Implementation of Power Electronics in Nuclear Power Plants:

DC Electrical System Conceptual Design and its Financial Analysis

By

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Abstract

A Power Electronic (PE) device is a semiconductor-based device which enable many advanced conversion of electricity which have been used widely in many industries. Due to the recent development in both circuit design and switches, these devices have become more competitive to traditional AC technologies. The design section of this study demonstrates the feasibility of high-level implementation of PE technology to a Nuclear Power Plant electrical system by conceptually designing a DC electrical system and comparing it to a reference AC system. The DC system meets the same design requirements as the AC system does. Furthermore, results from the financial analysis illustrate the advantages and disadvantages of implementing PE technology. Overall, the DC electrical system is able to significantly reduce generating costs due to, mostly, the more efficient pumping control with Variable Speed Drive. Other design options such as systems with less PE device implementation are examined in this study, which shows similar result. Besides, the technological benefit and challenge is discussed along with possible application to other plants, regulatory impacts, and scaling of the system. Additionally, several sensitivity analyses regarding the equipment cost and O&M cost are also performed. In summary, the implementation of PE technology seems to have financial and technological benefits, but there are also challenges associated with the technology itself and the standardization.

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Nomenclature

Abbreviation	Full name
AACE	American Association of Cost Engineering
AC	Alternative Current
ALMR	Advanced Liquid Metal Reactor
BJT	Bipolar Junction Transistor
BWR	Boiling Water Reactor
CAD	Canadian Dollar
CANDU	CANada Deuterium Uranium (reactor)
CSA	Canadian Standard Association
DC	Direct Current
EMP	Electromagnetic Pump
GCR	Gas Cooled Reactor
GTO	Gate Turn-off Thyristor
GW	Gigawatt
HVDC	High Voltage Direct Current
I&C	Instrumentation and Control
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated Gate Bipolar Transistor
IHTS	Intermediate Heat Transport System
kW	Kilowatt
LCC	Line Commutated Converter
LCOE	Levelized Cost of Electricity
LFR	Lead Fast Reactor
MCT	MOS Controlled Thyristor
MOS	Metal Oxide Semiconductor
MOSFET	MOS Field Effect Transistor
MSR	Molten Salt Reactor
MWe	Megawatt Electrical
MWh	Megawatt Hour
MWth	Megawatt Thermal
NEA	Nuclear Energy Agency
NPP	Nuclear Power Plant
O&M	Operation and Maintenance
OECD	Organisation for Economic Co-operation and
PE	Power Electronic
PHTS	Primary Heat Transport System
PHWR	Pressurised Heavy Water Reactor
PPI	Producer Price Index
PRISM	Power Reactor Inherently Safe Module (reactor)
PV	Present Value
PWM	Pulse Width Modulation

PWR	Pressurised Water Reactor
R&D	Research and Development
SCR	Silicon Controlled Rectifier
SCWR	Supercritical Water Reactor
SFR	Sodium Fast Reactor
SMR	Small Modular Reactor
SST	Station Service Transformer
USD	United States Dollar
USP	Uninterruptible Power supplies
UST	Unit Service Transformer
VAR	Voltage-Ampere Reactive
VSC	Voltage Source Converter
VSD	Variable Speed Drive
VSI	Voltage Source Inverter

1 Introduction

1.1 Research motivation

Power Electronic (PE) devices are critical to the modern world and can be found almost anywhere. In fact, they play vital roles in many daily products such as computers, vehicles, airplanes, power grid, etc.[1]

A PE device is a semiconductor-based switching device sharing the same principle with electronics used in computation applications, but instead of converting electrical signals, PE is meant to control electrical energy or electricity itself to achieve more advanced control features to an electrical system. The definition is *"Power electronics involves the study of electronic circuits intended to control the flow of the electrical energy. These circuits handle power flow at levels much higher than the individual device ratings."* [1].

