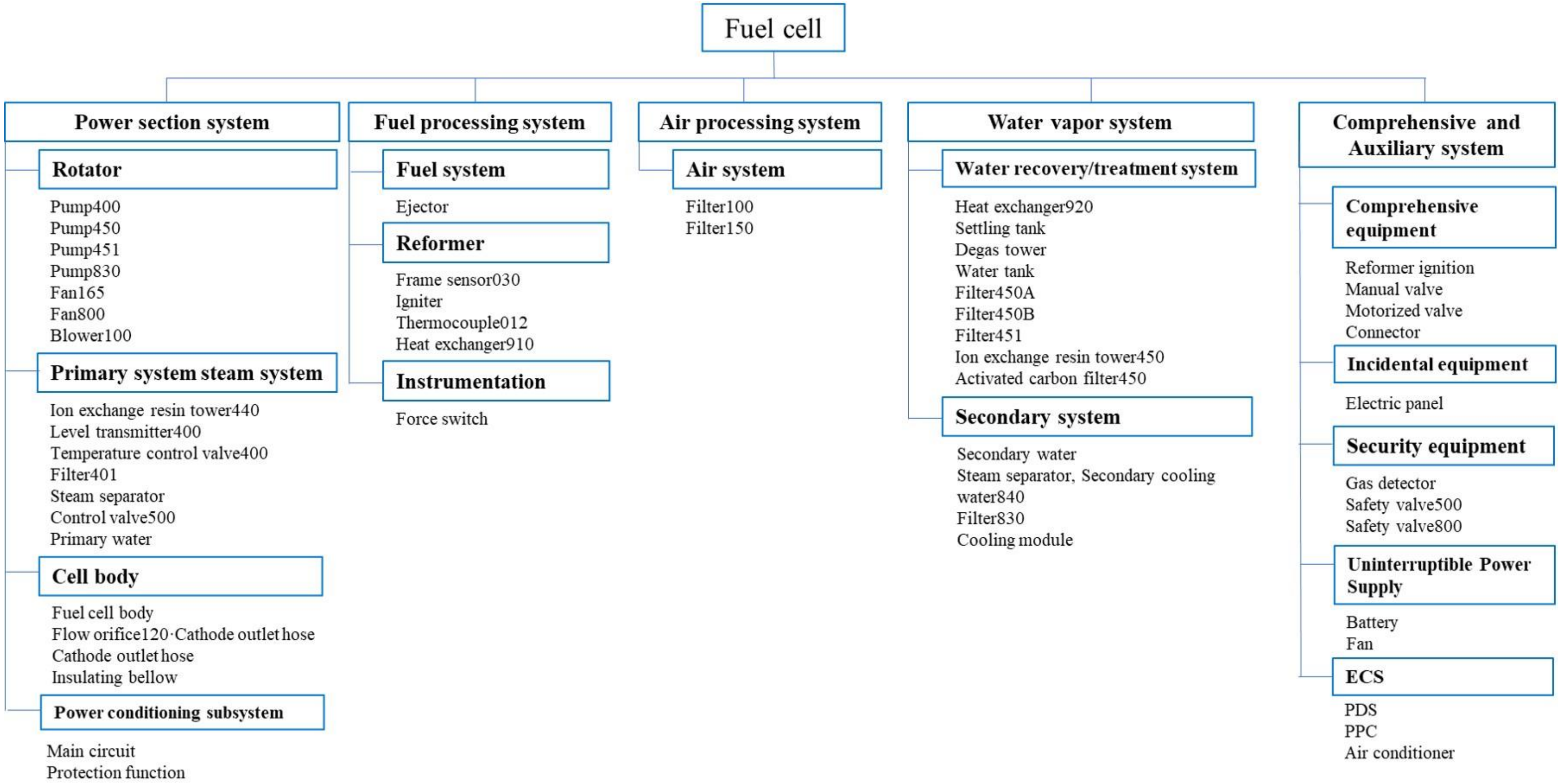

Fig.4-11 The equipment blocks diagram of fuel cell sub-system

Table 4-10 Details of failure modes of the main components of fuel cell

Subsystem	Device	Component	Failure mode	No.
Power Section system	Rotator	Pump400	Leakage	1
		Pump450/451	Malfunction	2
		Pump830	Leakage	3
		Fan165	Malfunction	4
		Cooling Fan 800	Abnormality	5
	Primary system /Steam system	Level transmitter400	Leakage	6
		Filter401	Deformation	7
		Control valve500	Leakage	8
	Cell body	Flow orifice120·Cathode outlet hose	Leakage	9
	Power Conditioning system	Main circuit	Appearance abnormality	10
Fuel processing system	Fuel system	Ejector	Do not work	11
	Reformer	Frame sensor030	Abnormality	12
		Igniter	Malfunction	13
		Thermocouple012	Malfunction	14
	Instrumentation	Force switch	Abnormality	15
Air processing system	Air system	Filter100/150	Abnormality	16
Water vapor system	Water recovery /treatment system	Settling tank	Malfunction	17
		Filter450A/B·451	Malfunction	18
Auxiliary system	Security equipment	Gas detector	Appearance abnormality	19
	ECS	Power distribution system	Abnormality	20
	Uninterruptible power supply	Battery/Fan	Malfunction	21
	Comprehensive equipment	Reformer ignition	Appearance abnormality	22
		Waste water pump	Anomalous sound and vibration	23

4.4.3. Failure Modes of Fuel Cell

The failure modes of fuel cell sub-system are reviewed in Table 4-10. There are total 23 component modes in the fuel cell sub-system are calculated. The failure modes include Leakage, Malfunction, Abnormality, Deformation, do not work, Anomalous sound and vibration. For this part, we only consider the failure modes that have occurred during the records of fuel cell. Some failure modes may be hidden during the current maintenance strategy of fuel cell.

4.4.4. FMEA Worksheets and Team Review for Fuel Cell

The FMEA worksheets of fuel cell are performed by the review team, the current maintenance strategy is evaluated by the Severity (S), Occurrence (O) and Detection (D), and the RPN was calculated; based on the current maintenance strategy and RPN, the new proposed maintenance is discussed and proposed.

The results of show that there are 9 component modes' RPN are more than 100, but did not more than 250. That means those 9 components are on the Level III, Failing an important mission. The other 14 component modes are more than 10 and less than 100. It means that those components are on the levelII, Duty unfulfilled. The numbers of Level III components are about 39% of total investigated components.

The most remarkable failure mode generated by the whole fuel cell system analysis had a 192 RPN. Failure modes of fuel cell with an RPN higher than 100 is shown in Fig.4-12. After the review of the maintenance planning of the current maintenance and RPN assessment, a new proposed maintenance strategy is discussed, and the maintenance actives that may be performed to improve maintenance are collated. But compare with the gas engine system the new proposed maintenance strategies of fuel cell are will simple, that because maintenance of fuel cell needs more profession engineers. Therefore, the new proposed maintenance strategies only include Replacement regularly, Regular cleaning, Increase the number of examinations, Change component material.

The proportion of failure modes in each subsystem of fuel cell is shown in Fig.4-13. The figure shows that most of failure will be occurred in the power section system of fuel cell, and the proportion is 43.48%. The second part is the fuel processing system and auxiliary system, the proportion of failure modes is 21.74%. The third part is water vapor system, the proportion of failure modes is 8.7%. And the proportion of air processing system failure modes is 4.35%. Therefore, the failure mode of power section system should be given more attention in fuel cell.

Table 4-11 The RPN results of FMEA process during current maintenance strategy of fuel cell

No.	Component	Failure mode	Failure cause	Failure effect	Current maintenance strategy	S	O	D	RPN	New proposed maintenance strategy	S	O	D	New RPN
1	Pump400	Leakage	Cracking or swelling	Fuel cell stoppage	Replacement	8	4	4	128	Replacement regularly	8	4	3	96
2	Pump450/451	Malfunction	Wear	Insufficient cooling water flow	Repair or replacement	6	3	5	90	Change component material	4	3	5	60
3	Pump830	Leakage	Cracking or swelling	Fuel cell stoppage	Replacement	6	4	4	96	Replacement regularly	6	4	3	72
4	Fan165	Malfunction	High resistance value	Fuel ventilation chamber defect	Exchange of FS 165	3	5	5	75	Replacement regularly	3	3	5	45
5	Cooling Fan 800	Abnormality	Wiring problem	Thermocouple high	Replacement	7	5	4	140	Replacement regularly	7	3	4	84
6	Level transmitter400	Leakage	Impulse pipe clogging	Fuel cell stoppage	Replacement	7	4	5	140	Replacement regularly	7	3	4	84
7	Filter401	Deformation	Breakage	Fuel cell stoppage	Replacement	7	4	6	168	Exchange regularly	7	3	6	126
8	Control valve500	Leakage	Cracking or swelling	Fuel cell stoppage	Replacement	8	4	6	192	Replacement regularly	8	3	6	144
9	Flow orifice120·Cathode outlet hose	Leakage	Damaged	Low power generation	Repair or replacement	5	3	5	75	Increase the number of examinations	5	3	5	75
10	Main circuit	Appearance abnormality	Component contaminated	Fuel cell stoppage	Replacement	8	5	4	160	Replacement regularly	8	3	4	96
11	Ejector	Do not work	Sensor problem	The ejector behaves abnormally	Replacement	6	5	3	90	Replacement regularly	6	3	3	54
12	Frame sensor030	Abnormality	Component contaminated	Reformer burner misfire	Cleaning	3	5	5	75	Regular cleaning	3	5	5	75

No.	Component	Failure mode	Failure cause	Failure effect	Current maintenance strategy	S	O	D	RPN	New proposed maintenance strategy	S	O	D	New RPN
13	Igniter	Malfunction	Catalyst life time, pressure loss increase	Fuel cell stoppage	Replacement	6	4	5	120	Replacement regularly	6	3	5	90
14	Thermocouple012	Malfunction	Disconnection	Thermocouple high	Replacement	4	4	5	80	Replacement regularly	4	3	5	60
15	Force switch	Abnormality	Component contaminated	Fuel cell stoppage	Replacement	6	2	7	84	Replacement regularly	6	2	5	60
16	Filter100/150	Abnormality	Component contaminated	Thermocouple high	Replacement	5	4	4	80	Replacement regularly	5	3	4	60
17	Settling tank	Malfunction	Component contaminated	Thermocouple high	Cleaning	6	5	6	180	Regularly cleaning	6	2	6	72
18	Filter450A/B·451	Malfunction	Component contaminated	Thermocouple high	Exchange	3	4	5	60	Replacement regularly	3	3	5	45
19	Gas detector	Appearance abnormality	Component contaminated	Reformer burner misfire	Cleaning	3	5	5	75	Regular cleaning	3	3	5	45
20	Power distribution system	Abnormality	Component contaminated	Fuel cell stoppage	Replacement	6	4	5	120	Exchange regularly	6	3	5	90
21	Battery/Fan	Malfunction	Catalyst Life / Phosphorus Life	Low battery voltage	Replacement	8	4	3	96	Replacement regularly	8	3	3	72
22	Reformer ignition	Appearance abnormality	Component contaminated	Fuel cell stoppage	Brake exchange	8	4	3	96	Replacement regularly	8	3	3	72
23	Waste water pump	Anomalous sound and vibration	Degradation	Vibration is large	Repair or replacement	7	3	4	84	Change component material	5	3	4	60

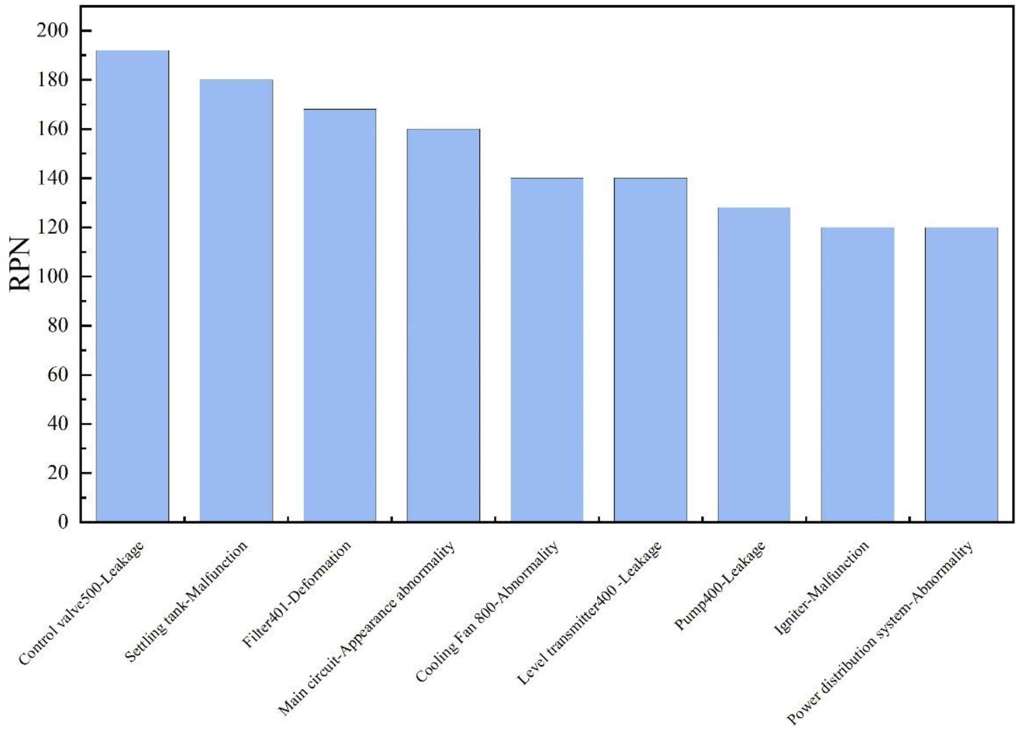

Fig.4-12 Failure modes of fuel cell with an RPN higher than 100

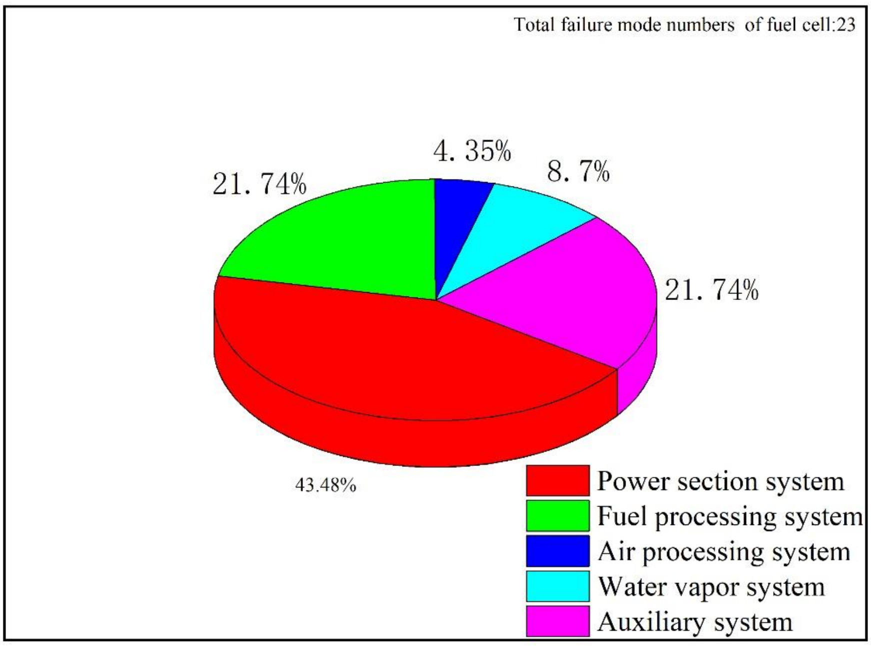

Fig.4-13 The proportion of failure modes in each subsystem of fuel cell

4.4.5. Evaluation of the Maintenance Actions within the Fuel Cell Maintenance Plan

According to the result of team review, the new proposed maintenance strategies can be performed for the maintenance optimization. The RPN results of FMEA process of fuel cell is shown in Fig.4-14.

The most reduction of PRN is 108, the RPN of Settling Tank-Malfunction is reduced from 180 to 72. The S index before corrective actions is 6, the S index after corrective actions is 6, no changed; the O index before corrective actions is 5, the O index after corrective actions is 2; this is changed 3 degree. the D index before corrective actions is 5, the D index after corrective actions is 2, that means the main reason of the RPN changed is the new proposed maintenance actions can reduce the occurrence degree of failure mode. The highest rate of RPN decrement is 60%, it also happened on Settling Tank-Malfunction. Other RPN have been significantly changed, but the No.9 and No.12 are not changed.

The trends of the three indexes (Severity, Occurrence and Detection), before and after the modifications are shown in Fig.4-15, Fig.4-16 and Fig.4-17, respectively. The results show that the main effect indices are occurrence index. The detection is difficult to changed, it because the fuel cell system needs more professional maintenance engineers to do this work. But the new maintenance actions also can improve the reliability of fuel cell system. The proportion of new proposed maintenance strategy for fuel cell is shown in Fig.4-18. We can find that there are 65.22% new proposed maintenance strategy is the replacement regularly.

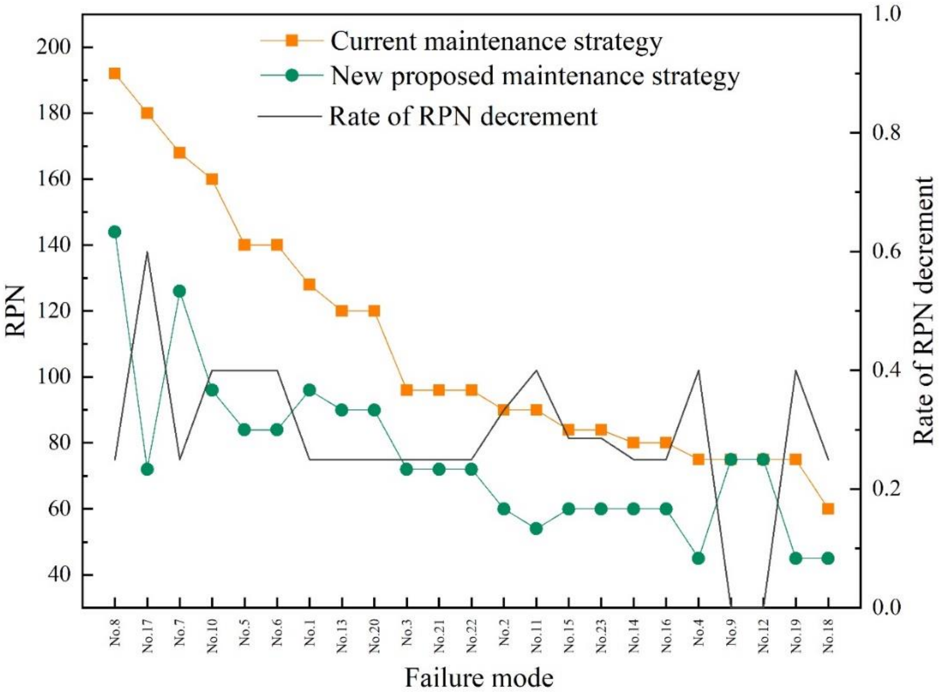

Fig.4-14 The RPN results of FMEA process of fuel cell

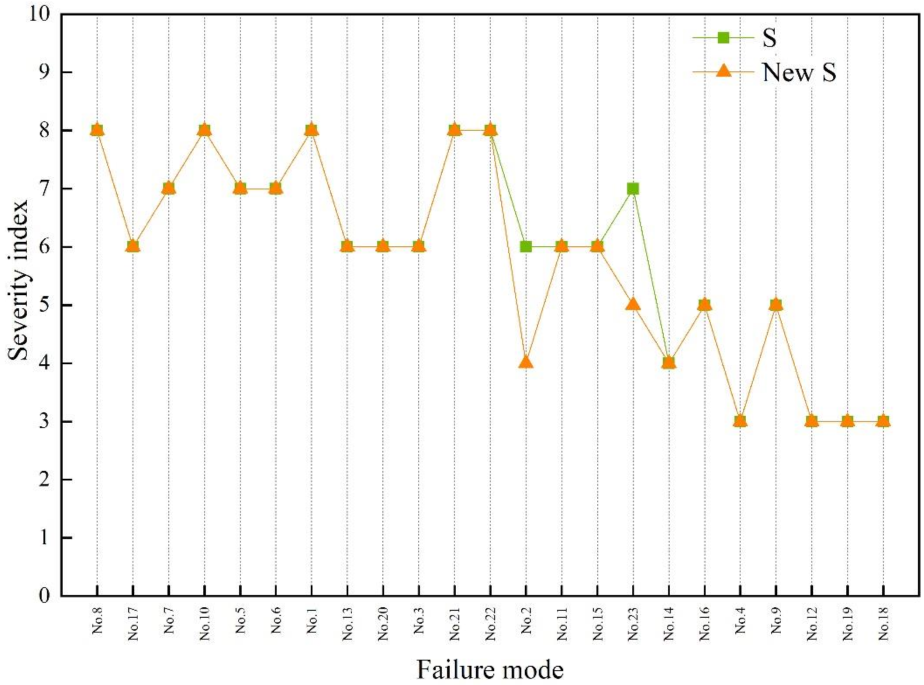

Fig.4-15 The S index modification with corrective actions for fuel cell

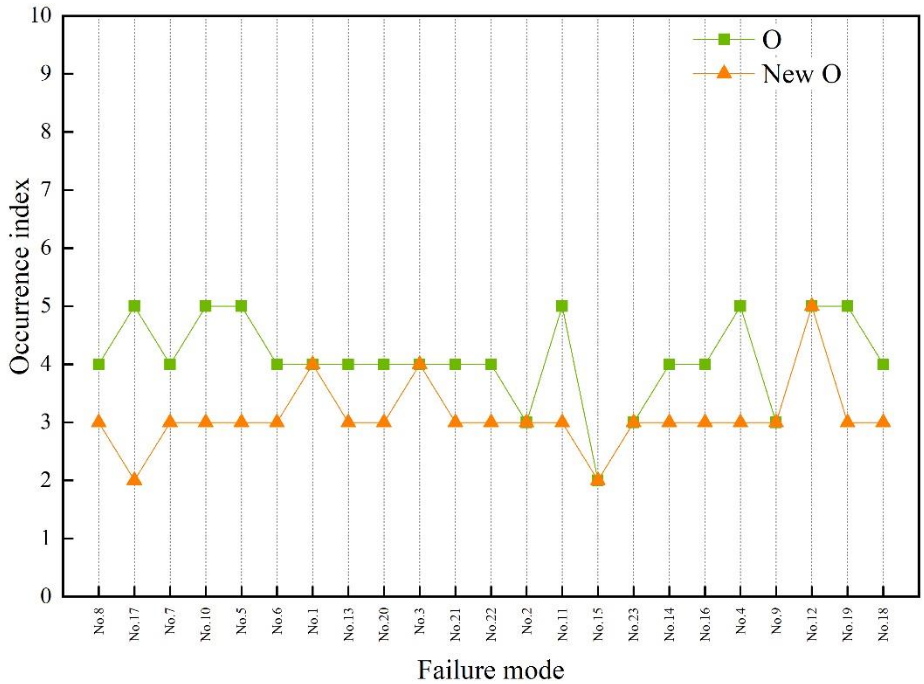

Fig.4-16 The O index modification with corrective actions for fuel cell

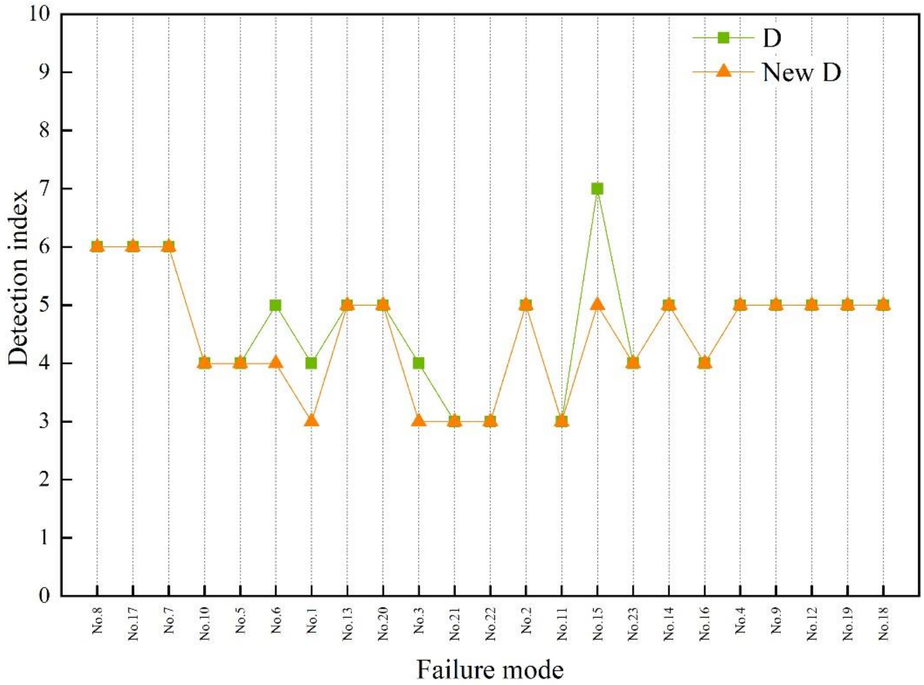

Fig.4-17 The D index modification with corrective actions for fuel cell

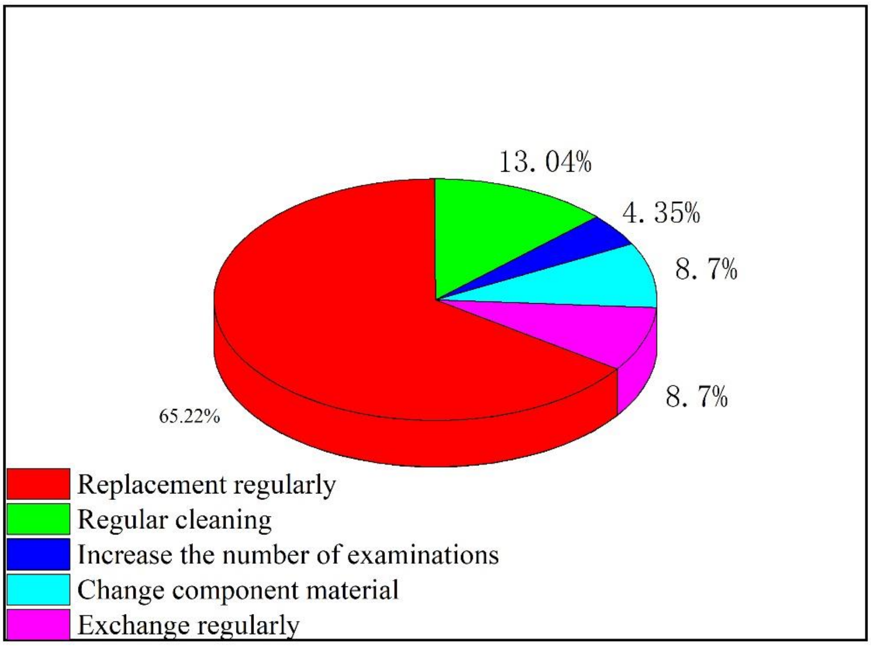

Fig.4-18 The proportion of new proposed maintenance strategy for fuel cell

4.5. Summary

In this chapter, the FMEA process of the DER system in Kitakyushu Science and Research Park had been presented. The data are from the Manual of DER system, Construction completion certificate of DER system, Construction plan state of DER system and the DER system inspection and maintenance work report. The main components of the DER system were classified into the two power generators related system. The gas engine system and fuel cell system. The FMEA process was performed for the maintenance optimization of the gas engine system and fuel cell system.

According to the FMEA process, the failure mode, failure cause and failure effect of the components are reviewed and discussed. The risk priority number (RPN) was adopted to evaluate the failure importance index of component if the failure of the component occurred. Therefore, through the FMEA process, we can find which components are the weakness of the system, the new proposed maintenance strategy will be proposed to meet the weakness point.

The results show that the most weakness system in the gas engine is the engine system, the proportion of failure modes will be occurred in engine system is 75.61%. And 8 failure modes' RPN are more than 100, it means that those failure modes are on the Level III, Failing an important mission. The RPN value changes differently in different maintenance modes. The most reducing failure mode is No.14, the rate of No.14 failure mode is 85.2%. The No.14 failure mode is Spark Plug-Poor ignition, the spark plug is an important component of engine system of gas engine. The Severity Index of the failure modes is not changed under the new proposed maintenance strategies in the gas engine FMEA process. A few of Occurrence Index can be reduced by the new proposed maintenance strategies. But most of Occurrence Index cannot be reduced. For the new proposed maintenance strategies of gas engine, the highest of proportion of new proposed maintenance strategy is Increase the number of inspections, it can help the maintainers and engineers to improve the reliability of system.

The failure modes of fuel cell system are less than the gas engine system. The results of show that there are 9 component modes' RPN of fuel cell are more than 100, but did not more than 250. That means those 9 components are on the Level III, Failing an important mission. The most of failure will be occurred in the power section system of fuel cell, and the proportion is 43.48%. The main effect indices are occurrence index. The detection is difficult to changed, it because the fuel cell system needs more professional maintenance engineers to do this work. But the new maintenance actions also can improve the reliability of fuel cell system. We can find that there are 65.22% new proposed maintenance strategy is the replacement regularly.

Through the FMEA process the weakness components of can be fined, and the new maintenance strategies can be proposed for the maintenance strategy optimization. The limited of this method is the team review step, this part related the experience and ability of the engineers.

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Chapter 5. Reliability and Maintenance Prioritization Analysis of the DER System

5.1. Introduction

CCHP system is a typical DER system. There have been great developments and applications in the past few decades. CCHP system is selected as a case study to study the index of system reliability priority.

A combined cooling, heating, and power (CCHP) system is a complex and repairable system containing many components and series of subsystems. When a failure occurs in one component, it might cause a failure of a subsystem or whole system. Traditional maintenance methods might lead to the waste of maintenance resources and a high cost of maintenance. The reliability and maintenance prioritization analyses can help managers optimize maintenance strategies and reduce the total cost. A reliability importance index is one of the factors in maintenance prioritization analysis. This paper aims at selecting the component reliability importance indices to identify the priority of component maintenance of a CCHP system from the perspective of maintenance cost. Failure cost importance index (FCI) and Potential failure cost importance index (PI) are developed for the maintenance prioritization analysis of a CCHP system. A Markov model based on the state–space method (SSM) is used to analyze the reliability and availability of a CCHP system. A set of actual survey reliability data of CCHP systems is used to support the validity of the reliability importance indices. The results indicate that the FCI and PI might lead to different rankings of maintenance prioritization. The FCI and PI will help managers make a reasonable decision for maintenance on a cost basis.

Recent research is focused on system management, operation, system optimization, size optimization, energy management, renewable energies, and more [1]. Some renewable energies and technologies have been applied in the CCHP system, such as fuel cells, heat pumps [2], photovoltaics (PV), wind turbines, and more [3, 4]. Integrating renewable energy into the CCHP system can further improve the system's energy efficiency and reduce carbon dioxide emissions; the renewable energies integrated into CCHP (RECCHP) systems can be used when the power grid is unavailable, for example, on islands, and in deserts [5]. Chen et al. [6] proposed a multi-objective optimization model of energy management for the integrated electrical and natural gas network with CCHP plants. Lo Basso et al. [2] analyzed the thermal management and off-design operation of coupling of combined heat and power (CHP) and heat pump for the energy retrofitting of residential buildings. Wang et al. [7] presented a comprehensive operation model to enhance the economic and environmental benefits through the improved CCHP strategy of MG. The main objective of optimization is to improve energy efficiency, maximize environmental benefits, and reduce the expense of the system. Some previous studies on system design and optimization of a CCHP system were often set to a constant, or assumed that the reliability and maintenance of the system were completely unfailing for operation [8]. The cost of operation and maintenance of a system account for more than 50% of the total cost of the whole life cycle [9] in fact. Thus, a reasonable maintenance strategy can improve the reliability of a system and reduce the maintenance cost.

Some articles on the operation, reliability, and maintenance of a CCHP system or microgrid are related to facilities' distribution and system optimization design. Ou [10] proposed an unsymmetrical faults analysis method to deal with the unsymmetrical faults of microgrid distribution systems adopting hybrid compensation. Ting-Chia Ou et al. studied the operation and control strategies for a microgrid which used renewable energies and fuel cells as power generators [11]; a technology was developed to improve the transient stability in the hybrid power multi-system [12]. Noussan et al. [13] proposed an optimization tool to enhance the operation of a CHP system combined with a heat pump. Zamani-Gargari et al. [14] proposed a method which combined the Monte Carlo Simulation (MCS) method to assess the reliability of a wind power system with energy storage. Yang et al. [15] proposed an approach to analyzing how the wind farm electrical system influenced the system when the electrical system faulted. Wang [16] presented a reliability and availability analysis of a redundant and non-redundant BCHP (building, cooling, heating, and power) system, but did not consider the component reliability of the system. Haghifam, and Manbachi [17] proposed a reliability and availability modeling of CHP systems to analyze the impact of CHP system reliability with improved gas-delivery, water-delivery, and hot water-delivery subsystems but did not model the reliability of individual components. Frangopoulos [18] analyzed the effect of optimization on the synthesis, design, and operation of a cogeneration system based on reliability considerations, but did not consider the effect of component reliability. El-Nashar [19] presented an optimal design model of a cogeneration system using the thermoeconomic theory to carry out the design optimization.

Only a few articles to date have studied the component reliability of the power generation plant, cogeneration system, and CCHP system. Sabouhi et al. [20] mentioned a reliability model to assess the combined cycle power generation plants and applied it to a reliability analysis for gas turbine power plants and steam turbine power plants. The reliability of components was used to compute the system availability and the study compared the availability, but did not mention the importance of maintenance regarding the components in one system. Carazas et al. [21] presented an availability analysis for component maintenance policies of a gas turbine, but did not assess the reliability of the whole power generation system. A CCHP system is a complex system, however, containing a large number of components and a series of subsystems. When a failure occurs on one component, it might cause a failure of a subsystem or the whole system. The reliability of the whole system is dependent on the reliability of each component of the system.

Traditionally, the maintenance of components in a system is managed by specifying a fixed schedule. Each component of a system has its own maintenance schedule performed according to the manufacturer's recommendations. It might lead to the waste of maintenance resources and a high cost of maintenance. To comprehensively evaluate the degree of maintenance importance regarding the components of a whole system and propose a reasonable maintenance strategy is a vital way to avoid the wastage of maintenance resources and reduce the total costs, therefore, the reliability and maintenance prioritization analysis of components of a whole system is necessary.

A reliability importance index is one of the methods to identify system weaknesses and provide a numerical value to determine which components are more important for the improvement of system reliability [22]. The reliability importance index can be used to assess which components are needing maintenance and which components are needing more attention to reduce maintenance costs [23]. It can provide a reference for system designers and managers to optimize the design plan and operation strategy for future design, redesign, and operation to reduce the total cost and improve reliability. Conventional reliability importance indices are a function of component reliability, however; they cannot be used directly to optimize maintenance costs.

Two new reliability importance indices are developed in this study based on the component failure cost for the identification of component maintenance priorities from the perspective of maintenance cost. A comparative analysis is performed between the new reliability importance indices and conventional reliability importance indices. Additionally, a Markov model based on the state–space method (SSM) is used to analyze the reliability and availability of components and subsystems of a CCHP System. This study is validated by actual survey reliability data of the CCHP system in Kitakyushu Science and Research Park (KSRP), Kitakyushu, Japan; the system has been operational since July 2001.

5.2. Introduction of Main Components in This Case

Several technologies have been applied to CCHP systems for power generation, waste heat recovery, thermal storage, and thermal energy conversion such as an Absorption chiller. The main components of technologies are the keys to system reliability. The main components and subsystem technologies of a CCHP system are listed in Table 5-1 [3, 24]. Some auxiliaries and components are not listed in this table, such as cooling pumps, cooling towers, control panels and so on, but these components also have an influence on the subsystem or system reliability. Hence, auxiliaries and components will be considered in the reliability analysis of the system.

Table 5-1 The main components of the CCHP system technologies

Technology	Function	Main Components/Subsystems
Fuel cell (FCs)	Power generation; Waste heat supply	Fuel processor, air processor, power section, power conditioner and so forth.
Reciprocating engines	Power generation; Waste heat supply	Engine, fuel processor, generator, cooling system, and so forth.
Gas turbines/engines	Power generation; Waste heat supply	Engine/turbine, generator, compressor, fuel compressor, power conditioner, cooling system, and so forth.
Photovoltaic system (PVs)	Power generation	Solar cells, power conditioner, DC/AC generator and so forth.
Wind energy conversion system (WECS)	Power generation	Winder turbines, generator, gearbox, yaw motor and so forth.
Small hydro-turbines	Power generation	Turbine, generator, power conditioner and so forth.
Boiler	Thermal supply	Burner, heat exchanger, supply lines, return lines, firebox, circulator pumps, deaerators/condenser and so forth.
Absorption chiller	Thermal supply	Thermal compressor, condenser, evaporator, cooling tower, solution pump and so forth.
Heat pump	Thermal supply	Compressor, condenser, expansion valve, evaporator and so forth.

The CCHP system at Kitakyushu Science and Research Park (KSRP) [25] is the analysis objective. The Kitakyushu Science and Research Park is located in Kitakyushu, Japan. The generation of electricity and thermal form of the CCHP system are used to meet the electricity load, space cooling load, space heating load, and hot water load of several buildings on the campus. The system scheme of the CCHP system at KSRP is shown in Fig. 5-1 [26]. The fuel cells and gas engines fueled by natural gas are used to drive the power generation units to generate electricity. Every power generation unit has an independent cooling water system. The waste heat from the power generation unit is recovered by the heat recovery steam generator (HRSG), and the 50% recovered heat from the fuel cell is used to drive the absorption chiller to meet the space cooling load in summer and the space heating load in winter. The 50% recovered heat from the fuel cell and all recovered heat from the gas engine are used to drive the heat exchanger to meet the hot water load. Since the electricity generation of the system cannot meet the electricity load of the campus, it is necessary to purchase electricity from the electricity grid. The available gas-fired absorption chiller fueled by natural gas meets the shortage of space cooling and space heating. An auxiliary boiler fueled by natural gas is used to complement the shortage of hot water. Details of the power generation units of the CCHP system in KSRP is shown in Table 5-2 [26].

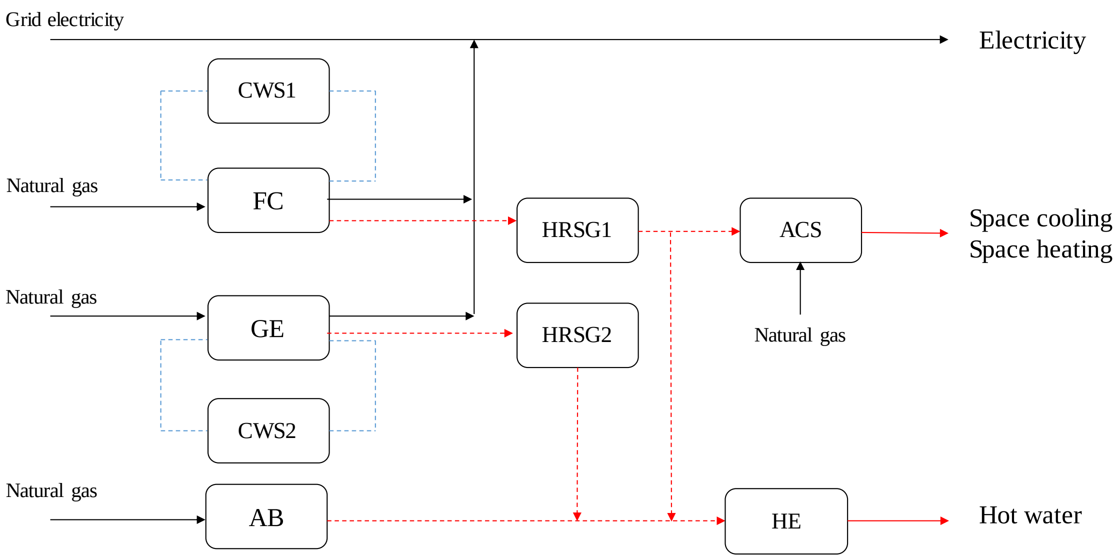

Fig.5-1 System scheme of the CCHP system at KSRP

(FC: fuel cell; GE: gas engine; CWS: cooling water system; AB: Auxiliary boiler; HRSG: heat recovery steam generator; ACS: absorption chiller system; HE: heat exchanger.)

Table 5-2 The details of the power generation units at KSRP

Type	**Fuel Cell**	**Gas Engine**
Capacity	200 kW	160 kW
Power generation efficiency (with 100% load)	40%	28.7%
Heat release efficiency (with 100% load)	20%, Collecting heat for hot water 20%, Collecting heat for space cooling and heating	47.7% Collecting heat for hot water
Operational mode	Run for 24 h over time Priority to run	Run for 14 h Run for 8:00~22:00

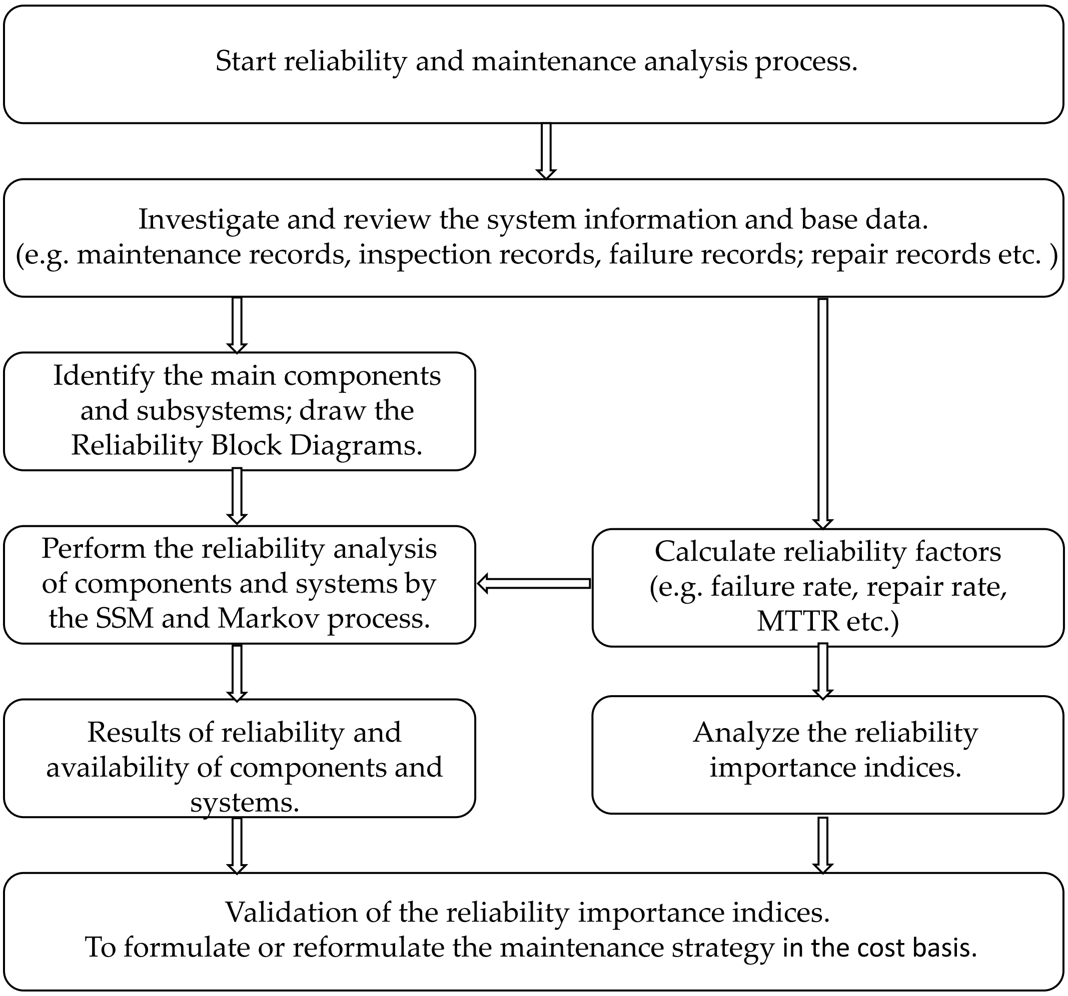

Fig.5-2 The research flowchart of reliability and maintenance prioritization analysis

The research flow of reliability and maintenance prioritization analysis is shown in Fig.5-2. Reliability and maintenance prioritization analyses will be applied to the components and subsystems of the CCHP system at KSRP. The following points of system reliability are assumed for the CCHP system at KSRP:

(1) The failure of a component or a subsystem is independent of each other. This analysis only considers one component failure and how it affects the system status and operation; multiple failures of components in the system will not be considered at this time.

(2) When a failure occurs in a power generation unit, the outage of electricity will be satisfied by the electricity grid and the failure of the electricity grid is not considered. Similarly, the outage of space cooling/heating, and hot water is considered satisfied when the corresponding system has failed.