High Voltage Direct Current (HVDC) transmission systems, for example, have been commercially operating for decades, which have demonstrated the ability of transmitting high power over long-distances and improving stability and performance of a large power grid by zoning or interconnection. Before the use of the thyristor which is a power electronic switching device, Mercury-Arc valves were used in the HVDC projects. The invention and implementation of thyristor-based switch theology quickly took over all HVDC projects due to numerous advantages provided by such solid-state devices[2].

The development and commercialization of power transistor not only makes daily life more convenient (e.g. much smaller and efficient DC changer) but also leads to the development of electric Variable Speed Drive (VSD), more powerful DC-DC converter, etc. Since the efficiency and power of those PE devices which provide essential functionalities of an electrical system have reached a desirable level, there are a few proposals of using DC distribution systems for residential area[3] or for facilities requiring mostly DC power such as a data centre[4]. However, the amount of information is limited as there are a few researches done in this area.
In a Nuclear Power Plant (NPP), its electrical system supplies power to all critical components keeping the reactor cooled and under control, the stability, reliability and performance of which is significant to plant safety. Additionally, a considerable amount

of power is consumed by the plant itself for coolant pumping. Reduction of the energy consumption can increase the profitability of a plant. Therefore, if power electronic technology can be implemented into a NPP, then it may potentially improve plants in both safety and economy.

The advanced conversion technology allows for fast control over individual converter technology in voltage output, power output, on/off stage to adopt different operating condition of a NPP so that the flexibility and stability of the plant can potentially be greatly improved. The stability concerns such as power factor and synchronization in an AC system can be qualitatively addressed since many PE devices are capable of altering those parameters independently and/or DC electrical system does not have the issues described above.

1.2 Contribution and challenge

This study is meant to make the first attempt to bring the PE technology to a NPP at a conceptual level and determine some high-level system characteristics which is to show how nuclear power may be benefited from current and future PE technology. Some contributions can be made by this work to both the nuclear industry by demonstrating the potential of this technology and the Power Electronics by showing industrial application possibility of PE and DC systems, which may raise more attention towards these topics.

Two challenges are the very limited information of DC distribution system with multiple voltage levels and the confidential nature of nuclear industry. Although there are several articles about DC distribution concept and its components, they are either in low voltage and low power or single voltage level distributed which does not meet the requirement of a NPP electrical system. Details can be found in literature review section. For example, one of the key components of DC distribution system--the DC-DC converter—is in a situation where most study focuses on theoretical study (e.g. circuit design and simulation)[5, 6], but few are built and tested to scale close to the need for a power plant. This is most due to the fact that, high power DC-DC converters are expensive to build and lack of industrial attention[7]. More information is found for the electrical system of a NPP which is the focal point of this study regarding to the design standards and actual systems [8-10]. The level of information is sufficient to achieve the accuracy described in the objective, but more detailed system designs which can improve the analysis are not publicly available.

1.3 Objective

The main objective of this study is to investigate the feasibility and financial impact of implementing Power electronic technology into a NPP electrical system. There are three sub-objectives needed to achieve the main objective.

1. Conceptually design an AC primary electrical system as a reference system using widely accepted standards, and a DC system having similar layout with power electronic components which also meets the same requirements.
2. Non-quantitatively determine the key improvements and drawbacks of implementing DC system in terms of performance, efficiency, and maintenance requirements, which is to show the technological potentials of PE technologies and help Decision-making.
3. Perform a comparative financial analysis of the DC system relative to the AC system in order to determine the impact to capital cost and Operation and maintenance (O&M) cost. The analysis includes sensitivity analysis to address the high uncertainty, help focus on the significant parameters and determine the state of this application.