Table 5-3 The nomenclature in Chapter 5

CCHP	Combined cooling heating and power
SSM	State-space method
KSRP	Kitakyushu science and research park
R	Reliability
A	Availability
U	Unavailability
P	Probability
f	Number of failures
λ	Failure rate (f/unit time)
μ	Repair rate
e	Napier’s constant
MTBF	Mean time between failure
MTTF	Mean time to failure
MTTR	Mean time to repair
t	Time
u	Unit price of grid electricity or city gas
L_u	Purchases of electricity or city gas
I	Importance index
BI	Birnbaum importance
CI	Criticality importance

FCI	Failure cost importance index
PI	Potential failure cost importance index
C_{TF}	Total failure cost (total cost/unit time)
C_R	Repair cost
C_A	Add cost during outage
JPY	Japanese yen
Subscript	
sys	System
k	Component number
i, j	Number of state
n	Failure numbers of one component in a certain period
Superscript	
B	Birnbaum importance index
C	Criticality importance index
F	Failure cost importance index (cost/f)
P	Potential failure cost importance index (cost/unit time)
Main units and components	
E	Generation unit of electricity
CH	Generation unit of space cooling and heating
HW	Generation unit of hot water
FC	Fuel cell
GE	Gas engine
CT	Cooling tower
CP	Cooling pump
HRSG	Heat recovery steam generator
AC	Absorption chiller
AB	Auxiliary boiler
HE	Heat exchanger
CWS	Cooling water system
ACS	Absorption chiller system

5.3. Reliability Importance Indices Methods

5.3.1. Reliability Importance Indices

The Markov process, based on the state–space method (SSM), is suitable to analyze the reliability of a CCHP system. More details have been introduced in Chapter 2.

According to the method, a two components system has applied and analyzed in chapter 2.3.5 (as shown in Fig.2-9). The probabilities of the system availability can be calculated. Therefore, the availability of component 1 is written as follows:

$$A_{component\ 1} = P_1 + P_3 \quad (5\text{-}1)$$

Where the availability of component 2 is written as follows:

$$A_{component\ 2} = P_1 + P_2 \quad (5\text{-}2)$$

Where the availability of the whole system (both component 1 and component 2 are functioning) is written as follows:

$$A_{whole\ system} = P_1 \quad (5\text{-}3)$$

Where the availability of the system (whole system or part of the system are functioning) is written as follows:

$$A_{system} = P_1 + P_2 + P_3 \quad (5\text{-}4)$$

Generally, a complex system consists of multiple series and parallel subsystems, thus, the reliability calculation methods for a series subsystem and parallel subsystem are different [27]. The reliability of a series system with n components is presented as follows:

$$R_{series} = R_1 R_2 R_3 \cdots R_n \quad (5\text{-}5)$$

The reliability of a parallel system with n components is presented as follows:

$$R_{parallel} = 1 - [(1 - R_1)(1 - R_2) \cdots (1 - R_n)] \quad (5\text{-}6)$$

5.3.2. Two New Reliability Importance Indices

Reliability importance indices can be used to determine project prioritization of components in a system. The Reliability importance indices methods and some previous study have been introduced and reviewed in Chapter 2.4.3. This paper presents new reliability importance indices based on Birnbaum's measure and Patrik Hilber's research. The failure cost of components has been used as an assessment factor for a reliability importance measure of a CCHP system. The component reliability importance index based on failure cost is defined as follows:

$$I_k^F = \frac{\partial C_{TF}}{\partial \lambda_k} \quad (5\text{-}7)$$

where I_k^F is the reliability importance index that is considered the failure cost. The unit I_k^F is failure cost per failure (failure cost/f).

Reliability importance index of failure cost (I_k^F) is affected by the repair cost of the component and the repair rate, but is not related to the failure rate. The second reliability importance index is related to failure rate and proposes a maintenance prioritization with comprehensive consideration of failure rate, repair rate and required repair cost. Potential failure cost importance index defines the expected cost of failure before the failure occurs. It is presented as the following:

$$I_k^P = I_k^F \lambda_k \tag{5-8}$$

The failure cost of a component of a CCHP system is defined as the total cost of the system during the failure time, including the component repair cost and the added cost for an unserved load (electricity or space cooling and heating, or hot water).

The total failure cost is defined as the following:

$$C_{TF}(k) = \sum_n \left[C_{R,n}(k) + C_{A,n}(k)\right] \tag{5-9}$$

where C_{TF} is total failure cost of component k's failure, C_R is the repair cost for k component, and the C_A is the added cost of the outage (electricity or space cooling and heating, or hot water).

The added cost during an outage is defined as the cost that should be paid in order to meet the insufficiency of the energy load when the failure occurred, such as when the power generator experiences a failure leading to an outage-state; the insufficient electricity will be met by the electrical grid and the insufficient heat from the waste heat will be met by gas boiler or gas-fired absorption chiller, thus, the total cost of electricity and natural gas for meeting the insufficiency are the added cost of the unserved load.

The added cost of the outage (electricity or space cooling and heating, or hot water) is calculated as the following:

$$C_A = u \times L_u \times MTTR \tag{5-10}$$

where u is the unit price of electricity or city gas; and L_u presents the amount of electricity or city gas are purchased, and MTTR is the mean time to repair. Generally, MTTR is defined as the total amount of time spent performing all corrective or preventative maintenance repair divided by the total number of those repairs. The mean time between failure (MTBF), the mean time to failure (MTTF), and the mean time to repair (MTTR) are the basic categories of failure rates [28].

5.3.3. Comparisons of Component Reliability Importance Indices

Failure cost importance and potential failure cost importance indices are developed to provide accurate cost indicators for managers to optimize the maintenance strategy to reduce the total maintenance cost and improve the system reliability. Comparisons of the four component importance indices are presented in Table 5-4. I^B and I^C are related to failure rate, and they show the probability of components that would fail at time t or before time t, respectively. However, the failure rate only depends on the component's properties and shows the maintenance results. I^B and I^C cannot accurately reflect the component's importance of maintenance when the maintenance costs are considered for the maintenance strategy. Thus, the failure cost should be used as a factor to evaluate the component importance index when the economics of maintenance are considered, due to the failure cost being related to the repair rate and component repair cost. Therefore, I^F and I^P as the importance indices, which are the comprehensive consideration of failure rate, repair cost, and repair rate, are developed in this paper.

Table 5-4 The comparisons of the component reliability importance indices

Importance Index	**Description**	**Relation of Maintenance Factors**
I^B	The probability of a component failing at time t	Failure rate
I^C	The probability of a component failing before time t	Failure rate
I^F	The expect failure cost if the component fails.	Repair rate, component repair cost.
I^P	The expect failure cost in a unit time caused by component failure.	Failure rate, repair rate, component repair cost.

5.4. Reliability Analysis of DER System

Reliability and availability analyses of components and subsystems are applied in the CCHP system at KSRP. The CCHP system is a complex system which can provide the electricity and thermal energies (cooling, heating, and hot water) to meet customer load, and is combined with a series of subsystems consisting of a power generation system, city gas supply system, water supply system, cooling water system, thermal supply system, and transfer system. Therefore, the reliability of this CCHP system must consider series subsystem reliability, which is too complex and difficult to be analyzed, hence, the reliability of this CCHP system was simplified as customer-oriented reliability; only the reliability of electricity, space cooling and heating, and hot water delivery to the customer were considered. The Markov processes and SSM were selected to analyze the reliability and availability of the electricity subsystem, space cooling and heating subsystem, hot water subsystem and the whole system.

A simple customer-oriented reliability model of the CCHP system is shown in Fig.5-3. Based on this model, the electricity subsystem, space cooling and heating subsystem, and hot water subsystem are described as a series connection. This is because the whole system reliability should be considered from the perspective of the customer. Thus, the reliability of the whole system is written as:

$$R_{CCHP} = R_{electricity} \cdot R_{cooling\,\&\,heating} \cdot R_{hot\ water} \tag{5-11}$$

When one of the subsystems fails but the other subsystems still function, it creates a situation of availability of the functioning subsystems but not the availability for the whole system. When a component or subsystem has stopped operating according to a schedule, its reliability is not cemented in the whole system's reliability. According to the schedule, for instance, the space cooling and heating subsystem will stop in the spring or autumn due to lack of need resulting from temperature changes, therefore, the whole system's reliability is only dependent on the electricity and hot water subsystem's reliability. Even though parts of the system are no longer functioning, the rest of the system can continue to function.

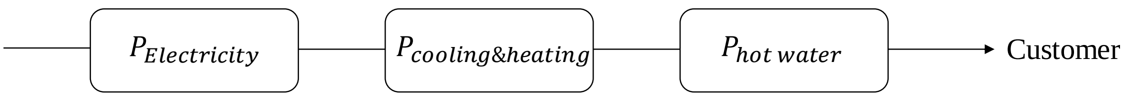

Fig.5-3 A simple customer-oriented reliability model of a CCHP system

5.4.1. Electricity Subsystem

The subsystem of electricity generation of the CCHP system of KSRP consisted of two generation units, a fuel cell unit (E1) and a gas engine unit (E2). The main components of the electricity subsystem of the CCHP system are presented in Table 5-5. The main components of the fuel cell unit included the fuel cell, cooling power1, and cooling pump1. The main components of the gas engine unit included the gas engine, cooling tower2, and cooling pump2.

A simplified reliability block diagram of the electricity subsystem of the CCHP system is shown in Figure5-4. Generally, the two generation units were regarded as having a parallel relationship, where at least one of them would be functioning, and the system was considered reliable and available. However, when one of the units failed, it caused the electricity supply to be in a lacking state. Thus, the situation where one of the units failed was considered as unavailable or partially available. The reliability of the whole system or a subsystem of the CCHP system was defined as all of the components of the system functioning under given conditions for the stated period. This system, considering customer-oriented reliability, could be described as all subsystems were reliable since the system can be viewed as a series system.

Table 5-5 The electricity subsystem of CCHP system

Generation Unit of Electricity	Main Component	Function
E1	Fuel cell (FC), Cooling tower1 (CT1), and Cooling pump1 (CP1).	Produce electricity
E2	Gas engine (GE), Cooling tower2 (CT2), and Cooling pump2 (CP2).	Produce electricity

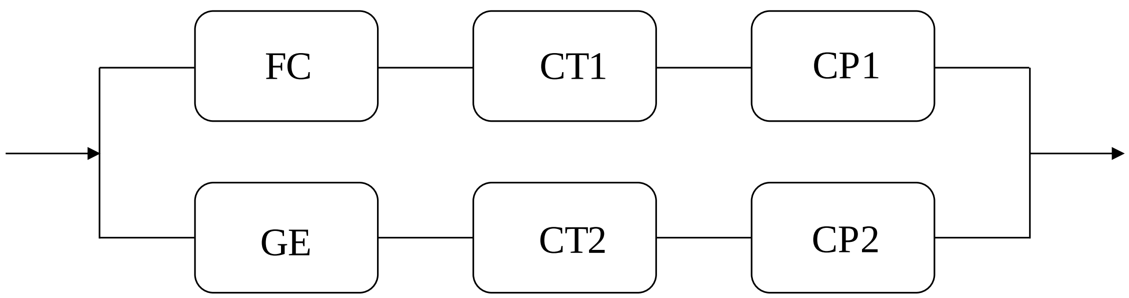

Fig.5-4 The reliability block diagram of an electricity subsystem of the CCHP system

Based on reliability analysis methods introduced in chapter 5.3, the operation states and reliability data for the electricity subsystem of the CCHP system is shown in Table 5-6. The operation states of the electricity subsystem included 4 states, the completely available state (State1), the partially available states (State2, State3), and the completely unavailable state (State4). The failure rate and repair rate of E1, E2, and the subsystems are symbolized in Table 5-6. The reliability of the electricity subsystem was dependent on the reliability of State1; thus, the reliability of the electricity subsystem was determined by both E1 and E2.

Table 5-6 The operation states and reliability data for the electricity subsystem of the CCHP system

Items	E1	E2	Electricity Supply	State Reliability
Failure rate	λ_{E1}	λ_{E2}	$\lambda_{electricity}$	----
Repair rate	μ_{E1}	μ_{E2}	$\mu_{electricity}$	----
State 1	1	1	E1 + E2	$R_{E1}R_{E2}$
State 2	0	1	E2 (lacking)	R_{E2}
State 3	1	0	E1 (lacking)	R_{E1}
State 4	0	0	0	0

A series system's reliability was expressed by Equation (5-1), thus, the reliability of E1 is presented as follows:

$$R_{E1} = R_{FC}R_{CT1}R_{CP1} \tag{5-12}$$

A reliability can be expressed by the failure rate as in the following equation:

$$R_k(t) = R_t^{-\lambda_k(t)} \tag{5-13}$$

Therefore, if the failure rates are constant, then Equation (5-12) can be expressed as

$$R_{E1} = e^{-\lambda_{E1}} = e^{-\lambda_{FC}}e^{-\lambda_{CT1}}e^{-\lambda_{CP1}} = e^{-(\lambda_{FC}+\lambda_{CT1}+\lambda_{CP1})} \tag{5-14}$$

Thus, the following equation is obtained from the above equation:

$$\lambda_{E1} = \lambda_{FC} + \lambda_{CT1} + \lambda_{CP1} \tag{5-15}$$

Similarly, the failure rate of E2 is obtained using

$$\lambda_{E2} = \lambda_{GE} + \lambda_{CT2} + \lambda_{CP2} \tag{5-16}$$

Moreover, the availability of the electricity subsystem is equal to the probability of State1, and it also is defined as $\mu/\lambda+\mu$, therefore, the availability of the electricity subsystem is expressed as

$$A_{electricity} = \frac{\mu_{electricity}}{\lambda_{electricity}+\mu_{electricity}} = \frac{\mu_{E1}\mu_{E2}}{(\lambda_{E1}+\mu_{E1})(\lambda_{E2}+\mu_{E2})} \tag{5-17}$$

Therefore, the repair rate of the electricity system is solved as

$$\mu_{electricity} = \frac{\lambda_{electricity}\mu_{E1}\mu_{E2}}{\lambda_{E1}\lambda_{E2}+\lambda_{E1}\mu_{E2}+\lambda_{E2}\mu_{E1}} \tag{5-18}$$

Let $r_{E1}=1/\mu_{E1}$, $r_{E2}=1/\mu_{E2}$, $r_{electricity}=1/\mu_{electricity}$, and then

$$r_{electricity} = \frac{1}{\lambda_{E1}+\lambda_{E2}}(\lambda_{E1}r_{E1}+\lambda_{E2}r_{E2}+\lambda_{E1}\lambda_{E2}r_{E1}r_{E2}) \tag{5-19}$$

Usually, $\mu_{E1} \gg \lambda_{E1}$, $\mu_{E2} \gg \lambda_{E1}$ and then, Equation (5-19) is written as

$$r_{electricity} \approx \frac{1}{\lambda_{E1}+\lambda_{E2}}(\lambda_{E1}r_{E1}+\lambda_{E2}r_{E2}) \tag{5-20}$$

Thus, the repair rate of the electricity subsystem is obtained by the following:

$$\mu_{electricity} = \frac{1}{r_{elecricity}} = \frac{\lambda_{E1}+\lambda_{E2}}{\lambda_{E1}/\mu_{E1}+\lambda_{E2}/\mu_{E2}} \tag{5-21}$$

Hence, for a series system consisting of *n* components, the failure rate and repair rate are presented as the following, respectively:

$$\lambda_n = \sum_{k=1}^{n}\lambda_k \tag{5-22}$$

$$\mu_n = \frac{\sum_{k=1}^{n}\lambda_k}{\sum_{k=1}^{n}\lambda_k/\mu_k} \tag{5-23}$$

Thus, the main reliability parameters of E1, E2, and the electricity subsystem are expressed as the following:

Failure rate of E1:

$$\lambda_{E1} = \lambda_{FC}+\lambda_{CT1}+\lambda_{CP1} \tag{5-24}$$

Failure rate of E2:

$$\lambda_{E2} = \lambda_{GE} + \lambda_{CT2} + \lambda_{CP2} \tag{5-25}$$

Failure rate of electricity subsystem:

$$\lambda_{electricity} = \lambda_{FC} + \lambda_{CT1} + \lambda_{CP1} + \lambda_{GE} + \lambda_{CT2} + \lambda_{CP2} \tag{5-26}$$

Repair rate of E1:

$$\mu_{E1} = \frac{\lambda_{FC}+\lambda_{CT1}+\lambda_{CP1}}{\lambda_{FC}/\mu_{FC}+\lambda_{CT1}/\mu_{CT1}+\lambda_{CP1}/\mu_{CP1}} \tag{5-27}$$

Repair rate of E2:

$$\mu_{E2} = \frac{\lambda_{GE}+\lambda_{CT2}+\lambda_{CP2}}{\lambda_{GE}/\mu_{GE}+\lambda_{CT2}/\mu_{CT2}+\lambda_{CP2}/\mu_{CP2}} \tag{5-27}$$

Repair rate of electricity subsystem:

$$\mu_{electricity} = \frac{\lambda_{FC}+\lambda_{CT1}+\lambda_{CP1}+\lambda_{GE}+\lambda_{CT2}+\lambda_{CP2}}{\lambda_{FC}/\mu_{FC}+\lambda_{CT1}/\mu_{CT1}+\lambda_{CP1}/\mu_{CP1}+\lambda_{GE}/\mu_{GE}+\lambda_{CT2}/\mu_{CT2}+\lambda_{CP2}/\mu_{CP2}} \tag{5-28}$$

The availability of the electricity subsystem:

$$A_{electricity} = \frac{1}{(\lambda_{FC}/\mu_{FC}+\lambda_{CT1}/\mu_{CT1}+\lambda_{CP1}/\mu_{CP1}+\lambda_{GE}/\mu_{GE}+\lambda_{CT2}/\mu_{CT2}+\lambda_{CP2}/\mu_{CP2})+1} \tag{5-29}$$

The reliability of the electricity subsystem:

$$R_{electricity} = R_{s1} = e^{-\lambda_{electricity}} \tag{5-30}$$

5.4.2. Space Cooling and Heating Subsystem

The space cooling and heating subsystem of the CCHP system at KSRP consisted of three space cooling and heating generation units, the generation units that used the waste heat from the fuel cell unit (CH1), and the generation units that assisted the absorption chiller fueled by natural gas (CH2 and CH3). More details of the space cooling and heating subsystem are shown in Table 5-7. The main components of CH1 included the fuel cell unit (E1), the heat recovery steam generator1, and the absorption chiller1. CH2 and CH3 only had one component, an absorption chiller fueled by natural gas.

A simplified reliability block diagram of the space cooling and heating subsystem of the CCHP system is shown in Fig.5-5. The space cooling and heating for customers came from three ways. The CH2 and CH3 each used the same component. The operation states and reliability data for the space cooling and heating subsystem of the CCHP system are presented in Table 5-8. Due to CH2 and CH3 only having one component, the failure rate and repair rate of CH2 and CH3 units were expressed by the component's failure rate and repair rate. The reliability and availability of the space cooling and heating subsystem were equal to the reliability and availability of State 1.

Table 5-7 The space cooling and heating subsystem of the CCHP system

Generation Unit of Cooling and Heating	Main Equipment	Function
CH1	Fuel cell unit (E1), Heat recovery steam generator1 (HRSG1), Absorption chiller 1 (AC1).	Supply cooling or heating by using the heat from heat recovery steam generator 1
CH2	Absorption chiller 2 (AC2).	Supply heating or cooling using natural gas
CH3	Absorption chiller 3 (AC3).	Supply heating or cooling using natural gas

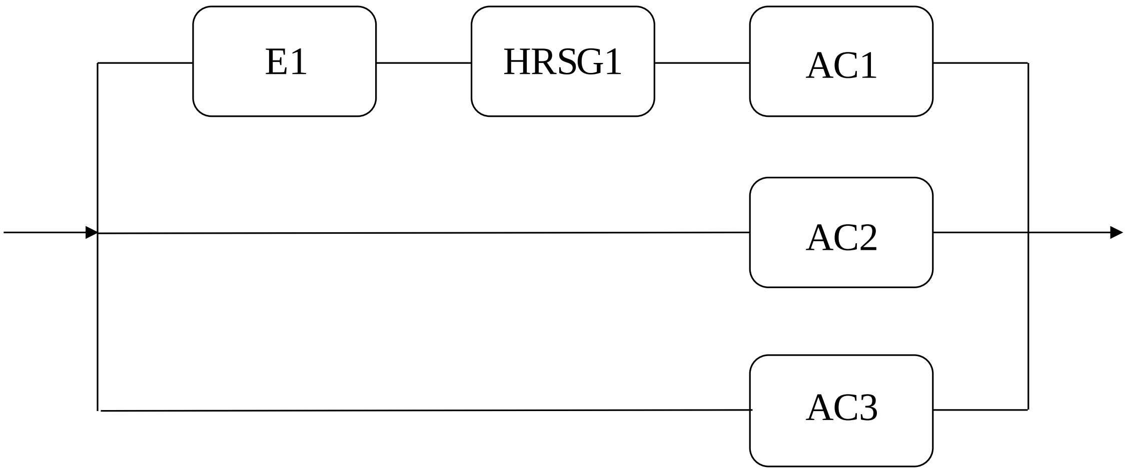

Fig.5-5 The reliability block diagram of the space cooling and heating subsystem of the CCHP system

Table 5-8 The operation states and reliability data for the space cooling and heating subsystem of the CCHP system

Items	CH1	CH2	CH3	Space Cooling and Heating Supply	State Reliability
Failure rate	λ_{CHI}	λ_{AC2}	λ_{AC3}	$\lambda_{cooling\ \&\ heating}$	----
Repair rate	μ_{CH1}	μ_{AC2}	μ_{AC3}	$\mu_{cooling\ \&\ heating}$	----

Items	**CH1**	**CH2**	**CH3**	**Space Cooling and Heating Supply**	**State Reliability**
State 1	1	1	1	$CH_1 + CH_2 + CH_3$	$R_{CH1}R_{CH2}R_{CH3}$
State 2	1	0	1	$CH_1 + CH_3$ (lacking)	$R_{CH1}R_{CH3}$
State 3	1	1	0	$CH_1 + CH_2$ (lacking)	$R_{CH1}R_{CH2}$
State 4	1	0	0	CH_1 (lacking)	R_{CH1}
State 5	0	1	1	$CH_2 + CH_3$ (lacking)	$R_{CH2}R_{CH3}$
State 6	0	1	0	CH_2 (lacking)	R_{CH2}
State 7	0	0	1	CH_3 (lacking)	R_{CH3}
State 8	0	0	0	0	0

According to Equations (5-22) and (5-23), the main reliability parameters of the CH1 unit and space cooling and heating subsystem are expressed as the following:

Failure rate of CH1:

$$\lambda_{CH1} = \lambda_{E1} + \lambda_{HRSG1} + \lambda_{AC1} \tag{5-31}$$

Repair rate of CH1:

$$\mu_{CH1} = \frac{\lambda_{E1} + \lambda_{HRSG1} + \lambda_{AC1}}{\lambda_{E1}/\mu_{E1} + \lambda_{HRSG1}/\mu_{HRSG1} + \lambda_{AC1}/\mu_{AC1}} \tag{5-32}$$

Failure rate of the space cooling and heating subsystem:

$$\lambda_{cooling\,\&\,heating} = \lambda_{E1} + \lambda_{HRSG1} + \lambda_{AC1} + \lambda_{AC2} + \lambda_{AC3} \tag{5-33}$$

Repair rate of the space cooling and heating subsystem:

$$\mu_{cooling\ \&\ heating} = \frac{\lambda_{CH1}+\lambda_{AC2}+\lambda_{AC3}}{\lambda_{CH1}/\mu_{CH1}+\lambda_{AC2}/\mu_{AC2}+\lambda_{AC3}/\mu_{AC3}} \quad (5\text{-}34)$$

The availability of the space cooling and heating subsystem:

$$A_{cooling\ \&\ heating} = \frac{1}{(\lambda_{CH1}/\mu_{CH1}+\lambda_{AC2}/\mu_{AC2}+\lambda_{AC3}/\mu_{AC3})+1} \quad (5\text{-}35)$$

The reliability of the space cooling and heating subsystem:

$$R_{cooling\ \&\ heating} = e^{-\lambda_{cooling\ \&\ heating}} \quad (5\text{-}36)$$

5.4.3. Hot Water Subsystem

The hot water subsystem of the CCHP system at KSRP consisted of three hot water generation units and a heat exchanger unit. The generation unit (HW1) used the recovery heat from E1, the generation unit (HW2) used the recovery heat from E2, and an auxiliary boiler (HW1) fueled by natural gas produced the hot water when the heat from HW1 and HW2 was not enough. A heat exchanger unit (HE) was used to exchange the heat to hot water. More details of the main components of the hot water subsystem are shown in Table 5-9. The main components of HW1 included the fuel cell unit and heat recovery steam generator1. The main components of HW2 included the gas engine unit and heat recovery steam generator2, while HW3 had only one component, the auxiliary boiler.