1.4 Thesis layout

The background chapter answers the questions of how it works, and presents most up-to-date information about what other researchers contribute. The basic design and operation principle about a Sodium Fast Reactor (SFR) as an example along with a typical electrical system layout of a NPP is discussed, and the principles of the PE devices used in this study and DC electrical system concept are also discussed. These includes the how electricity is alternated within different forms (e.g. voltage and frequency alternating in AC and equipment in DC system serving the equivalent functionalities, etc.) Also, major types of Electromagnetic Pumps (EMPs) and their basic operating principle are presented. Lastly, a state-of-art review of DC electrical systems discussing the general idea, the existing system designs for several applications is presented followed by the explanations of the engineering economics techniques used in this study.

The methodology chapter discusses the details about how the study is conducted. The system design part of the work includes the selection of the reference reactor and the NPP electrical system models, the approaches to the AC reference system and the DC system designs, and the determination of system loads characteristics. In the financial analysis section, there are discussions about the methodology of estimating the equipment cost as well as the operation and maintenance (O&M) cost of system components, how the data is processed and sensitivity analysis is carried out.

The result chapter shows the layout and the system characteristics of the conceptually designed DC electrical system, and the comparison between the DC and AC systems. Then the estimated equipment cost and O&M cost is processed for Present Value (PV) of both systems which is followed by several types of sensitivity analysis. These analysis help determine the state and potentials of the PE technology in a NPP. Additionally, some other comments on the aspects that are out of the scope of this study but important to be mentioned are stated.

The conclusion chapter summaries the achievement in this work and gives a recommendation for decision-making regarding to implementing power electronics into a NPP. Future work briefly discusses the next step that may be taken for the further development.

2 Background and literature review

In this chapter, the fundamentals of all major components of the electrical system which are encountered in this study are presented in terms of their technological principles. This includes summaries of available design options, principles of operation, advantages and disadvantages, and their current states.

2.1 Nuclear relative background information

In this section, some information of a Sodium Fast Reactor (SFR) which is related to later analysis is given and discussed. Since the SFR is chosen later as a reference reactor layout for electrical system design, it is the only reactor discussed in this section. In terms of the NPP electrical system, a typical electrical system as described in IEEE and IAEA standards is discussed in this section followed by more detailed description about Canadian 4-class electrical system which is the referenced electrical system model in this study. The reason of choosing this electrical system over others is its available information in literature and the clearness in classification.

2.1.1 Sodium Fast Reactor

Sodium fast reactors are operating in a fast neutron spectrum which is to close the fuel cycle (fully release the energy in uranium), reduce high-level waste (long-lasting radioactive waste, actinides such as plutonium) and burn out nuclear materials that can be potentially used for nuclear weapons. As such, this design is a strong candidate for future builds. Since it uses liquid metal-- sodium as coolant, the power density of the reactor allows a SFR to have a much higher power while maintaining the same volume compared to a water reactor, and its high outlet temperature can improve the thermal efficiency. There are numerous designs in literature which vary in terms of safety features (e.g. fully passive safety) and sizes (from Small Modular Reactor (SMR) to gigawatt-level power units. Currently, much attention from many countries leads to a wide range of designs and attempts to commercialization.[11, 12]

All SFR are cooled by sodium, but there are different layouts. There are two main types in existing sodium fast reactor designs, the loop-type designs (e.g. Clinch River Breeder Reactor, BN350) and pool-types designs (e.g. EBR II, BN-600) [11, 13, 14]. There is a new layout from Idaho National Laboratory called the “hybrid loop-pool design” that will not be considered here for there is no reactor built on this configuration[15]. A pool-type design is an integrated design with the reactor core, primary sodium coolant, primary heat exchanger and electromagnetic pump, if applicable, integrated inside the reactor vessel and submerged under liquid sodium, whilst a loop-type design is where sodium is pumped through pipes into and out of the core with other components located outside the vessel. Both pool-type and loop-type designs have advantages and disadvantages. For pool types, “the reactor core, primary pumps, intermediate heat exchangers and direct reactor auxiliary cooling system heat exchangers all are immersed in a pool of sodium coolant within the reactor vessel, making a loss of primary coolant extremely unlikely.” However, this layout has larger reactor vessels for all systems are inside it. Loop designs, on the other hand, are easier to inspect, maintain and repair, but have higher possibility of sodium leakage[15]. The configurations of these two main types of SFR are illustrated in Figure 2-1.

From the perspective of the electrical system, the characteristics of the loads in the Nuclear Steam Supply System differ from water reactors due to the pumping and intermediate loop of liquid sodium which separates water from radioactive sodium. Since sodium-water reaction is violent and causes serious safety problem, this additional loop of sodium is added between the Primary Heat Transport System (PHTS) and the Steam Generator to prevent radioactive sodium from leaking out and reacting with water in the case of a leakage[12]. This loop is called the Intermediate Heat Transport System (IHTS). In many designs, the sodium is circulated by EMPs which have many advantages over mechanical pumps[13]. Details of EMPs are discussed in a later section. In the Balance of Plant System, the loads are similar to water reactors in terms of types (e.g. motors) as long as the plant is running on a steam cycle[16].

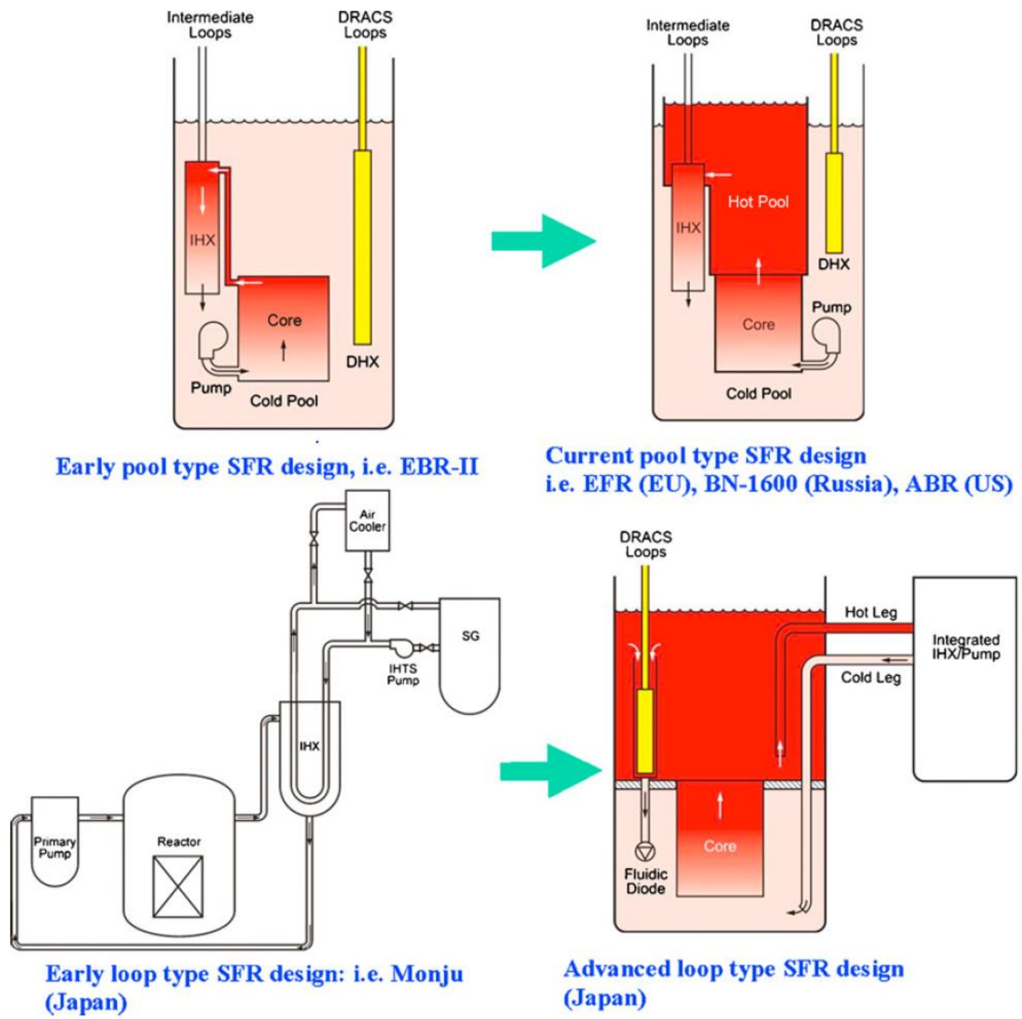

Figure 2-1 Different SFR design configurations[17]

2.1.2 Typical Electrical System for Nuclear Power Plant

The electrical system of a NPP is categorized according to the importance of a component. Different design standards utilize different classification schema. For instance, IEEE standards categorize the system into Class 1E and non-Class 1E. Class 1E, by definition in [8], is "The safety classification of the electric equipment and systems that are essential to emergency reactor shutdown, containment isolation, reactor core cooling, and containment and reactor heat removal, or are otherwise essential in preventing significant release of radioactive material to the environment." Other components that are not essential to system safety are under non-Class 1E. In CANDU nuclear power plant design, a 4-Class electrical system is used, also according to importance to safety [10, 18]. Due to the clear classification and available details in literature, the Canadian 4-class electrical system is the referenced model for further analysis.

2.1.3 Canadian 4-Class Electrical System

The loads and power sources are categorized into four classes according to the tolerance to interruption. System load characteristics are summarised from Reference [10] shown in Table 2-1.