Table 5-9 The hot water subsystem of the CCHP system

Generation Unit of Hot Water	**Main Equipment**	**Function**
HW1	Fuel cell unit (E1), Heat recovery steam generator 1. (HRSG1)	Supply heat for hot water from HRSG1
HW2	Gas engine unit (E2), Heat recovery steam generator 2 (HRSG2).	Supply heat for hot water from HRSG2.
HW3	Auxiliary boiler (AB).	Supply heat for hot water using natural gas.
HE	Heat exchanger (HE).	Exchanged the heat for hot water.

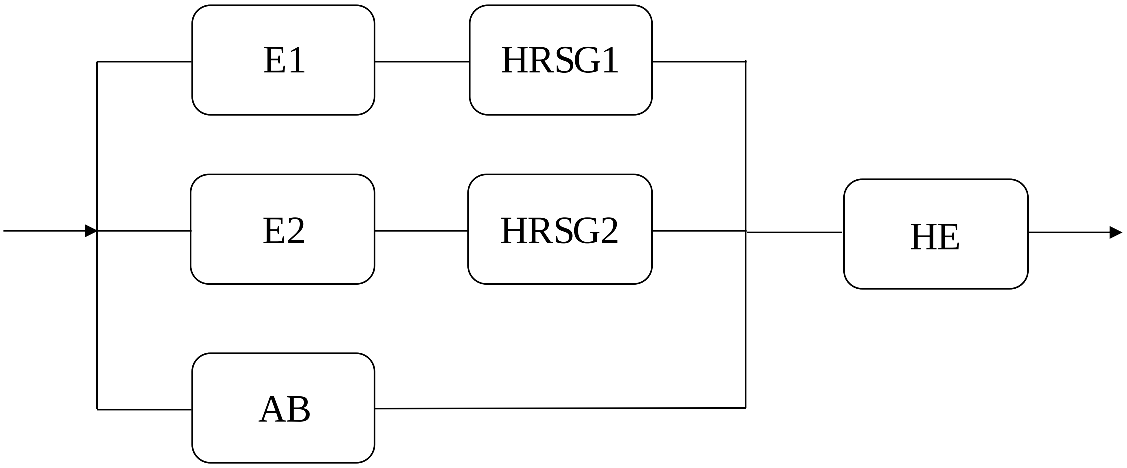

Fig.5-6 The reliability block diagram of the hot water subsystem of the CCHP system

Table 5-10 The operation states and reliability data for the hot water subsystem of the CCHP system

Items	**HW1**	**HW2**	**HW3**	**HE**	**Hot Water Supply**	**State Reliability**
Failure rate	λ_{HW1}	λ_{HW2}	λ_{AB}	λ_{HE}	$\lambda_{Hot\ water}$	----
Repair rate	μ_{HW1}	μ_{HW2}	μ_{AB}	μ_{HE}	$\mu_{Hot\ water}$	----
State 1	1	1	1	1	$HW_1 + HW_2 + HW_3$	$R_{HW1}R_{HW2}R_{HW3}R_{HE}$
State 2	1	1	0	1	$HW_1 + HW_2$(lacking)	$R_{HW1}R_{HW2}R_{HE}$
State 3	1	0	1	1	$HW_1 + HW_3$(lacking)	$R_{HW1}R_{HW3}R_{HE}$
State 4	0	1	1	1	$HW_2 + HW_3$(lacking)	$R_{HW2}R_{HW3}R_{HE}$
State 5	1	0	0	1	HW_1(lacking)	$R_{HW1}R_{HE}$
State 6	0	1	0	1	HW_2(lacking)	$R_{HW2}R_{HE}$
State 7	0	0	1	1	HW_3(lacking)	$R_{HW3}R_{HE}$
State 8	0	0	0	1	0	0
State 9	1	1	1	0	0	0

A simplified reliability block diagram of the hot water subsystem of the CCHP system is shown in Fig.5-6. The hot water subsystem was regarded as a series system consisting of the three hot water generation units and a heat exchanger unit. When the heat exchanger unit failed, the hot water supply was interrupted and the hot water subsystem was unavailable. The operation states and reliability data for the hot water subsystem of the CCHP system is shown in Table 5-10. There were 9 states of the hot water subsystem. The reliability and availability of the hot water subsystem were equal to the reliability and availability of State1. Thus, the main reliability parameters of HW1, HW2, and the hot water subsystem were obtained as follows:

Failure rate of HW1:

$$\lambda_{HW1} = \lambda_{E1} + \lambda_{HRSG1} \tag{5-37}$$

Repair rate of HW1:

$$\mu_{HW1} = \frac{\lambda_{E1}+\lambda_{HRSG1}}{\lambda_{E1}/\mu_{E1}+\lambda_{HRSG1}/\mu_{HRSG1}} \tag{5-38}$$

Failure rate of HW2:

$$\lambda_{HW2} = \lambda_{E2} + \lambda_{HRSG2} \tag{5-39}$$

Repair rate of HW2:

$$\mu_{HW2} = \frac{\lambda_{E2}+\lambda_{HRSG2}}{\lambda_{E2}/\mu_{E2}+\lambda_{HRSG2}/\mu_{HRSG2}} \tag{5-40}$$

Failure rate of the hot water subsystem:

$$\lambda_{hot\,water} = \lambda_{HW1} + \lambda_{HW2} + \lambda_{AB} + \lambda_{HE} \tag{5-41}$$

Repair rate of the hot water subsystem:

$$\mu_{hot\,water} = \frac{\lambda_{HW1}+\lambda_{HW2}+\lambda_{AB}+\lambda_{HE}}{\lambda_{HW1}/\mu_{HW1}+\lambda_{HW2}/\mu_{HW2}+\lambda_{AB}/\mu_{AB}+\lambda_{HE}/\lambda_{HE}} \tag{5-42}$$

The availability of the hot water subsystem:

$$A_{hot\,water} = \frac{1}{(\lambda_{HW1}/\mu_{HW1}+\lambda_{HW2}/\mu_{HW2}+\lambda_{AB}/\mu_{AB}+\lambda_{HE}/\lambda_{HE})+1} \tag{5-43}$$

The reliability of the hot water subsystem:

$$R_{\mathrm{hot\ water}} = e^{-\lambda_{hot\,water}} \tag{5-44}$$

5.5. Numerical Calculation and Discussion

The numerical calculation and analysis of the DER system at KSRP is discussed in this section. All the base reliability data (failure rate, MTTR and so forth.) were obtained from actual records, such as operation records, maintenance records, repair records, and more.

5.5.1. Reliability Calculation

Based on the actual investigation, the failure rate and MTTR of the main components of the CCHP system at KSRP are shown in Table 5-11. The failure rate and MTTR were the actual data gathered from inspection and repair records of the CCHP system at KSPR from April 2002 to March 2011. During this investigation, the repair data of the cooling pumps of the cooling water system, the heat recovery steam generators, and the absorption chillers were difficult to separate because the same components were maintained and repaired at the same time, generally. Therefore, the three components assumed the same failure rate and MTTR even though they were in different generation units. The failure rate and MTTR of the tree type components were obtained based on the total number of failures and the number of components. Table 5-11 shows that the gas engine had the highest failure rate and that the fuel cell had the second highest failure rate, thus, the power generation unit had a higher failure rate than other units. The auxiliary boiler and heat exchanger had the lowest failure rate. The fuel cell and absorption chiller had the highest MTTR in this system. All the reliability data were a true reflection of the actual situation of the system under the current operation and maintenance strategies. Each component had an independent maintenance strategy according to the manufacturer's recommendations.

Table 5-11 The failure rate and MTTR of the main component of the CCHP system in KSRP

Main Components	**Component Symbol**	**Failure Rate (Failure/Day)**	**MTTR (Days)**
Fuel Cell	FC	0.002982	2.0
Cooling tower for fuel cell	CT1	0.001210	1.0
Cooling pump for fuel cell	CP1	0.001534	1.0
Gas engine	GE	0.008037	1.4
Cooling tower for gas engine	CT2	0.001143	1.0
Cooling pump for gas engine	CP2	0.001534	1.0
Heat recovery steam generator for fuel cell	HRSG1	0.001217	1.5
Heat recovery steam generator for gas engine	HRSG2	0.001217	1.5
Absorption chiller	AC1 to 3	0.005265	2.0
Auxiliary boiler	AB	0.000930	1.0
Heat exchanger	HE	0.000846	1.0

The reliability and availability of the CCHP system at KSRP was analyzed in chapter 5.3. Based on that analysis, the calculation results are present here. The reliability of all components in the CCHP system is shown in Fig.5-7. The reliability of each component was related to failure rate. The reliability of the electricity generator and absorption chiller was lower than other components in this system, and the heat exchanger and auxiliary boiler had the higher reliability.

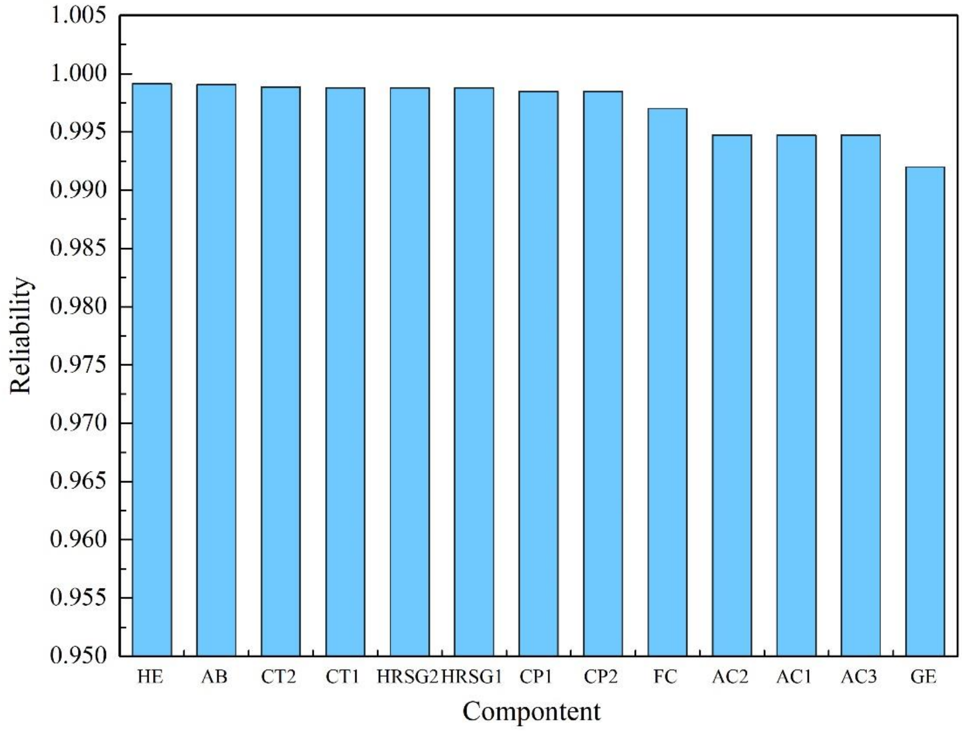

Fig.5-7 The reliability of all components in the CCHP system

The reliability of the electricity, space cooling and heating, and hot water generation units are shown in Fig.5-8. Comparing the reliability of two electricity generation units, the fuel cell unit was higher than the gas engine unit because the gas engine had a higher failure rate than the fuel cell, while the cooling water system's failure rates were similar. The reliability of the space cooling and heating generation unit (CH1) that combined with the waste heat recovery unit was lower than the reliability of the generation units, which only had the gas-fired absorption chiller. Comparing the three hot water generation units, the reliability of the hot water generation units (HW1, HW2), which combined with the waste heat recovery unit, were lower than the reliability of the auxiliary boiler. Fig.5-9 and 5-10 show the reliability and availability of the subsystems and the whole system. The space cooling and heating system was more unreliable than other subsystems because the absorption chiller's reliability was lower. The results show that the reliability of the CCHP system depended on each component's reliability due to it being a series system.

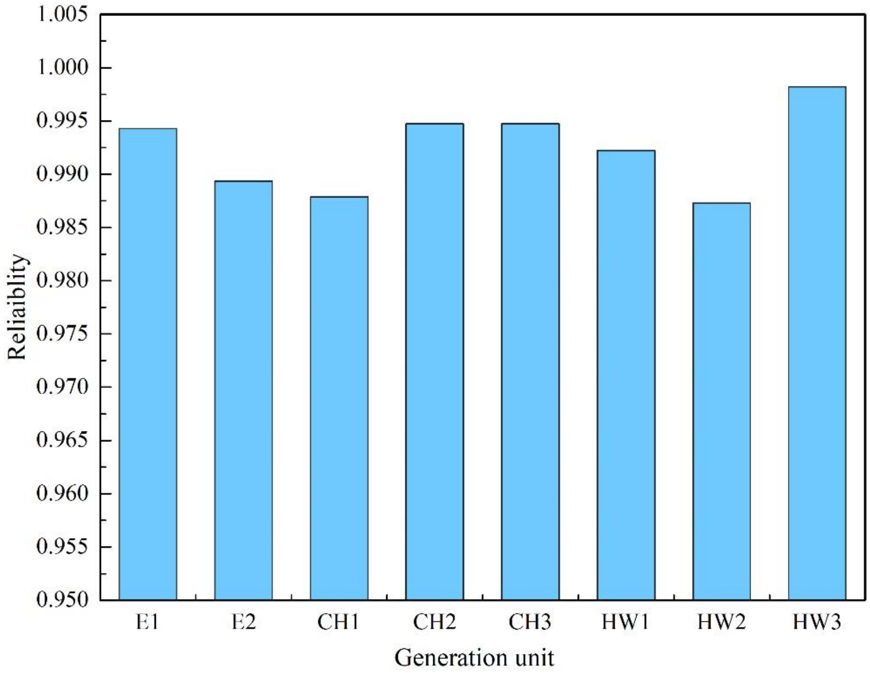

Fig.5-8 The reliability of the generation units of the CCHP system

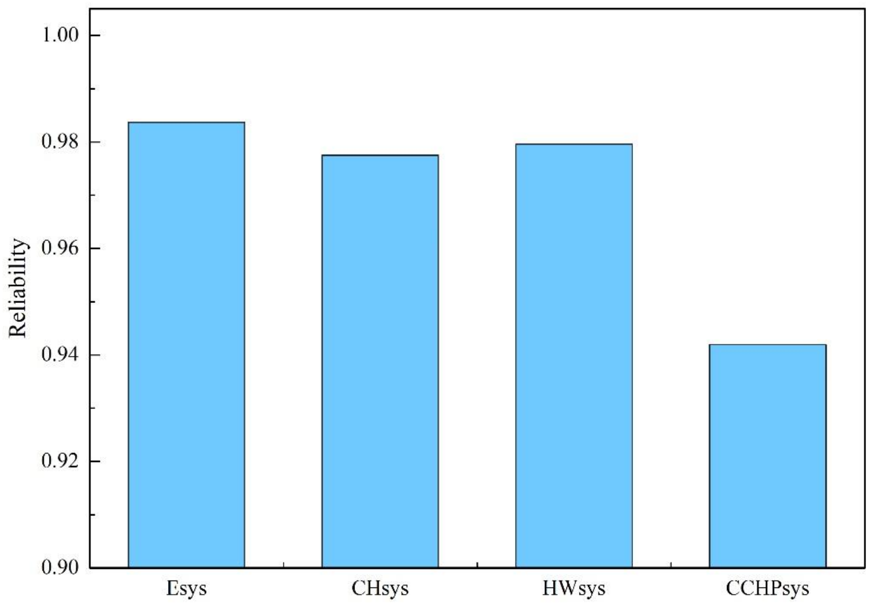

Fig.5-9 The reliability of the systems of the CCHP system at KSRP

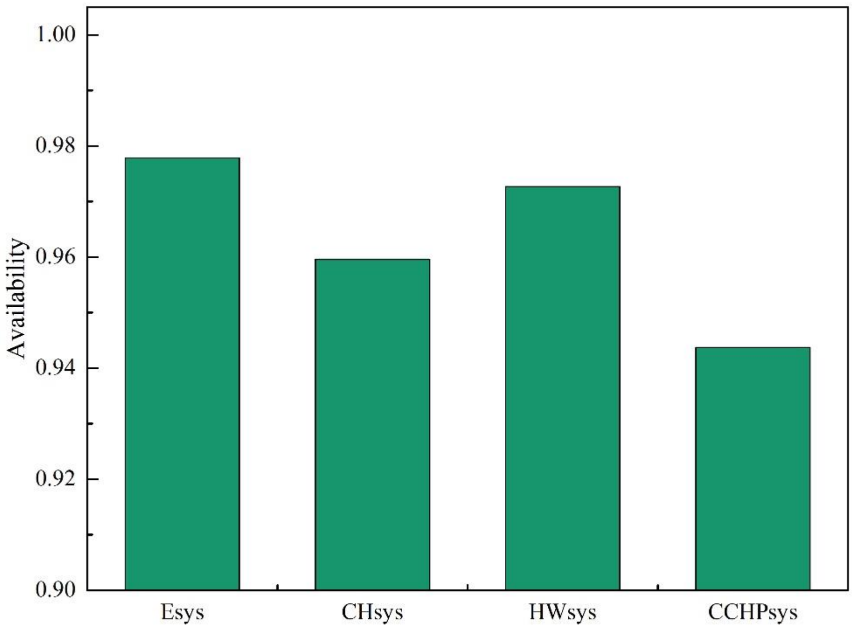

Fig.5-10 The availability of the systems of the CCHP system at KSRP

5.5.2. Component Importance Calculation

The Birnbaum importance (BI) and criticality importance (CI) methods were applied in this system to evaluate the subsystem and components' importance levels over the whole system and to give a maintenance prioritization of components within this system. Simultaneously, the failure cost importance index (FCI) described in Chapter 5.3.2 was calculated in this section, and the results of the failure cost reliability importance are compared to BI and CI.

The BI values of the components of the CCHP system are shown in Fig.5-11. The maintenance prioritization of the components using the BI values is GE > AC > FC > CP2 > CP1 > HRSG1 > HRSG2 > CT1 > CT2 > AB > HE. The reliability importance of the power generation unit and absorption chiller was higher than the other components. Fig.5-12 shows the CI values of the components of the CCHP system. The order of the priority maintenance actions is the same as the BI analysis results. However, the criticality importance of the gas engine is much larger than other components, for instance, the cooling pump, cooling tower, auxiliary boiler, heat exchanger, and heat recovery steam generator.

The failure cost importance indices were introduced in chapter 5.3.2. The failure cost includes the repair cost of the failure component and the cost of the outage due to component failure. The cost of outage can be calculated by Equation (5-9), and the outage data of electricity, space cooling and heating, and hot water due to the component failure is shown in Table 5-12. The failure of the fuel cell unit (E1) led to the outage of electricity, space cooling and heating, and hot water. The failure of the gas engine led to the outage of electricity and hot water. Since AC2 and AC3 do not use waste heat, their failure can be equated to no added cost of failure. The repair cost of each component is calculated according to the actual data from April 2002 to March 2011.

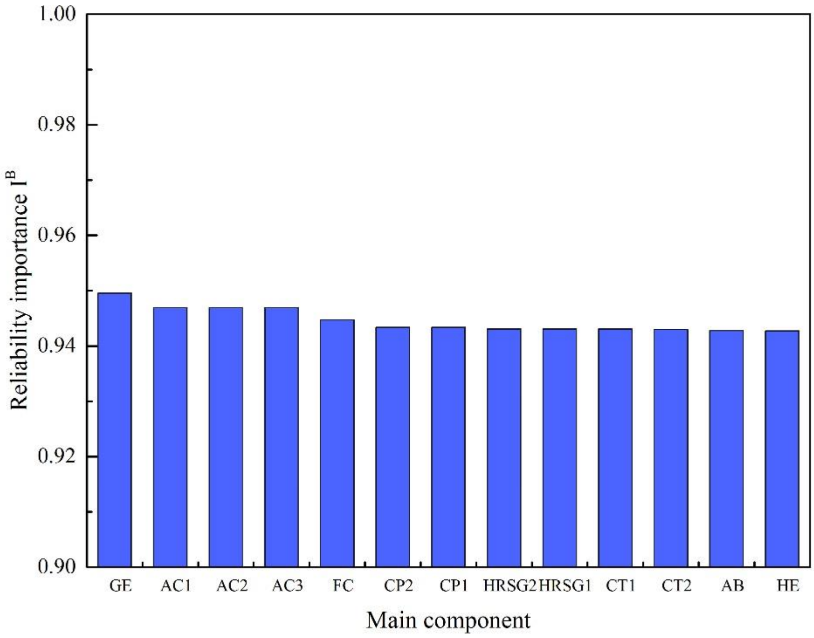

Fig.5-11 The BI values of the components of the CCHP system

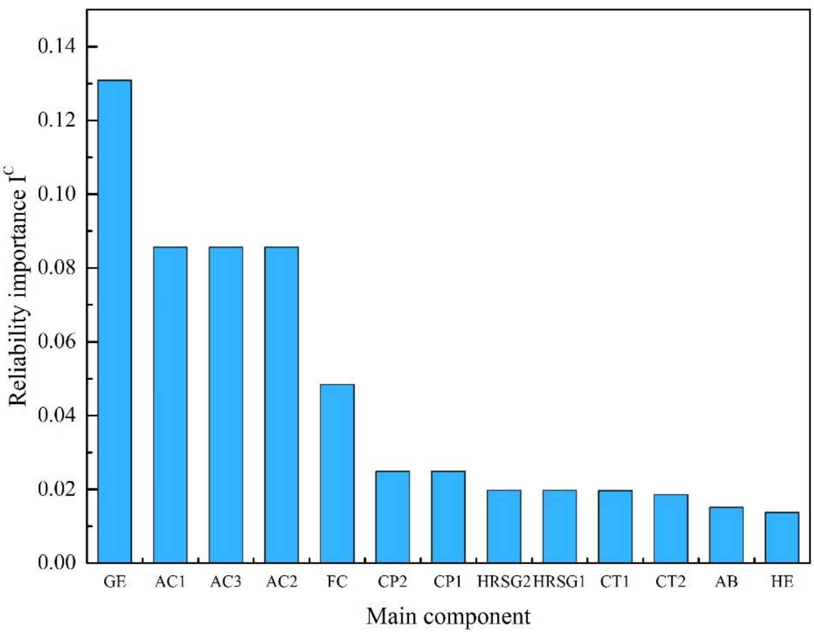

Fig.5-12 The CI values of the components of the CCHP system

Table 5-12 The outage data of electricity, space cooling and heating, and hot water due to component failure

Main Component	Component Symbol	Outage		
		Electricity (kWh/day)	Hot Water (kWh/Day)	Heat/Cooling (kWh/Day)
Fuel Cell	FC	4800	2280	2280
Cooling tower for fuel cell	CT1	4800	2280	2280
Cooling pump for fuel cell	CP1	4800	2280	2280
Heat recovery steam generator for fuel cell	HRSG1	---	2280	2280
Gas engine	GE	1600	2520	---
Cooling tower for gas engine	CT2	1600	2520	---
Cooling pump for gas engine	CP2	1600	2520	---
Heat recovery steam generator for gas engine	HRSG2	---	2520	---
Absorption chiller	AC1	---	---	2280
	AC2	---	---	---
	AC3	---	---	---
Auxiliary boiler	AB	---	463	---
Heat exchanger	HE	---	5263	---

The failure cost importance index values of the components of the CCHP system are shown in Fig.5-13. The order of prioritized maintenance is GE > HRSG2 > HRSG1 > FC > AB > HE > CT1 > CT2 > CP > AC. The gas engine had the higher failure cost than other components. The failure cost of the absorption chiller was lowest in the CCHP system. Potential failure cost importance index values of the components of the CCHP system are presented in Fig.5-14. This result shows the potential failure cost before the failure occurred. It presents the importance of the component maintenance from the perspective of operation and maintenance costs. The order of prioritized maintenance based on potential failure cost importance index values is GE > FC > AC > HRSG2 > HRSG1 > CP > CT1 > CT2 > AB > HE. Comparing the failure cost importance index and potential failure cost importance index, the gas engine was the most important component of this CCHP system. The reliability importance of the fuel cell and heat recovery steam generator were second in importance to the gas engine. The difference between the failure cost importance index and the potential failure cost importance is that the failure rate is considered in the potential failure cost importance. The auxiliary boiler and heat exchanger, for instance, had the highest failure cost of one component, but had the lowest potential failure cost due to the low failure rate. This point should be considered in the system design and maintenance strategies.

The four reliability importance indices have been applied in this system, and the results are presented. Comparing the four reliability importance indices, the BI and CI were only related to the failure rate, generally, which can be reduced by improving the maintenance level and optimizing the maintenance strategy for repairs of a complex system. Reducing the system operation and maintenance costs is one of the main goals of maintenance optimization. Thus, the reliability importance indices that consider the repair and outage costs were applied to assess the priority of component maintenance within the system. The failure cost importance index was related to the MTTR and the repair cost of each component. The potential failure cost importance index was not only related to the MTTR and repair cost, but to the failure rate. Therefore, the failure cost importance and potential failure cost importance indices can provide a comprehensive analysis measure for the component maintenance optimization.

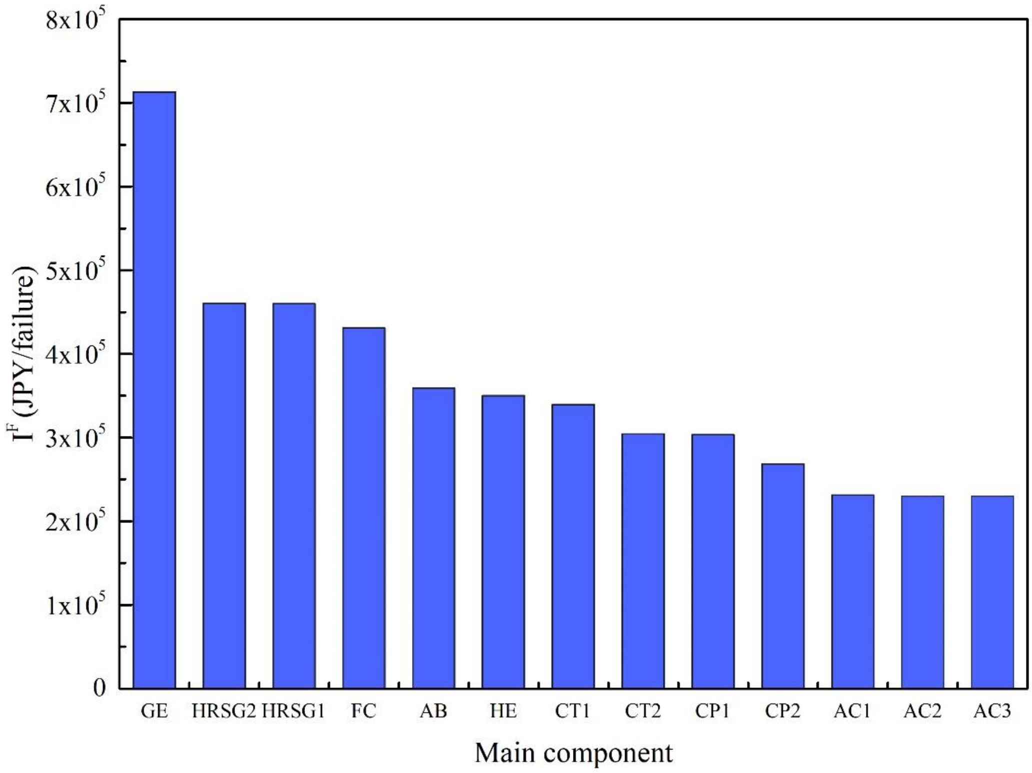

Fig.5-13 The failure cost importance index values of components of the CCHP system

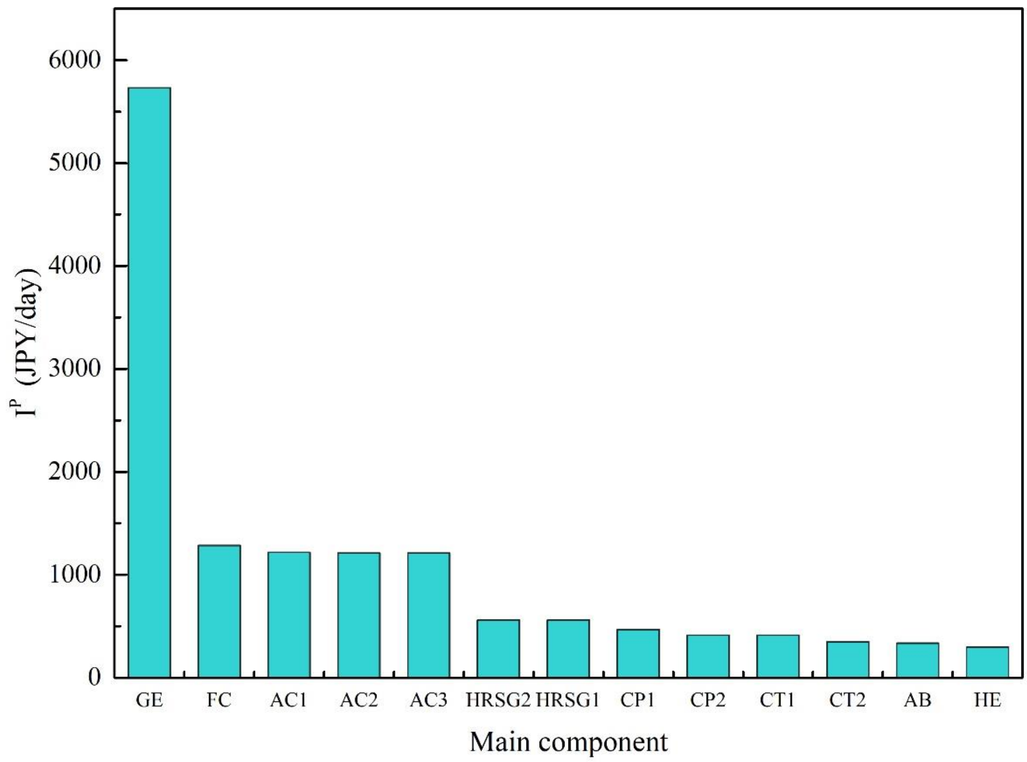

Fig.5-14 The potential failure cost importance index values of components of the CCHP system

5.6. Summary

This chapter focuses on the reliability and availability analysis and components maintenance prioritization analysis of the CCHP system. Failure cost importance index (FCI) and potential failure cost importance index (PI) were developed for the maintenance prioritization analysis of the CCHP system. A Markov model based on a state–space method was used to analyze the reliability and availability of the CCHP system. The reliability and availability of the components, subsystems, and whole system were deduced.

This paper aimed at selecting the component reliability importance indices to identify the priority of the component maintenance from the perspective of maintenance cost. The BI and CI were used to compare to FCI and PI. It was observed that the FCI and PI might lead to different rankings. FCI enabled the system managers to know the cost of a one-time failure of each component in a system. PI enabled the system managers to know the cost before the failure occurred for a one-time failure of each component in a system. The two indices would help managers to make a reasonable decision for maintenance on the cost basis, and help designers to optimize the system on the cost basis.

The reliability of the CCHP system is the product of the reliability of each component when the reliability is considered the energy supply. The system reliability can be ensured by improving the components' failure rates. The auxiliary boiler (low failure rate with high failure cost) can improve the reliability of the subsystem.

The reliability and availability analysis method are the only study on how one component failure can affect the system as a whole or in part; the reliability of multiple failure states and the time-variances were ignored. Moreover, the CCHP system is a complex and repairable system, generally with high maintenance and reliability, where failure data is difficult to obtain, thus, the degradation data can be used to optimize the maintenance strategy based on the component reliability importance indices.

The proposed component reliability importance indices of the maintenance prioritization analysis in this paper can be applied to other cogeneration systems or to other maintenance problems. The reliability importance indices will be further validated in CCHP systems which use renewable energies and other technologies like PV, wind power, or heat pumps.

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Chapter 6. Availability Analysis and Cost Optimization of Redundant DER System

6.1. Introduction

A reasonable DER system design and O&M strategy can improve the reliability and reduce the total lifecycle cost.

Most previous studies are focused on the optimization and analysis of the DER system to reduce the total lifecycle cost. For instance, Kaveh Akbari et al. [1] developed a robust optimization model for the investment and unit capacity, the investment cost, O&M cost, carbon emission cost and revenue were adopted to constrain the optimization function. E.D. Mehleri et al. [2] presented a optimization model to determine the combination and allocation of distributed energy resource (DER) technologies and operation strategy, the economic impact was discussed through the investment cost, O&M cost and energy cost. Hyeunguk Ahn et al. [3] performed an economic feasibility analysis to evaluate the CCHP system in difference electricity tariffs and energy demand application regions; for the high operation cost of application, it may not be economically viable. The operation cost includes the O&M, grid electricity, natural gas in the conventional separate heat and power (SHP) system; and the electricity cost also includes the reservation, customer, demand and other energy charges [3]. A CCHP system driven by the Stirling engine fired by the helium and hydrogen was proposed, the economic and environmental was evaluated [4]. A lot of literatures of cost optimization of CCHP system were relate to some research points; such as multi-objective optimization design [5, 6], combine with solar energy [7-9],biomass energy [10], environmental impacts [11], energy management [12, 13], storage technology [14], operation strategy [15], other renewable technologies [16, 17] etc.. In the above studies, the reliability of component or system is generally ignored, and the cost of operation and maintenance is regarded as a constant or a proportional value.

Only a few literatures were studied the reliability and availability analysis of power generation plant or a DER system. Jiang et al. [18] proposed two component reliability importance indices to evaluated the maintenance prioritization of the components in the CCHP system; the two indices is related to the failure cost during the component failure and repair. Haghifam et al. [19] divided a combined heating and power(CHP) system into three sub-systems: gas-delivery sub-system, water-cooled cogeneration sub-system and hot-water-delivery sub-system; a Markov process model was applied to analyze the reliability and availability of an island, standby and parallel CHP system. Wang et al. [20] presented a reliability and availability analysis approach based on the state-space method; and an evaluation of redundant design of CCHP system was analyzed. Wang et al. [21] presented a redundant design of building cooling, heating and power (BCHP) system, compared the primary energy consumption (PEC), annual total cost (ATC) and the CO_2 emission reduction ratio of the separation production (SP) system, non-redundant design BCHP system and redundant design system respectively. However, the redundancy design did not take into account the redundancy of the number of devices; and the reliability analysis was not applied to the system capacity design and evaluation.

A reasonable redundant design may not only improve the reliability and availability of the system but can also provide better economic benefits. In this paper, a reliability analysis of redundant design is proposed and analyzed. The k-out-of-n model is performed to calculate the reliability indices of the CCHP system with redundant design. A model for reliability and cost analysis of non-redundant and redundant design in a CCHP system is developed and evaluated, and a conventional energy supply system is adopted as reference benchmarks for the non-redundant and redundant design in a CCHP system for the cost analysis.

6.2. Introduction of DER System in This Case

A schematic of DER system is shown in Fig.6-1, the main units of the DER system include: a power generation unit for electricity supply; the heat recovers unit for waste heat recovery from the power generation unit; the absorption chiller for space cooling supply by using recycled heat or natural gas-fired; heat exchanger unit for heat (space heating and hot water) supply by using recycled heat or heat from auxiliary boiler. Generally, two operation strategies of DER system is frequently adopted, following electrical load (FEL) and following thermal load (FTL) [22]. When the DER system follows the electrical load, the excess heat may be recovered and stored in the storage tank to improve thermal efficiency, it can also be easily exhausted if it cannot be used. When the DER system follows the thermal load, the excess electricity may be produced. If in the region where the excess electricity is allowed to be sold to the city's electricity grid, the economics of the DER system may be increased. However, it's not easy to dispose the excess electricity in the remote region or the region where the excess electricity is not allowed to be sold to the city's electricity grid. Thus, the analyzed DER system in this paper is following electrical load.

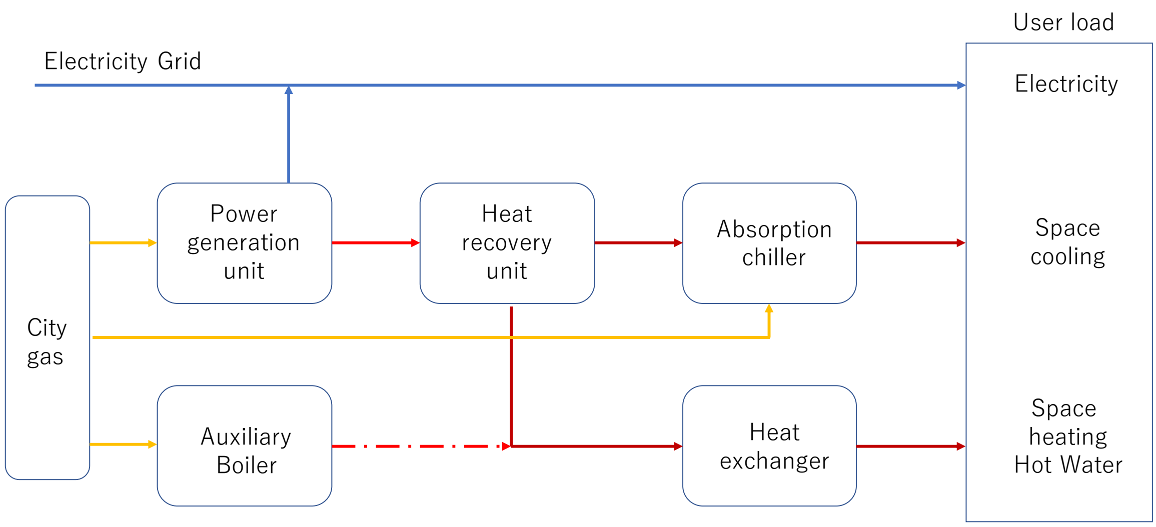

Fig.6-1 A schematic of DER system

Many technologies have been applied into the DER system; for instance, Fuel cell, gas turbines, gas engine, Photovoltaic, wind turbine etc.[18]. For a power generation unit or other units, it can be a combination of different technologies with different capacities. In this paper, the devices in a unit are simplified to combination of a one technology and fixed capacity of one device; but the capacity of whole system can be added or reduced by change the numbers of device. The points of the DER system are considered as the following: 1) The electrical load of the user is met by the power generation unit, firstly; the shortage of the load will purchase from the electricity grid. 2) The heat for the space heating and hot water are met by the heat recovery unit or auxiliary boiler. 3) The space cooling is met with the gas-fired absorption chiller; the thermal comes from the heat recovery unit or the gas-fired. More details of system operation will be discussed in chapter 6.3.

The research flowchart of the reliability and cost analysis process of a redundant design DER system is shown in Fig.6-2.

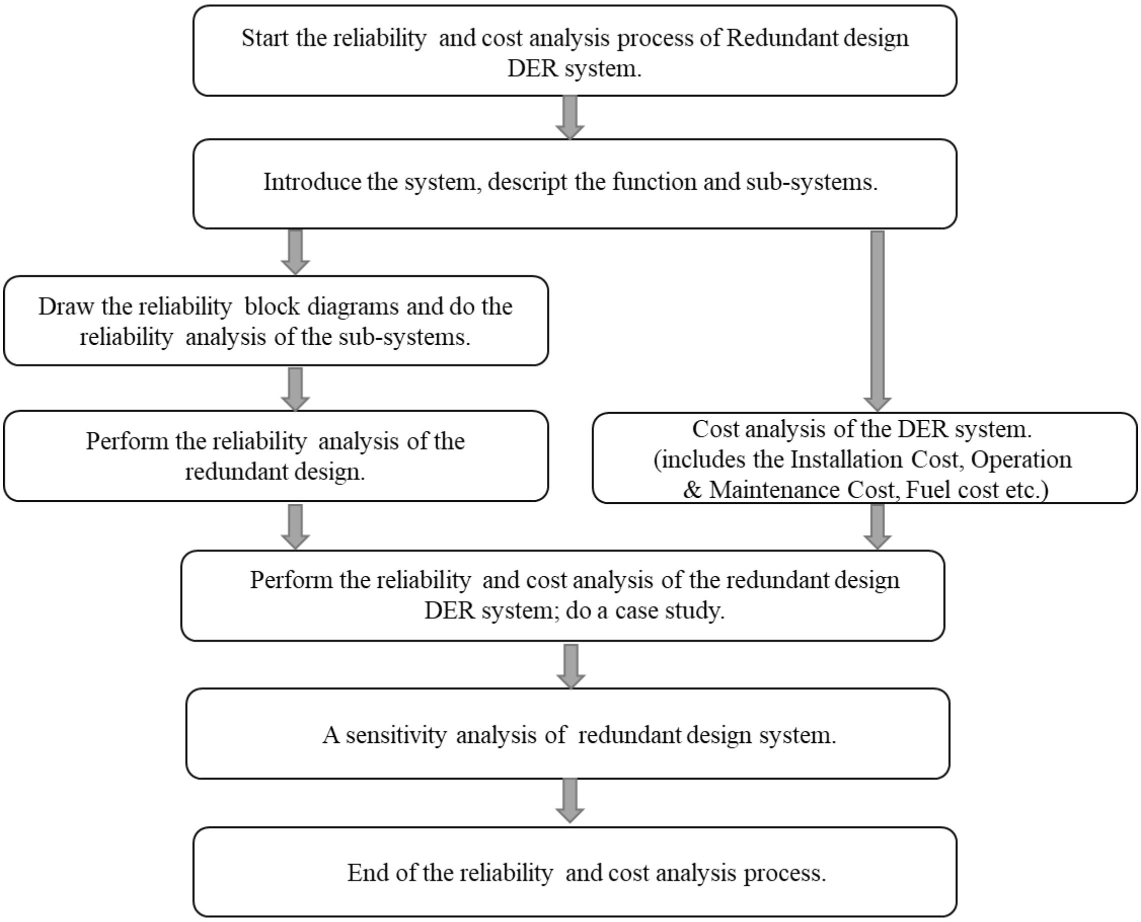

Fig.6-2 The research flowchart of the reliability and cost analysis process of a redundant design DER system

Table 6-1 The nomenclature in Chapter 6

CCHP	combined cooling heating and power
E	electricity supply subsystem
CL	space cooling supply subsystem
H	heating supply subsystem
PGM	power generation module
λ	Failure rate, *failure/1000hours*

μ	repair rate, */1000hours*
MTTF	mean time to failure
MTTR	mean time to repair
MTBF	mean time between failure
R	Reliability
A	Availability
SI	sensitivity index
L	design lifecycle, *year*
t	operation time, *hour*
η	efficiency
COP	coefficient of performance
n	number of base devices
x	number of redundant devices
$P_{gridelec}$	electricity price of electrical grid, *$/kWh*
P_{gas}	price of city gas, *$/m*^{3}
P_u	price of energy (gird electricity or fuel)
Q_i	installed capacity of device i, *kWh*
$Q_{outage,i}$	failed outage capacity of device i, *kWh*
Q_{Epur}	electricity of purchase from electricidal gird, *kWh*
Q_{Gpur}	amount of gas purchase from city gas gird, *kWh*
Q_{Eload}	electricity load, *kWh*
$Q_{E,pgu}$	produced electricity by power generation unit, *kWh*
$Q_{gas,pgu}$	amount of gas used by power generation unit, *kWh*
$Q_{gas,ac}$	amount of gas used by absorption chiller, *kWh*
$Q_{gas,ab}$	amount of gas used by auxiliary boiler, *kWh*
$C_{repair,i}$	mean repair cost of per failure for device i, *$/kW*
C_{Inc}	increased energy cost, *$*
C_{Loss}	fixed loss cost, *$*
C_{Epur}	electricity purchase cost, *$*
C_{Gpur}	gas purchase cost, *$*
C_{cha}	Total cost after the key variables changed, *$*
C_{base}	base cost before the key variables changed, *$*

V_{cha}	variable value after the key variables changed
V_{base}	variable value in before the key variables changed
Q_{CLload}	space cooling load, kWh
Q_{Hload}	heating load, kWh
C_{Total}	total cost, *$*
$C_{O\&M}$	operation and maintenance cost, *$*
C_{Energy}	energy cost, *$*
C_{Inv}	investment cost, *$*
$C_{unitInv,i}$	unit investment cost of device i, *$/kW*
$C_{O\&schM}$	operation & scheduled maintenance cost, *$*
C_{unschM}	unscheduled maintenance cost, *$*
C_{Down}	down time cost, *$*
$C_{unitO\&schM,i}$	unit value of O & scheduled M cost of device i, *$/kW*
Subscript	
gs	city gas supply
pgu	power generation unit
eg	electrical grid
hr	heat recovery unit
ac	absorption chiller
ab	auxiliary boiler
he	heat exchanger
hbs	heat recovery unit with auxiliary boiler
pgm	power generation module
$S1$	scenario 1
$S2$	scenario 2
i	device type

6.3. Reliability Analysis of DER System

Reliability is defined as the ability of an item to perform a required function given conditions for a stated period [23]. In this section, some reliability indices will be introduced firstly, and then the reliably analysis of DER system divide in to three sub-systems: electricity supply sub-system, space cooling sub-system and heating (includes the space heating and hot water) supply sub-system.