In Class I, DC power is used to supply critical loads relating to reactor safety such as control logic, protection circuit, etc. The power cannot be interrupted and is backed up by battery banks which are capable of providing power to Class I directly and Class II through inverters for 60 minutes. Under normal operation (power generation), Class I power is drawn from Class III buses through "power rectifiers". The capacity of each power electronic device is enough to charge the battery banks and supply all loads in Class I and Class II at the same time. However, different DC voltages which are necessary for various loads in Class I are achieved by a set of inverter, transformer and another rectifier. This DC-AC-DC process is inefficient and costly to implement and the interference and power factor issues caused by having such kinds of load, inverter and rectifier is also significant[1].

In Class II, loads are also critical to reactor safety such as digital control computers, reactor regulation instrumentation, etc. The power source for Class II is the inverters converting DC power from Class I to AC power which is to make sure the battery banks are able to supply power to Class II loads. There are 3 different inverter sets for ensuring the redundancy. If the inverters are not operating, the Class III power source will provide power to Class II. This setup ensures that the loss of inverters does not affect the availability of Class II power.

Class III power is used by the fuel cooling system in the event of loss of Class IV, and the tolerance to interruption is 5 minutes which is the time allowed for standby generator to start up and restore power to Class III loads.

Class IV power supply is the only class that can withstand infinite outage without threatening plant safety. The source of Class IV power is the main generator through the unit service transformer (UST), and it can also obtain power from the grid through the station service transformer (SST) if UST is not available in cases such as UST maintenance or generator trip. It is important to note that though Class IV is not essential to reactor safety shutdown, its performance in terms of efficiency and availability is critical to plant net electricity output which directly influences the plant economics. One of the reasons is that it carries the largest loads in the heat transport system, steam system, etc. which are necessary for a power generating process.

There is no evidence that this categorization cannot be applied to SFR type of plant. The specific loads in a SFR may differ from an existing plant in Canada, but this classification according to the importance of loads still holds.