6.3.1. Reliability Indices

According to review of theories and methods in Chapter 2, some reliability indices which will used in this chapter are list as followings.

1) Failure rate and mean time to failure

Failure rate (λ) is the frequency that a component or system failed during a period (unit: failure/ unit time). Mean time to failure (MTTF) is the mean operation time of a component or system. The failure rate can be expressed as

$$\lambda = \frac{1}{MTTF} \tag{6-1}$$

2) Repair rate and mean time to repair

Repair rate (μ) is the frequency that the failed component or system gets repaired, the unit of repair rate is same with failure rate. Mean time to repair (MTTR) is the mean repair time of the component or system get repaired. The repair rate can be expressed as

$$\mu = \frac{1}{MTTR} \tag{6-2}$$

3) Mean time between failure

Mean time between failure (MTBF) is the mean passed time from one failure time to next failure. It's a cycle time of the component or system failed and then repaired. Therefore, the MTBF can be expressed as

$$MTBF = MTTF + MTTR = \frac{1}{\lambda} + \frac{1}{\mu} \tag{6-3}$$

For a component or system which has a much higher repair rate than failure rate, the MTBF can be approximated by the MTTF

$$\mathrm{MTBF} \approx \mathrm{MTTF} = \frac{1}{\lambda} \tag{6-4}$$

4) Reliability function

Reliability function is usually expression as survives function, the reliability function of a component or system a time t can be expressed as

$$\mathrm{R(t)} = e^{-\lambda t} \quad (6\text{-}5)$$

4) Availability

Availability is defined as the probability of a component or system can be operating during a period.

$$\mathrm{A} = \frac{MTTF}{MTTF+MTTR} = \frac{\mu}{\lambda+\mu} \quad (6\text{-}6)$$

A CCHP system is a complex system with diverse and vast components, therefore the system reliability indices depend on the reliability of each component of the system. In addition, the components connection modes of a complex system are divided into series and parallel. The DER system reliability indices have been proposed in some literatures[18-20]. Therefore, for a series system, the reliability indices can be expressed as following:

Failure rate of series system

$$\lambda_{system} = \lambda_1 + \lambda_2 + \cdots + \lambda_n \quad (6\text{-}7)$$

Repair rate of series system

$$\mu_{system} = \frac{\lambda_1+\lambda_2+\cdots+\lambda_n}{\lambda_1/\mu_1+\lambda_2/\mu_2+\cdots+\lambda_n/\mu_n} \quad (6\text{-}8)$$

For a parallel system, let $\mathrm{r} = 1/\mu$, the reliability indices can be presented as the following [20]:

Failure rate of parallel system

$$\lambda_{system} \approx (r_1 + r_2 + \cdots + r_n)\lambda_1\lambda_2 \cdots \lambda_n \quad (6\text{-}9)$$

Repair rate of parallel system

$$\mu_{system} = \mu_1 + \mu_2 + \cdots + \mu_n \quad (6\text{-}10)$$

For a DER system, the reliability of the whole system means each sub-system must be reliable [18]. Therefore, the DER system is a series system for each sub-system. the reliability of a CCHP system can be expressed as

$$R_{system} = R_E \cdot R_{CL} \cdot R_H \quad (6\text{-}11)$$

The reliability indices of electricity supply sub-system, space cooling supply sub-system and heating supply sub-system is discussed in the following sections.

6.3.2. Reliability Analysis of Electricity Supply Subsystem

From the electricity supply flow in Fig.6-1, the reliability block diagram of electricity supply sub-system is shown in Fig.6-3. The system reliability of electricity supply sub-system depends on the reliability of the city gas system, power generation unit and electrical grid. There are two scenarios to describe the reliability relationship in the electricity supply sub-system.

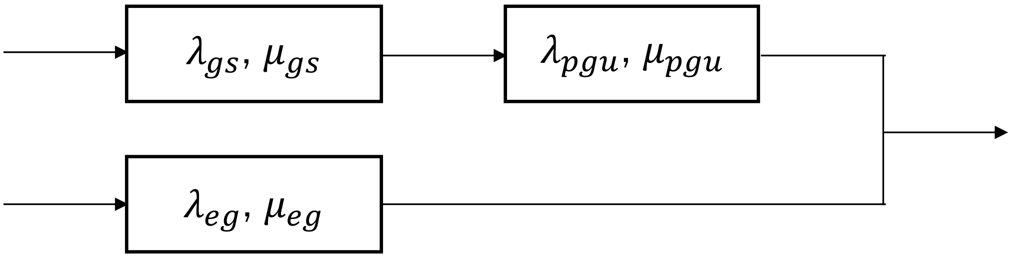

Fig.6-3 Reliability block diagram of electricity supply subsystem

Scenario 1: the electricity produced of the power generation unit cannot meet the demand of user, the electrical load should be jointly met by the power generation unit and electrical grid. In this scenario, the electricity sub-system is a series system, the reliability can be presented as followings.

Failure rate of electricity supply scenario 1:

$$\lambda_{E,S1} = \lambda_{gs} + \lambda_{pgu} + \lambda_{eg} \tag{6-12}$$

Repair rate of electricity supply scenario 1:

$$\mu_{E,S1} = \frac{\lambda_{gs}+\lambda_{pgu}+\lambda_{eg}}{\lambda_{gs}/\mu_{gs}+\lambda_{pgu}/\mu_{pgu}+\lambda_{eg}/\mu_{eg}} \tag{6-13}$$

Availability of electricity supply scenario 1:

$$A_{E,S1} = \frac{1}{\lambda_{gs}/\mu_{gs}+\lambda_{gpu}/\mu_{gpu}+\lambda_{eg}/\mu_{eg}+1} \tag{6-14}$$

Scenario 2: the electricity produced by the power generation unit can meet the demand of user independently, the electrical load is met by the power generation unit or electrical load. The electricity supply sub-system is a parallel system. For this scenario, the reliability of electricity supply sub-system is equal to the reliability of electrical grid or the reliability of power generation unit. The reliability of electrical gird depends on the reliability of power generation plant and gird distribution system. Therefore, we only analyze the reliability and availability of the power generation unit as the followings.

Failure rate of electricity supply scenario 2:

$$\lambda_{E,S2} = \lambda_{gs} + \lambda_{pgu} \tag{6-15}$$

Repair rate of electricity supply scenario 2:

$$\mu_{E,S2} = \frac{\lambda_{gs}+\lambda_{pgu}}{\lambda_{gs}/\mu_{gs}+\lambda_{pgu}/\mu_{pgu}} \tag{6-16}$$

Availability of electricity supply scenario 2:

$$A_{E,S2} = \frac{1}{\lambda_{gs}/\mu_{gs}+\lambda_{pgu}/\mu_{pgu}+1} \tag{6-17}$$

6.3.3. Reliability Analysis of Space Cooling Supply Subsystem

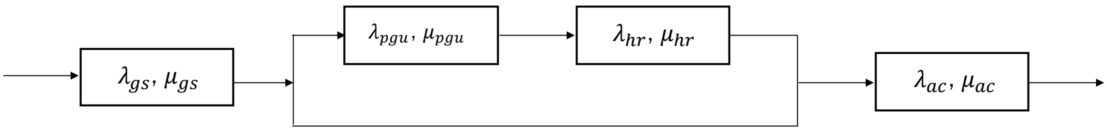

Fig.6-4 Reliability block diagram of space cooling supply sub-system

According to the space cooling supply in Fig.6-1, the reliability block diagram of space cooling supply sub-system shown in Fig.6-4. The reliability of space cooling system depends on the reliability of city gas system, power generation unit, heart recovery unit and gas-fired absorption chiller. For the space cooling sub-system, the thermal demand of space cooling is met by the waste heat form power generation unit or gas-fired. When the recovered heat cannot meet the demand of space cooling load, the shortage can meet by the gas-fired. If the power generation unit or heat recovery unit are failed, the demand of space cooling can meet by the gas-fired. When the gas-fired absorption chillers are failed the space cooling cannot meet. Therefore, the space cooling supply sub-system is a series system, and the gas-fired absorption chiller is the key for the system reliability. The reliability indices can be expressed as the followings.

Failure rate of space cooling supply:

$$\lambda_{CL} = \lambda_{gs} + \lambda_{pgu} + \lambda_{hr} + \lambda_{ac} \tag{6-18}$$

Repair rate of space cooling supply:

$$\mu_{CL} = \frac{\lambda_{gs}+\lambda_{pgu}+\lambda_{hr}+\lambda_{ac}}{\lambda_{gs}/\mu_{gs}+\lambda_{pgu}/\mu_{pgu}+\lambda_{hr}/\mu_{hr}+\lambda_{ac}/\mu_{ac}} \tag{6-19}$$

Availability of space cooling supply:

$$A_{CL} = \frac{1}{\lambda_{gs}/\mu_{gs} + \lambda_{pgu}/\mu_{pgu} + \lambda_{hr}/\mu_{hr} + \lambda_{ac}/\mu_{ac} + 1} \quad (6\text{-}20)$$

6.3.4. Reliability Analysis of Heating Supply Subsystem

According to the heat supply flow in Fig.6-1, the reliability block diagram of heating supply sub-system shown in Fig.6-5. The reliability of heating supply sub-system depends on the reliability of city gas system, power generation unit, heat recovery unit, auxiliary boiler and heat exchanger. When the recovered heat cannot meet the demand of heating, the auxiliary boiler will meet the shortage demand. Therefore, there are two scenarios to present the reliability relationship of the waste heat recovery unit and auxiliary boiler.

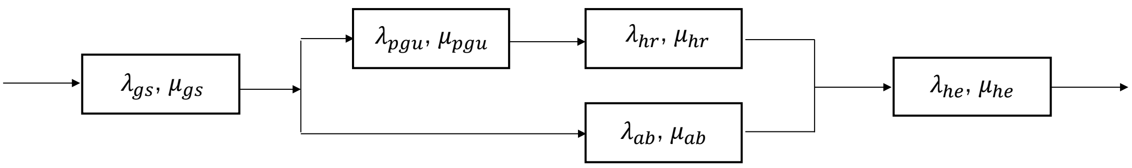

Fig.6-5 Reliability block diagram of heat supply sub-system

Scenario 1: the recovered heat cannot meet the demand of heat; the auxiliary boiler must meet the shortage demand. The auxiliary boiler and the heat recovery unit are in series system. The reliability indices of the heating supply sub-system can be expressed as the followings.

Failure rate of heating supply scenario 1:

$$\lambda_{H,S1} = \lambda_{gs} + \lambda_{pgu} + \lambda_{hr} + \lambda_{ab} + \lambda_{he} \quad (6\text{-}21)$$

Repair rate of heating supply scenario 1:

$$\mu_{H,S1} = \frac{\lambda_{gs}+\lambda_{pgu}+\lambda_{hr}+\lambda_{ab}+\lambda_{he}}{\lambda_{gs}/\mu_{gs} + \lambda_{pgu}/\mu_{pgu} + \lambda_{hr}/\mu_{hr} + \lambda_{ab}/\mu_{ab} + \lambda_{he}/\mu_{he}} \quad (6\text{-}22)$$

Availability of heating supply scenario 1:

$$A_{H,S1} = \frac{1}{\lambda_{gs}/\mu_{gs} + \lambda_{pgu}/\mu_{pgu} + \lambda_{hr}/\mu_{hr} + \lambda_{ab}/\mu_{ab} + \lambda_{he}/\mu_{he} + 1} \quad (6\text{-}23)$$

Scenario 2: the recovered heat can meet the demand of heat; the auxiliary boiler is standby the heating supply sub-system. Therefore, the auxiliary boiler and the heat recovery unit are in parallel system. The total failure rate and repair rate of power generation unit and heat recovery unit:

$$\lambda_{pgu+hr} = \lambda_{pgu} + \lambda_{hr} \tag{6-24}$$

$$\mu_{pgu+hr} = \frac{\lambda_{pgu}+\lambda_{hr}}{\lambda_{pgu}/\mu_{pgu}+\lambda_{hr}/u_{hr}} \tag{6-25}$$

According to reliability indices of the parallel system which has shown in Eq. (6-9) and Eq. (6-10), the failure rate of heat recovery unit with auxiliary boiler standby can be presented as:

$$\lambda_{hbs} \approx (r_{pgu+hr} + r_{ab})\lambda_{pgu+hr}\lambda_{ab} \tag{6-26}$$

$$\mu_{hbs} = \mu_{pgu+hr} + \mu_{ab} \tag{6-27}$$

Therefore, the reliability indices of heating supply sub-system can be expressed as followings.

Failure rate of heating supply scenario 2:

$$\lambda_{H,S2} = \lambda_{gs} + \lambda_{hbs} + \lambda_{he} \tag{6-28}$$

Repair rate of heating supply scenario 2:

$$\mu_{H,S2} = \frac{\lambda_{gs}+\lambda_{hbs}+\lambda_{he}}{\lambda_{gs}/\mu_{gs}+\lambda_{hbs}/\mu_{hbs}+\lambda_{he}/\mu_{he}} \tag{6-30}$$

Availability of heating supply scenario 2:

$$A_{H,S2} = \frac{1}{\lambda_{gs}/\mu_{gs}+\lambda_{hbs}/\mu_{hbs}+\lambda_{he}/\mu_{he}+1} \tag{6-31}$$

6.4. Reliability Analysis of Redundant Design

The reliability analysis of the DER system has been analyzed in Chapter 3. Above analysis result shows that the most importance devices of the system reliability include power generation unit, gas-fired absorption chiller and heat exchanger. When the power generation unit, gas-fired absorption chiller and heat exchanger failed, the electricity supply, space cooling supply and heating supply will be interrupted respectively. The reliability of power generation unit is the key of the reliability of all the sub-system in the DER system. A redundant design of devices can improve the system reliability [24]. The reliability indices of the DER system shown in Table 6-2. Table 6-2 presents that the failure rate of the power generation unit and absorption chiller are higher than other devices, the availability of power generation unit and absorption chiller are lower than 0.999. However, the availability of auxiliary boiler and heat exchanger are higher than 0.999. The availability of the heat recovery unit is approximately 0.999. Thus, the redundant design of power generation unit and absorption chiller should be considered, but the redundant design of auxiliary boiler and heat exchanger may not be of great significance for improving the availability of DER system.

Table 6-2 The reliability indices of DER system [18-20]

Name of device	Failure rate (per thousand hours)	Repair rate (per thousand hours)	Availability
Power generation module	0.66767	31.00	0.97892
Heat recovery unit	0.05071	27.78	0.99818
Absorption chiller	0.219375	20.83	0.98958
Auxiliary boiler	0.03875	41.67	0.99907
Heat exchanger	0.03525	41.67	0.99915
Electric chiller	0.038052	20.83	0.99818
Electrical grid	0.12742	41.67	0.99695
City gas	0.11986	41.67	0.99713

6.4.1. Redundant Design of Power Generation Unit

For the redundant design of power generation unit in the DER system, the power generation unit is assumed to be parallel system composed of multiple power generation module (PGM). The power generation modules are independent in the power generation unit. The structure of power generation unit with n PGM and x PGM is presented in Fig.6-1.

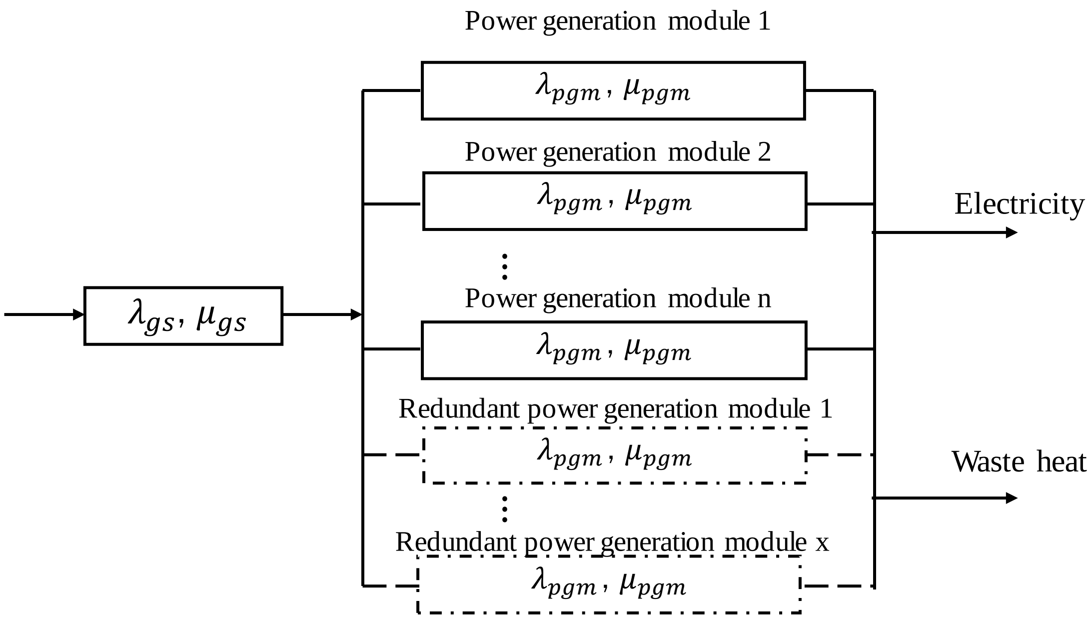

Fig.6-6 The structures of power generation unit with n PGM and x PGM

For a parallel and independent power generation unit with n+x power generation modules, the system is satisfying the k-out-of-n: G model. This model is defined as: for an n-component system that good components (or is "works") if and only if at least k of the n components good (or are work) is called a k-out-of-n: G model [25]. Therefore, the reliability of the power generation unit can be presented as the following:

$$R_{n+x} = \sum_{j=n}^{n+x} \binom{n+x}{n} R^{i} (1-R)^{n+x-j} \tag{6-32}$$

For a parallel and independent system, the repair rate is equal to the repair rate of power generation module; the failure rate of the n+x parallel power generation unit can be expressed as:

$$\lambda_{n+x} = \frac{1}{MTBF_{n+x}} = \frac{1}{\frac{1}{\lambda}\sum_{j=n}^{n+x}\frac{1}{j}} \tag{6-33}$$

The Availability of the n+x parallel power generation unit can be expressed as:

$$A_{n+x} = \sum_{j=n}^{n+x} \binom{n+x}{n} A^{j} (1-A)^{n+x-j} \tag{6-34}$$

When the redundant design is applied in the power generation unit, the variation of failure rate and availability of power generation unit are shown in Fig.6-7 and Fig.6-8 respectively. Fig.6-7 shows that the failure rate of power generation unit is reduced by adding the redundant power generation module; but with the increase of redundant power generation modules, the reduction range of failure rate becomes increasingly smaller. Fig.6-8 shows that the availability of power generation unit is increased by adding the redundant power generation module; when the redundant modules were added to 2 and 3 (x=2 or x=3), the availability of power generation unit is trend to 100%.

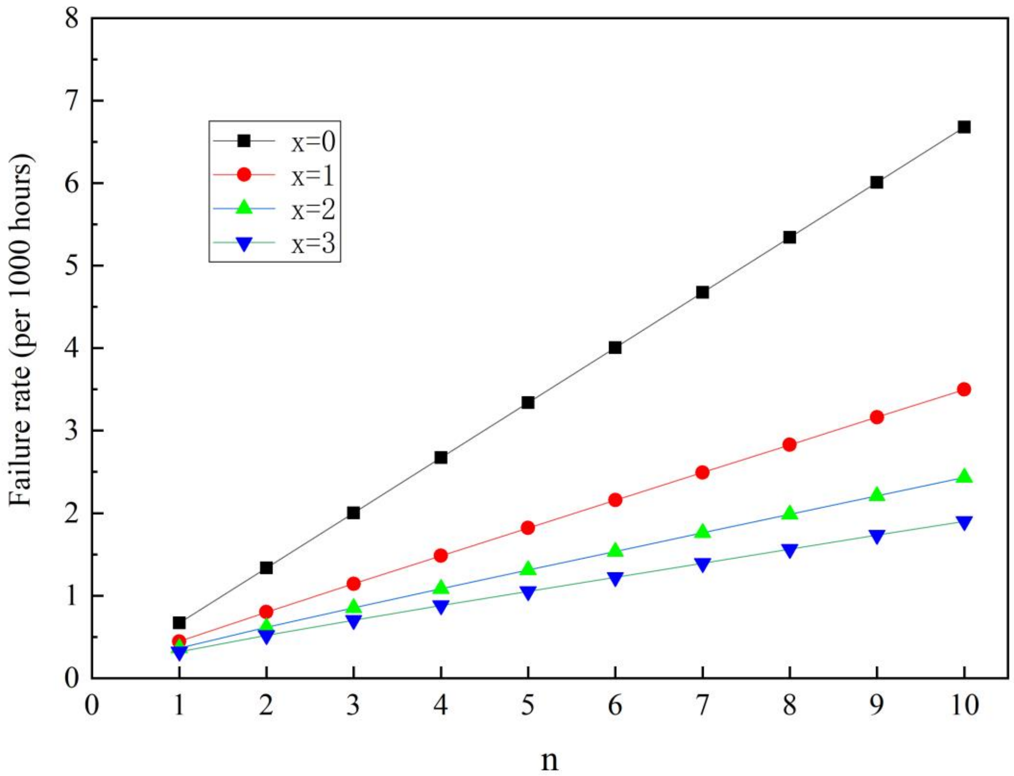

Fig.6-7 Failure rate variation of an n+x redundant design of power generation unit

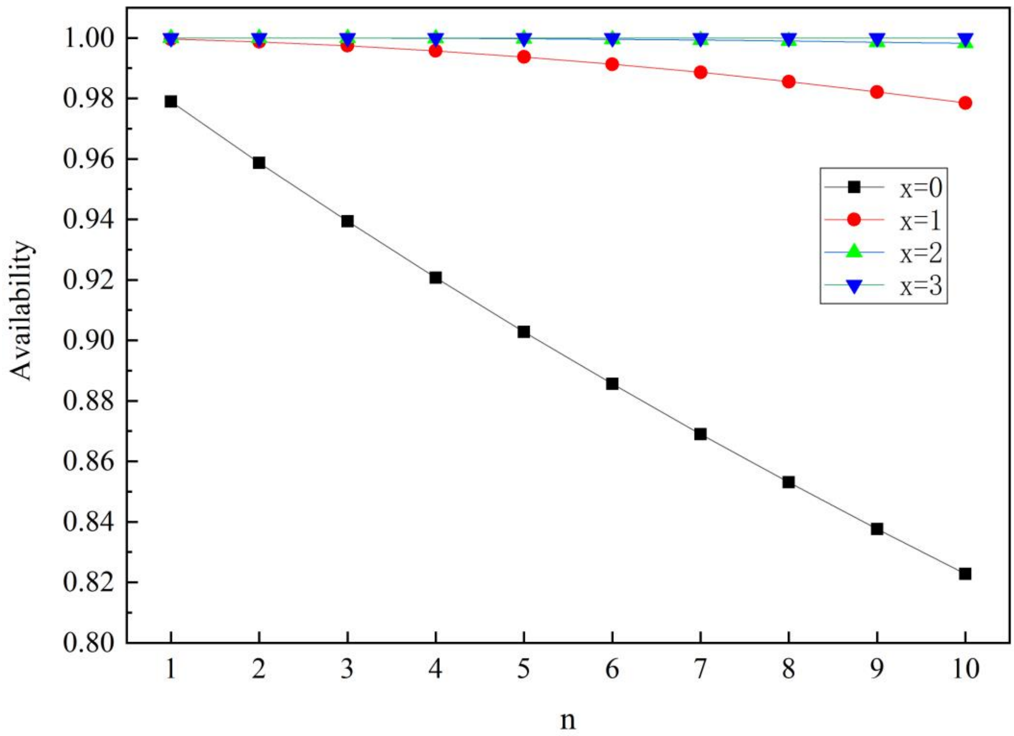

Fig.6-8 Availability variation of an n+x redundant design of power generation unit

6.4.2. Redundant Design of Absorption Chiller

When the redundant design is applied in the absorption chiller of space cooling sub-system, the variation of failure rate and availability of an m+y redundant design of absorption chillers are presented in Fig.6-9 and Fig.6-10. Fig.6-10 shows that the availability of absorption chiller is increased by adding the redundant number of absorption chiller; when the redundant absorption chiller was added to 2 (y=2), the availability of power generation unit is trend to 100%. When the number of redundant absorption chiller was added to 3(y=3). The availability of absorption chiller is equal to 100%, but it is an ideal state.

The result of redundant design of power generation unit and absorption chiller shows that the availability of a system can be improved by increase the redundant devices; and regardless of the value of n (or m), the failure rate and availability of system will not change much after the redundant devices added to a value (x=3 or y=2). In addition, the number of redundant devices depends on the failure rate of device; if the failure rate is higher, the greater number of redundant devices required, and vice versa. Although the reliability analysis of redundant design provides the information for improving the reliability of the system by adding the redundant devices. However, when adding the redundant devices into the system, the investment cost and O&M cost of system will be huge. Therefore, the cost analysis of the redundancy design of the CCHP system in next Section.

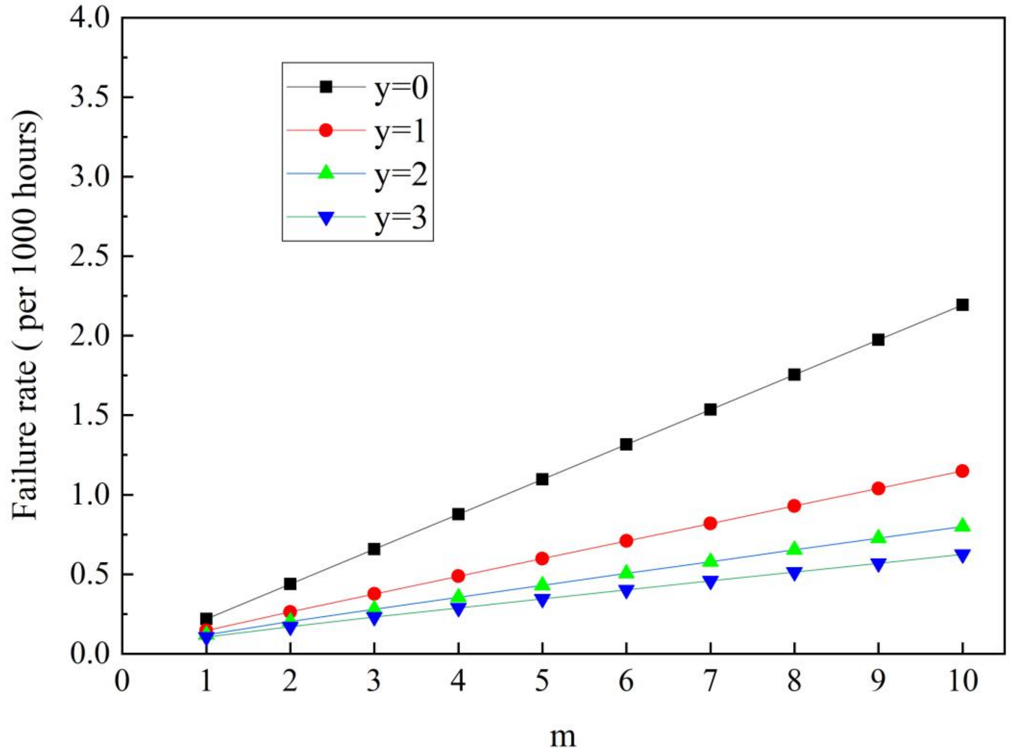

Fig.6-9 Failure rate variation of an m+y redundancy design of absorption chiller

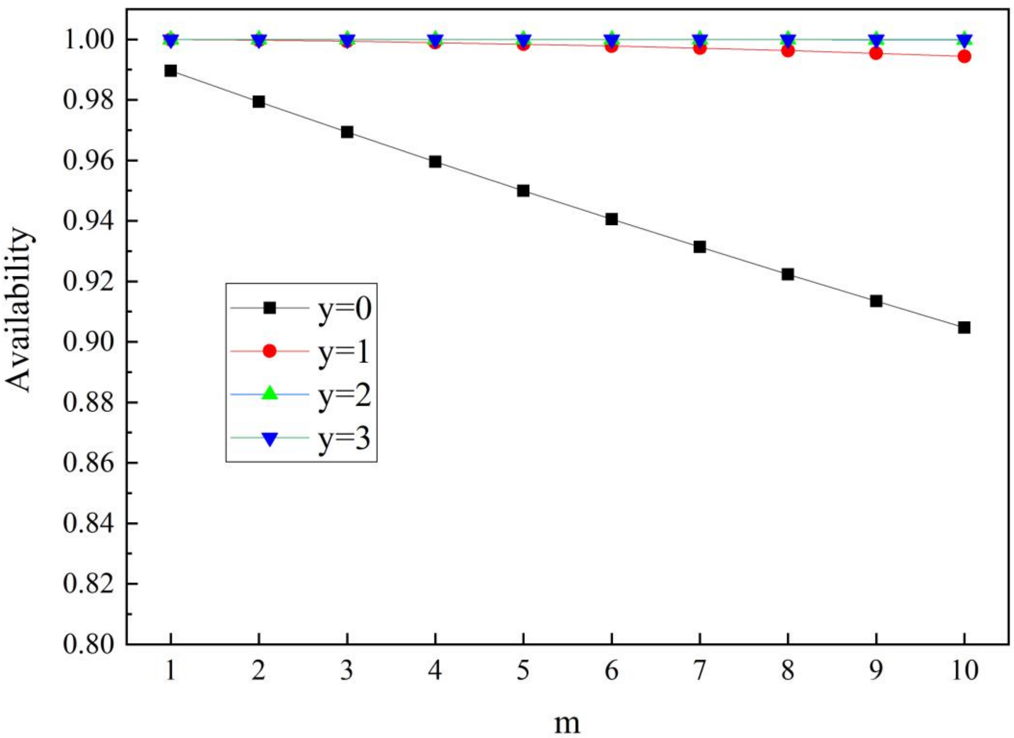

Fig.6-10 Availability variation of an m+y redundancy design of absorption chiller

6.5. Cost analysis of DER System

Minimum total lifecycle cost is the economic objective of optimization of a DER system. the diagram of total cost of a DER system is presented in Fig.6-11. As shown in Fig.6-11, the total cost of DER system includes the investment cost, operation & maintenance cost and energy cost.

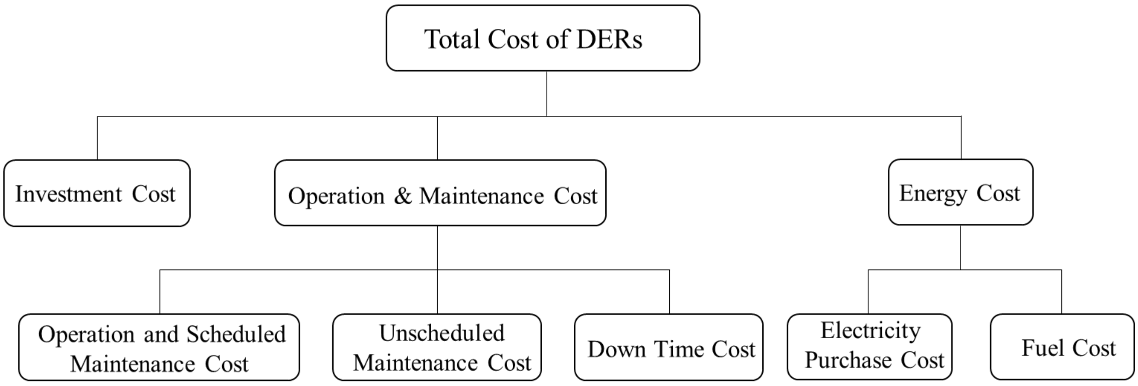

Fig.6-11 Diagram of total cost of DER system

The total cost of DER system can be expressed as:

$$C_{Total} = C_{Inv} + C_{O\&M} + C_{Energy} \tag{6-35}$$

The investment cost of the system includes the cost of all the devices. Therefore, the investment cost of the devices can be presented as:

$$C_{Inv} = \sum_i C_{unitInv,i} \times Q_i \times (1 + \frac{x_i}{n_i}) \tag{6-36}$$

Where C_{Inv} is the total investment cost; i is the device type, for instance, power generator, absorption chiller and so on; $C_{unit,i}$ is the unit investment cost of device i (unit: \$/kW). Q_i is the installed capacity of device i(kW). n_i is the number of the device i, x_i is the number of the redundant device i.

The O&M cost of a DER system includes the operation & scheduled maintenance cost ($C_{O\&schM}$), unscheduled maintenance cost (C_{unschM}) and down time cost (C_{Down}). The O&M cost is presented as follow.

$$C_{O\&M} = C_{O\&schM} + C_{unschM} + C_{Down} \tag{6-37}$$

The operation & scheduled maintenance cost depend on the capacity of devices and the maintenance strategy. The scheduled maintenance is performed in order to prevent faults from occurring [26]. It is usually treated as a constant in the design period. The operation & scheduled maintenance cost can be presented as:

$$C_{O\&schM} = \sum_i C_{unitO\&schM,i} \times Q_i \times L_i \tag{6-38}$$

Where $C_{unitO\&schM,i}$ is the unit value of operation & scheduled maintenance cost of device i (unit: \$/kW); L_i is the design lifecycle.

The unscheduled maintenance cost also can be called the corrective maintenance cost; the unscheduled maintenance cost is occurred after the failure [27]. Thus, the unscheduled maintenance cost is the cost for repair and recovery the device from the failed state to operation state. So, the unscheduled maintenance cost the depends on the failure rate and repair rate of the device or system.

$$C_{unschM} = \sum_i C_{repair,i} \times \lambda_i \times L_i \tag{6-39}$$

Where $C_{repair,i}$ is the mean repair cost of per failure for the device i (unit: \$/failure).

The down time cost of power outage for a power supply is difficult to estimate, generally deviled into direct and indirect costs [28]. The indirect for the DER system is difficult to defined. However, the direct down time cost of the energy supply system is composed of two parts, one is the fixed loss cost of the investment of devices, another is increased energy cost. Increased energy cost is defined that the cost should be paid in order to meet the insufficiency of energy load when failed occurred [18]. The increased energy cost can be expressed as:

$$C_{Inc,i} = P_u \times Q_{outage,i} \times MTTR_i \times \lambda_i \times L_i \tag{6-40}$$

Where $C_{Inc,i}$ is the increased energy cost of device i (\$); P_u is the price of energy (gird electricity or fuel); $Q_{outage,i}$ is the failed outage capacity of device i.

The fixed loss cost (C_{Loss}) is defined as the average investment cost of device i during design lifecycle. The fixed loss cost can be presented as:

$$C_{Loss,i} = C_{Inv,i} \times MTTR_i \times \lambda_i \tag{6-41}$$

Where $C_{Inv,i}$ is the investment cost of device i.

Therefore, the down time cost of system can be presented as:

$$C_{Down} = \sum_i (P_u \times Q_{outage,i} \times L_i + C_{Inv,i}) \times MTTR_i \times \lambda_i \tag{6-42}$$

The total energy cost of system is equal to the electricity purchase cost plus the fuel cost. Hence, the total cost of energy can be expressed as:

$$C_{Energy} = C_{Epur} + C_{Gpur} \tag{6-43}$$

The electricity purchase cost (C_{Epur}) and the fuel purchase cost (C_{Gpur}) can be presented as the followings.

$$C_{Epur} = \sum_t P_{gridelec} \times Q_{Epur}(t) \tag{6-44}$$

$$C_{Gpur} = \sum_t P_{gas} \times Q_{Gpur}(t) \tag{6-45}$$

Where the $P_{gridelec}$ is the electricity price of electrical grid ($/kWh); P_{gas} is the price of city gas ($/m^3); Q_{Epur} is the electricity of purchase from electricidal gird (kWh); Q_{Gpur} is the amount of gas purchase from city gas gird; t is the operation time (unit: hour).

Here, the energy balance of energy should be discussed. The electricity balance is presented as the follows.

$$Q_{Epur}(t) = Q_{Eload}(t) - Q_{E,pgu}(t) \tag{6-46}$$

Where the Q_{Eload} is the electricity load of the user. $Q_{E,pgu}$ is the produced electricity by the power generation unit. Eq. (43) is satisfied to $Q_{Eload}(t) \geq Q_{E,pgu}(t)$.

$$Q_{Gpur}(t) = Q_{gas,pgu}(t) + Q_{gas,ac}(t) + Q_{gas,ab}(t) \tag{6-47}$$

Where the $Q_{gas,pgu}$ is the amount of gas used by the power generation unit. $Q_{gas,ac}$ is the amount of gas used by the gas-fired absorption chiller. $Q_{gas,ab}$ is the amount of gas used by the auxiliary boiler.

The balance of space cooling load can be presented as:

$$Q_{CLload}(t) = Q_{gas,pgu}(t) \cdot (1 - \eta_{pgu}) \cdot \eta_{rec} \cdot COP_{ac} + Q_{gas,ac}(t) \cdot \eta_{ac} \tag{6-48}$$

The balance of heating load can be presented as:

$$Q_{Hload}(t) = Q_{gas,pgu}(t) \cdot (1 - \eta_{pgu}) \cdot \eta_{hr} \cdot \eta_{he} + Q_{gas,ab}(t) \cdot \eta_{ab} \cdot \eta_{he} \tag{6-49}$$

Where the Q_{CLload} and Q_{Hload} is the space cooling and heating load of user respectively. η_{pgu}, η_{hr}, η_{ac}, η_{he} and η_{ab} are the efficiency of power generation unit, heat recovery unit, gas-fired absorption chiller, heat exchanger and auxiliary boiler. COP_{ac} is the coefficient of performance of gas-fired absorption chiller.

For the total cost of a DER system, when the redundant design is applied, the investment cost and operation & scheduled maintenance cost will be increased, and the unscheduled maintenance cost and down time cost will be reduced. It may have some relationship between the total cost and reliability of the DER system.

6.6. Case Study

In order to analyze the effect of the redundant design of the DER system on system reliability and life cycle cost, a university campus data is selected for case study. This campus is located in Kitakyushu Science and Research Park [29], Kitakyushu City, Japan; the campus has been applied the

DER system from 2001, some studies have used the campus as the object of case study [6, 18, 30].

6.6.1. Energy Demand

In this case, the hourly load demand of 8760 hours for electricity, space cooling and heating (space heating and hot water) are selected based on the energy load in 2009 (shown in Fig.6-12). The total energy demand, peak value and time of operation are presented in Table 6-3. The peak value of electric demand, heating demand and space cooling demand are 1790.0 kW, 2972.5 kW, 2040.8kW respectively. the peak values are used to determine the capacity of the power generator and energy exchangers.

Table 6-3 The energy demand in one year

	Electric demand	**Heating demand**	**Space cooling demand**
Total (kWh)	7.0876×10^6	2.1394×10^6	2.4574×10^6
Peak value (kW)	1790.0	2972.5	2040.8
Time of operation (h)	8760	3551	3717

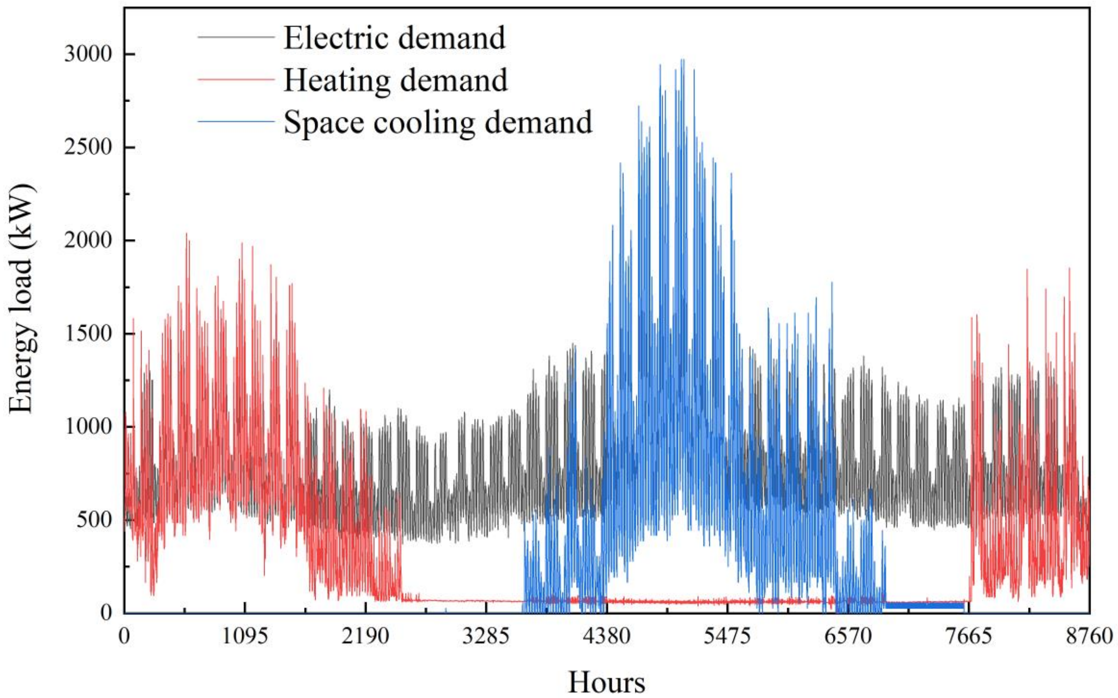

Fig.6-12 Hourly electricity, heating and space cooling demand in one year

6.6.2. Description of Redundant DER System

As shown in Fig.6-1, a DER system includes power generation unit, heat recovery unit, absorption chiller unit, auxiliary boiler and heat exchanger. In addition, a conventional energy supply system is used to compare with the redundant design DER system. for the conventional energy supply system, the electrical demand is met by the city electrical grid, the space cooling demand is met by the electrical chiller, and the heating demand is met by the boiler and heat exchanger. The description of redundant design DER system in this case study are presented as the following.

1) *Capacity.* We assume that only the capacity of power generation unit is changed by changing the number of generator modules. A capacity of power generation module is 100kW, and the composition of the power generation modules is shown in chapter 6.4.1. The capacity of heat recovery unit varies with the capacity of the power generation unit. And the capacity of absorption chiller, auxiliary boiler and heat exchanger is assumed to meet the peak demand independently.

2) *Cost parameter.* The cost parameters of the main devices are shown in Table 6-4. The data are investigated from the previous studies; the operation & scheduled maintenance cost data of heat recovery unit, auxiliary boiler and heat exchanger are assumed 4% of the investment cost [31]. The unit energy price is shown in Table 6-5.

Table 6-4 The cost parameters of the main devices [18, 32-35]

	Main equipment	Investment cost ($/kW)	Operation & Scheduled Maintenance Cost ($/kW·yr)	Mean repair cost ($/ kW·failure)
1	Power generation module	1195	120	38.0
2	Heat recovery unit	130	5.2 [a]	25.1
3	Absorption chiller	197	15	3.5
4	Auxiliary boiler	62	2.48 [a]	7.0
5	Heat exchanger	33	1.32 [a]	6.8
6	Electric chiller	230	14	---

a: operation & scheduled maintenance cost is assumed 4% of the investment cost [31].

4) *Technical parameter.* The efficiency and coefficient of performance (COP) of the main devices is presented in Table 6-6.

5) *Reliability indices.* The reliability indices have been shown in Table 6-1. The data are investigated from the previous studies. The unit of failure rate and repair rate is the amount of failure or repair per thousand hours.

6) *Redundant design of CCHP system.* In this case study, only the power generation unit adopts the redundant design. The capacity of power generation unit is added from 100kW to 800kW (n=1 to 8). According to the analysis result in chapter 6.4.1. The availability of power generation unit is trend of 100% when the number of redundant power generation modules is equal to 3 (x=3). Therefore, the number of redundant power generation modules is performed from 1 to 3 (x=1 to 3). The other devices are non-redundant design.