Table 2-1 Canadian 4-class electrical system classification [10]

Class of Power	Electricity form	Tolerance to Interruption	Backup Power source
IV	AC	Infinite	N/A
III	AC	5 minutes	Backup Generators
II	AC	4 milliseconds	Class I inverters
I	DC	Cannot be interrupted	Battery banks

2.1.4 Critical loads in a nuclear power plant

There are dozens of systems in a nuclear power plant, some are for reactor radioactivity control, some are for turbine and generator systems, some are for pressure regulation etc. Limited by the recourses available, it is impractical to gather information of all the loads, large or small in a nuclear power plant. Furthermore, from an electrical system point of view, small loads have very little influence to the whole system since the power difference between one large load and the small is very large and the disturbances caused by these small loads are also relatively small. Therefore, only major loads are included in this study. These major loads are either large in power or important to plant safety. For example, main boiler feed pumps are included for their power consumption while a digital control computer is considered because it is one of the critical loads in a plant which is electronic devices. Instrument air compressor in Class III or the pressuriser are excluded for the power is only a small fraction of other loads such as service water pump. Other excluded loads are: generator excitation system, HVAC system, fire water pumps, protective relays, instrument air compressor, etc.

The load information in Table 2-1Table 8-1(Appendix I) is summarized from Reference [10, 19-21] showing the major loads in a CANDU 6 reactor[1]. They are categorized by their classes and this categorization is consistent across this thesis.

2.1.5 Nuclear regulation environment and safety design

Nuclear power is an abundant carbon free energy source, but it is also a complex system and hazardous. The potential issues (e.g. core melt down or release of radioactive materials) which may cause public health issue and significant economic losses mean that nuclear power system must be well designed and regulated.

Regulators are usually experienced people authorized by the government to provide independent verification to most or all of a plant's life cycle (e.g. site selection, design, operation, etc.) by critically challenging it against the relevant regulations. [10]

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[1] The CANDU stands for Canada Deuterium Uranium which is Canadian pressurized heavy water power generation reactor design. CANDU 6 is its 600MWe class variation.

There are several regulatory approaches including a risk-based approach, a highly prescriptive approach, and those in between. The risk-based approach leaves more space to the designer about how to meet the risk target. The advantages are that it encourages innovative solution, but the disadvantage is that it is more subjective and less prepared for unknown failures. In the highly prescriptive approach, on the other hand, designers are required to follow detailed rules set by regulators which tends to encourage conservative designs. The advantage is that it increases the regulatory certainty, but the disadvantage is that it shifts the burden from the designers to the regulators. [10]

If a component is safety relevant (e.g. coolant pumps), then the number of criteria in regulation against the design is much higher than a non-safety relevant component. For such components, a design verification is mandatory which is to demonstrate it will function properly and reliably, and the amount of verification is influenced by many factors including repeat design or new design; standardized or no standard; proven technology or unproven, etc. The amount of verification performed also largely impacts the cost. For example, a new design requires a lot of verification (e.g. testing, details documentary) which brings much cost to the components.

2.2 Power electronics

2.2.1 AC system versus DC system

In a traditional AC system, power is generated by a 3-phase AC generator at a certain voltage and frequency while the voltage may be altered according to the purpose of the electrical energy which is done by transformers. Other parameters such as frequency, number of phases and so on are usually unchangeable. Voltage drop, usually caused by imbalanced reactive power[2], and frequency shift, mostly due to imbalanced active power between load and generation, could lead to generator desynchronization which is considered a major incident in an electrical system. Such an incident can cause a wide and maybe long-term outage. Therefore, stability control is key to maintain for the reliable and safe operation. Stability is harder to achieve in an AC system as it has

[2] Reactive power: it occurs in AC electrical system when there is a difference in phase between voltage and current.

reactive power and is less flexible. [2] For example, during peak hours, much compensation (capacitors are commonly used) must be provided for reactive power in a transmission line, but this amount of compensation could be excessive in a low-load situation. Sometimes, the reactive power may be negative due to the capacitor effect of the transmission line. This is also a threat to system stability. Similarly, a sudden disconnection of a large load such as a main boiler feed pump tripped out, resulting in a significant imbalance in reactive power, may raise some stability concern.