Table 6-5 The unit energy price

Item	**City gas**	**Electrical grid**
Price	0.81 $/m^3	0.22$/kWh

Table 6-6 The Technical parameters of main device [36, 37]

	Main equipment	**Parameter**	**Symbol**	**Value**
1	Power generation module	Efficiency	η_{pgm}	0.3
2	Heat recovery unit	Efficiency	η_{rec}	0.8
3	Gas-fired absorption chiller	COP	COP_{ac}	0.7
		Efficiency of gas-fired	η_{ac}	0.8
4	Auxiliary boiler	Efficiency	η_{ab}	0.8
5	Heat exchanger	Efficiency	η_{he}	0.8
6	Electric chiller	COP	COP_{ec}	3.0

6.6.3. Result and Discussion

According to the methods of reliability and cost analysis which have been introduced in chapter 6.4 and chapter 6.5, the total lifecycle cost of non-redundant and redundant design DER system is shown in Fig.6-13. Fig.6-13 shows that with the increase of the capacity, the total cost of DER system is increased. However, from the 200kW ($n \geq 2$) capacity, the total cost of redundant design is less than the total cost of non-redundant design of DER system. The result of reliability analysis has shown that the redundant design can reduce the failure rate in chapter 6.4. According to the Eq. (6-36) and the Eq. (6-38), the investment cost and operation & scheduled maintenance cost will be increased when the capacity is increased. And according to the Eq. (6-39) and Eq. (6-42), the unscheduled maintenance cost and down time cost will be reduced when the failure rate is reduced. Thus, the total cost reduced of redundant design is because that the reducing of unscheduled maintenance cost and down time cost is more than the increasing of the investment cost and scheduled maintenance cost. In the 100kW capacity ($n=1$), the increasing of the investment cost and operation & scheduled maintenance cost is more than the reducing of the unscheduled maintenance cost and down time cost. In the 300kW capacity, the total cost of non-redundant design DER system is close to conventional systems, the cost redundant design DER system is less than the conventional system, obviously. In addition, the total cost of 300kW capacity with 2 redundant PGM ($n=3$, $x=2$) is lower than the cost of 300kW capacity with 3 redundant PGM ($n=3$, $x=3$). From an economic perspective, the 300kW capacity with 2 redundant PGM ($n=3$, $x=2$) is better than the 300kW capacity with 3 redundant PGM ($n=3$, $x=3$). But the availability of the 300kW capacity with 2 redundant PGM ($n=3$, $x=2$) is less than the 300kW capacity with 3 redundant PGM ($n=3$, $x=3$). It should have a balance between the reliability and cost.

A cost compression of non-redundant and redundant design of the 300kW capacity DER system is shown in Fig.6-14. The cost of non-redundant design shows that the most of cost in DER system is the unscheduled maintenance cost. And the unscheduled maintenance cost can be reduced so observably, because of the reducing of failure rate. For the redundant design, the investment cost and operation & scheduled maintenance cost is increased with the number of redundant devices increasing. The variation of unscheduled maintenance cost and down time cost is more less with the number increased of redundant devices. The total investment and operation & scheduled maintenance cost are trending to level off; it may be increased after the availability of power generation unit is equal to 100%; and the curve of total investment and operation & scheduled maintenance cost is a bathtub curve.

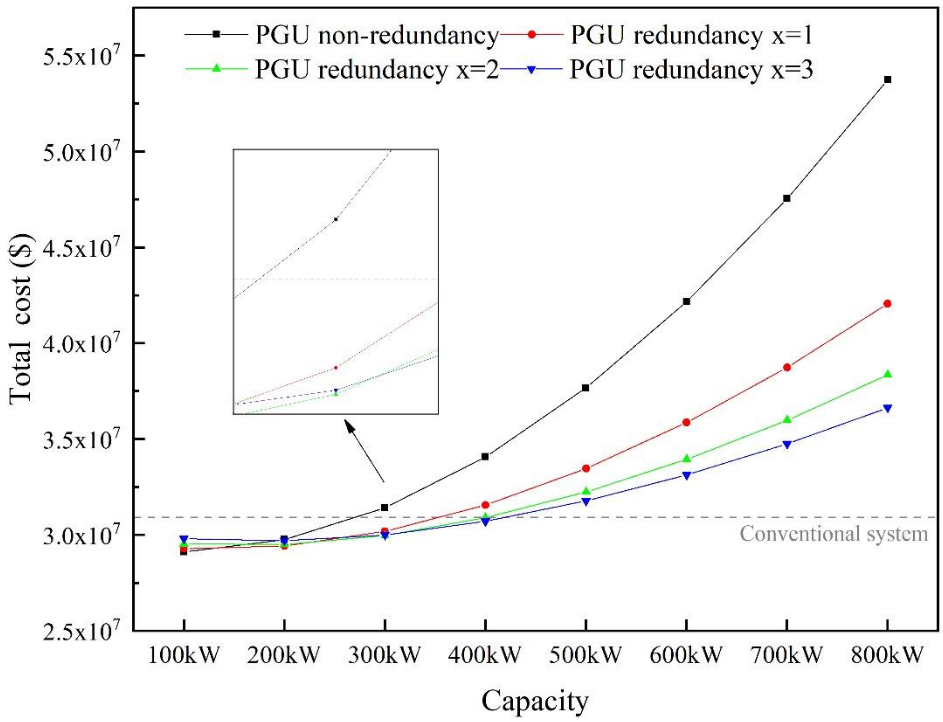

Fig.6-13 The total cost of non-redundant and redundant design of DER system

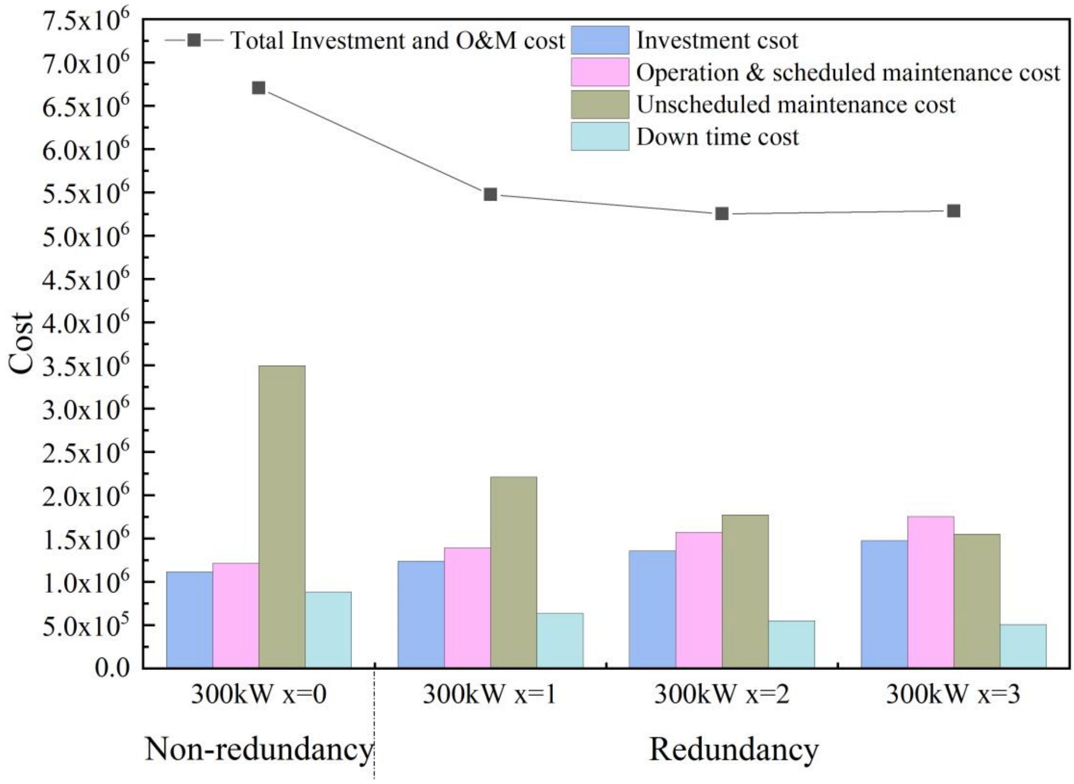

Fig.6-14 A cost compression of non-redundant and redundant design of the 300kW capacity DER system

For the 300kW capacity DER system, the electrical demand is met by the power generation unit and electrical grid, the space cooling demand is met by heat recovery unit and city gas fired, the heating demand is met by the heat recovery unit and auxiliary boiler. Therefore, according to the reliability analysis in Section 3, the reliability of the E sub-system, CL sub-system and H sub-system can be calculated by the Eq. (6-13), Eq. (6-19) and Eq. (6-22) respectively. Fig.6-15 shows the reliability result of non-redundant and redundant design of the 300kW capacity DER system. The result shows that the redundant design can improve the availability observably, especially for the availability of the whole DER system. The magnitude of increasing from non-redundant design to x=1 redundant design is more than the magnitude of increasing from x=2 redundant design to x=3. The result presents that the magnitude of increasing is more and more less with the number increasing of redundant design. Compare the availability of the E subsystem, CL subsystem and H sub-system, the availability of the CL subsystem is less than the E sub-system and H sub-system that because the failure rate of absorption chiller is higher than the failure rate of auxiliary boiler and heat exchanger.

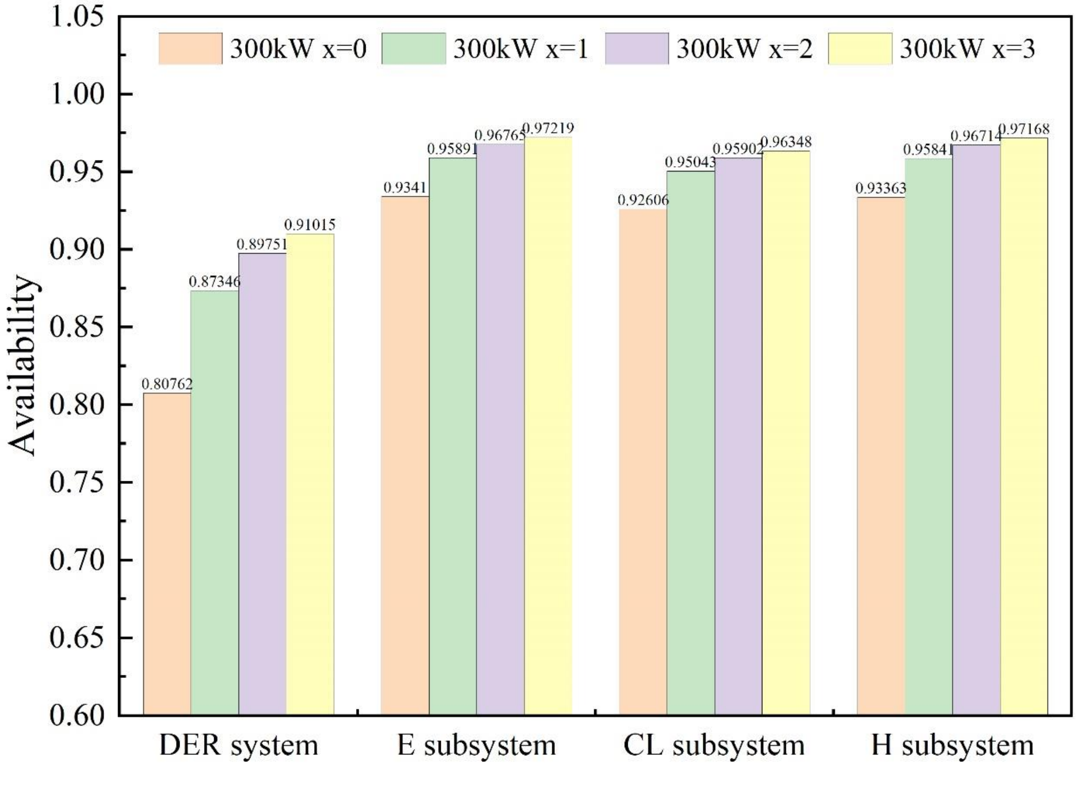

Fig.6-15 The availability result of non-redundant and redundant design of the 300kW capacity DER system

6.7. Sensitivity Analysis

In the above case study, we find that the redundant design can reduce the total cost of DER system, the cost and availability of the 300kW capacity DER system has been analyzed. In this section, sensitivity analysis is carried out to investigate the impact of parameter variation on the presented reliability and cost analysis model.

The steps of conducting sensitivity analysis of the important parameters to the reliability and cost analysis as the following.

Step 1, identify the key variables.

Step 2, calculate the effects of changing variables.

According to the cost analysis equations in chapter 6.5, the key variables of the reliability and cost analysis model is shown in Table 6-7. In order to quantify the sensitivity of the key variables, a sensitivity index (SI) is calculated for each key variable to the total cost of DER system. The SI is expressed as follow[24].

$$\mathrm{SI} = \frac{(C_{base} - C_{cha})/C_{base}}{(V_{base} - V_{cha})/V_{base}} \tag{6-50}$$

Where, SI is the sensitivity index; the C_{cha} is the total cost after the key variables changed, C_{base} is the base cost before the key variables changed; the V_{cha} is the variable value after the key variables changed in the sensitivity test; and V_{base} is the variable value in before the key variables changed.

The effect of the changing the key variables to non-redundant and redundant design DER system is analyzed. The key variables are changed as shown in Table 6; each key variable is added 10% based on the base case. And the 300kW capacity DER system is adopted as the base case.

The sensitivity analysis results of non-redundant and redundant design of 300kW capacity DER system is presented in Fig.6-16. The SI results show that the total cost of non-redundant design DER system is most sensitive to the PGU failure rate. The SI value of PGU failure rate is 0.11407, that means the total cost is increased during the PGU failure rate increasing. In addition, the SI value of mean repair cost is 0.11132, it also has the high effect of the total cost in non-redundant design DER system (x=0). The SI value of the PGU repair rate in non-redundant design DER system is -0.01688, that mean the total cost is reduced during the PGU repair rate increasing. that's because the increase in the PGU repair rate shortens the MTTR of PGU, as shown in Eq. (6-2). For the redundant design of DER system, the SI values of mean repair cost, PGU failure rate and PGU repair rate is reduced with the number of redundant devices increasing. That means the effect of the three key variables is reducing with the number of redundant devices increasing. However, the effect of investment cost and operation & scheduled maintenance cost is increased with the number of redundant devices increasing. But the SI values of investment cost and operation & scheduled maintenance cost are not more than

0.06. Thus, the key variables of the total cost in reliability and cost analysis model are mean repair cost and PGU failure rate.

Table 6-7 The key variables of the reliability and cost analysis model

Key variables	Change
Investment cost ($/kW)	+10%
Operation & scheduled maintenance cost ($/kW·yr)	+10%
Mean repair cost ($/kW·failure)	+10%
PGU failure rate (per thousand hours)	+10%
PGU repair rate (per thousand hours)	+10%

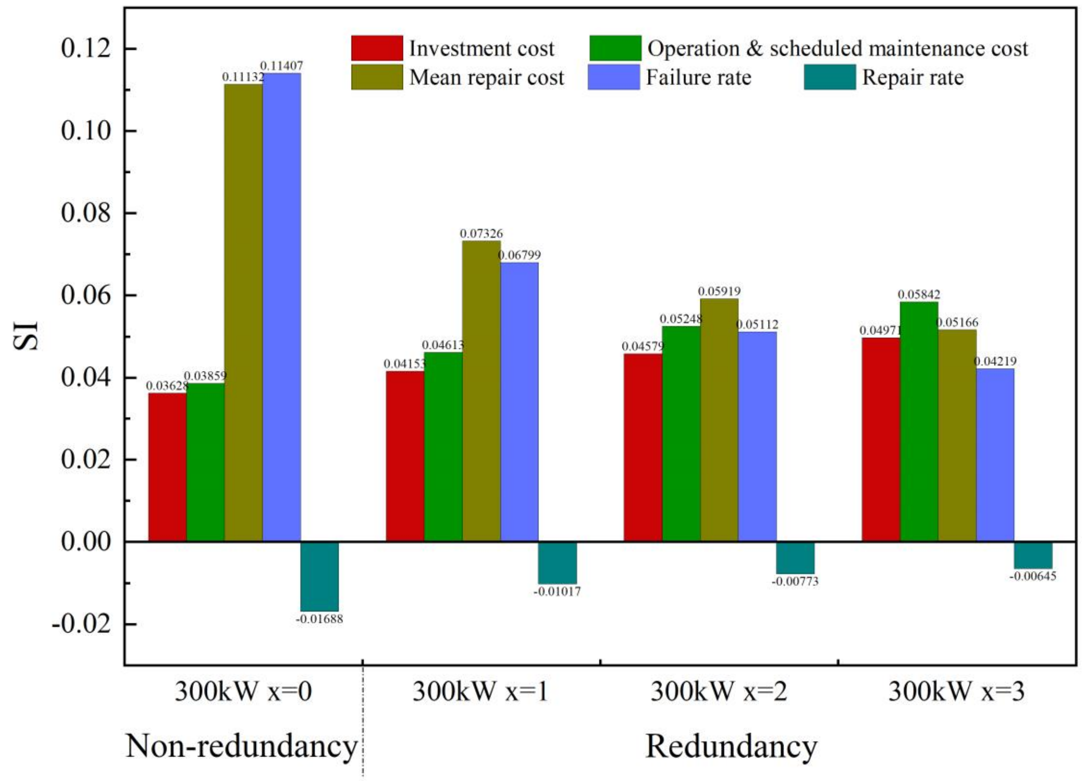

Fig.6-16 The sensitivity analysis results of non-redundant and redundant design of 300kW capacity DER system

6.8. Summary

This chapter proposed a model for reliability and cost evaluation of non-redundant and redundant design DER system. The reliability analysis approach and cost calculation method based on the reliability indices are developed. The effect of redundant design for reliability indices is evaluated. Two cost of a system which relate to failure rate and MTTR (unscheduled maintenance cost and down time cost) are introduced and used to perform the total cost analysis. A case study for total cost of non-redundant and redundant design DER system is performed.

The result shows that the redundant design can improve the availability observably, especially for the unit with low reliability. When the failure rate of the power generation module is higher, the more redundant modules are needed in order to improve the availability value to 100%. The total cost of the DER system can be reduced in the redundant design if the increased cost of the investment cost and operation & scheduled maintenance cost is lower than the reduced cost of unscheduled maintenance cost and down time cost. The main effect of the redundant design is to reduce the unscheduled maintenance cost and down time cost because of the reduction of failure rate and MTTR. It should have a balance between the reliability. There is a balance between reduced maintenance cost due to increased reliability and increased costs due to redundant design. This result can provide reference for the design of the DER system.

The redundant design of the DER system can improve the availability of the sub-systems and whole system. For a normal operation strategy of DER system, the system can be regarded as a series system. The reliability of each unit in the DER system has a great impact on the whole system or sub-system. The redundant design is a way to improve the reliability and availability of the unit in the DER system.

The most effect parameters for total cost of non-redundant DER system is the failure rate and mean repair cost of the device. The redundant design can reduce the failure rate, but the mean repair cost depends on the severity of failure. Therefore, the effect of maintenance strategies, maintenance level and management should be investigated and analyzed in the future in order to improve the availability and reduce the total cost.

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Chapter 7. Conclusions

Maintenance management and reliability are the key factors of an equipment or a system to make the equipment or system complete the function within a production period. The DER system has been developed and applied for decades, and the application of the DER system still has a growing trend. However, the DER system is a complex and repairable system with the power generation, energy conversion and energy management. Thus, the DER system may contain a lot of components, and to meet a variety of functions. Each component has a different mode of operation and maintenance. If the maintenance management resources are insufficient or the maintenance strategy is unreasonable, it may cause equipment or system failure and loss; if the maintenance management resources are excessive, it can result the waste of cost. Therefore, this research focus on the maintenance management and reliability analysis of DER system. For the maintenance management, we are committed to finding an assessment method of maintenance priority to identify the weak components in the system. According to the assessment result to allocate maintenance management resources, it can help the managers make the reasonable maintenance strategy, and reduce the maintenance cost. For the reliability analysis, a reliability analysis was applied to the DER system, and a reliability design model was evaluated. The conclusions of this research are summarized as follows.

In chapter one, **Previous Study and Purpose of This Study**, investigated the current development situation of the DER system; and the technologies that can be applied to distributed energy systems are introduced. As well as the development history and concepts reliability analysis and maintenance management are presented. The previous studies about the reliability and maintenance management research are reviewed.

In chapter two, **Theories and Methods of Maintenance Management and Reliability**, reviewed the reliability concepts, reliability analysis methods, maintenance analysis theories and methods. Some reliability analysis methods are introduced and compared, the FMEA method is a suitable method to perform the maintenance analysis for the DER system. And the maintenance priority of complex system is reviewed.

In chapter three, **Investigation on the Operation and Maintenance of the DER system in Kitakyushu Science and Research Park**, investigated and analyzed the DER system in Kitakyushu Science and Research Park. In order to illustrate the operation and maintenance status of DER system, the investigation and analysis contents include the management and maintenance strategy, operation status, replacement and failure, maintenance cost, effect analysis of maintenance. The results show that the maintenance management strategies of each equipment are different, the routine maintenance, scheduled maintenance, planned maintenance and corrective maintenance are applied to the DER system. The PM and CM are performed, we can find that the high PM cost can reduce the incidence of failure. The proportion of component cost of the device is about half of the total CM cost, but the gas engine more than 70%. According to the power generation efficiency of power generation equipment, we can find that the power generation efficiency will be decreasing with the time increasing. And Maintenance can significantly improve equipment performance. Maintenance management is very important in the operation of distributed energy system.

In chapter four, **Maintenance Optimization of the DER System Based on the FMEA Method**, present the maintenance priority analysis for the DER system in KSRP. This chapter focus on the failure mode, failure cause and failure effect of each component. And the risk priority number (RPN) is calculated and optimization by the FMEA approach worksheets and team review works. Through the FMEA process the weakest components of can be fined, and the new maintenance strategies can be proposed for the maintenance strategy optimization. The limited of this method is the team review step, this part related the experience and ability of the engineers.

In chapter five, **Reliability and Maintenance Prioritization Analysis of the DER System**. Failure cost importance index (FCI) and potential failure cost importance index (PI) were developed for the maintenance prioritization analysis of the DER system. A Markov model based on a state–space method was used to analyze the reliability and availability of the DER system. The reliability and availability of the components, subsystems, and whole system were deduced. The BI and CI were used to compare to FCI and PI. It was observed that the FCI and PI might lead to different rankings. FCI enabled the system managers to know the cost of a one-time failure of each component in a system. PI enabled the system managers to know the cost before the failure occurred for a one-time failure of each component in a system. The two indices would help managers to make a reasonable decision for maintenance on the cost basis, and help designers to optimize the system on the cost basis.

In chapter six, **Availability Analysis and Cost Optimization of Redundant DER System**, proposed a model for reliability and cost evaluation of non-redundant and redundant design DER system. The reliability analysis approach and cost calculation method based on the reliability indices are developed. The effect of redundant design for reliability indices is evaluated. Two cost of a system which relate to failure rate and MTTR (unscheduled maintenance cost and down time cost) are introduced and used to perform the total cost analysis. A case study for total cost of non-redundant and redundant design DER system is performed. The result shows that the redundant design can improve the availability observably, especially for the unit with low reliability. When the failure rate of the power generation module is higher, the more redundant modules are needed in order to improve the availability value to 100%. The total cost of the DER system can be reduced in the redundant design if the increased cost of the investment cost and operation & scheduled maintenance cost is lower than the reduced cost of unscheduled maintenance cost and down time cost. The redundant design of the DER system can improve the availability of the sub-systems and whole system. For a normal operation strategy of DER system, the system can be regarded as a series system. The reliability of each unit in the DER system has a great impact on the whole system or sub-system. The redundant design is a way to improve the reliability and availability of the unit in the DER system. The most effect parameters for total cost of non-redundant DER system is the failure rate and mean repair cost of the device.