A DC system is inherently more stable as there is no synchronization issue since the voltage is not alternating nor is reactive power needed, which means a much stronger system that can withstand a worse disruption than an AC system could. The stability of a DC system is one of the reasons why engineers use a back-to-back HVDC system[3] to improve power grid stability and why some researchers propose a DC distribution system. [2, 22] However, unlike an AC system, the DC voltages cannot easily be altered to supply various loads. This is because DC cannot maintain an alternating magnetic field in a transformer and no DC power passes through a traditional transformer. In fact, a DC system mostly exists in a point-to-point transmission system (including back-to-back setup) where no voltage change is needed [2, 23] even though a DC power system has many advantages over an AC system. The recent advance in Power Electronics makes it feasible to alter DC voltage and, hence, to have multi-voltage level DC electrical systems to be created.

2.2.2 Electricity conversion and electricity converter

There are four main electric energy conversions in terms of its forms: AC/AC conversion between voltages at the same frequency is done by a traditional transformer; AC/DC conversion is done by a rectifier; DC/AC conversion is done by an inverter; and DC/DC conversion between different voltage levels is done by a DC-DC converter which is a power electronic converter. It needs to be clear that when the term “AC/AC converter” is used, it may refer to a system which has a rectifier and an inverter with a DC link in between. Sometimes, it may be referred to AC/DC/AC system and this is how a back-to-

[3] Back-to-back HVDC system: a HVDC system without transmission line. This is usually designed to connect AC systems with different voltage and/or frequency, or separate a large AC system into zones.

back HVDC system works. Also, a traditional mean of DC/DC conversion uses an inverter-transformer-rectifier system. This is used in Class I in the CANDU reactor. Table 2-2 below summarizes these converters, and the detail of which will be discussed in later sections. In this thesis, the term electricity converter is proposed by the author for the convenience of referring to all types of converters stated above, especially when comparing an AC and a DC system. It is a device that alters electric form in terms of its voltage, frequency or both.

Table 2-2 Different kinds of electricity converters

Functionality	Input/output	Converter
AC/AC conversion (same frequency)	Change the voltage but not the frequency of AC	Transformer
AC/DC conversion	Convert AC power to DC, may be in different voltage	Rectifier
DC/AC conversion	Convert DC power to power, may be in different voltage	Inverter
DC/DC conversion	Change the voltage of DC	DC-DC converter
AC/AC conversion (different frequency)	Change the voltage, frequency or both of AC	Rectifier and inverter with DC link
DC/DC conversion (traditional method)	Change the voltage of DC	Inverter, transformer and rectifier

2.2.3 Solid-state devices

There are many types of switching devices which have different functions and performance, as well as several essential parameters are important to this research including controllability, voltage, current/power, switching frequency and losses. The controllability of a device means its ability to be turned on or off. Some devices, such as a diode, can be turned neither on nor off while some others like regular thyristor can be turned on but not off if the current is positive (the commutation of thyristor relies on the grid providing negative voltage). The voltage and current mean the maximum voltage or current a device can withstand, the limit of which can constraint the power output. Last but not least, frequency is also a very important performance indicator influencing harmonics. In a power electronic application, harmony is often an issue causing electromagnetic interference, higher losses in the transformers on the AC side, which engineers need to address. In short, a Total Harmonic Distortion (THD) can be reduced by a proper switching frequency, and usually, the higher the frequency is, the less THD a system has[24]. A device usually has two main losses which are the switching losses and condition losses. [25] Not only do they affect the efficiency of the overall system making it less competitive to an AC system, but also they may require a more complicated cooling system raising the system weight. Table 2-3 summarizes the basic information presented in Reference [25] about the most commonly used switching devices.

Due to the close relationship and development of these devices, it is usual to see one device being integrated into another. For example, metal–oxide–semiconductor controlled Thyristor (MCT) is one of the thyristor family. MCT is actually an improved thyristor by pairing a metal–oxide–semiconductor field-effect transistor (MOSFET) which is easier to control, faster to switch and higher in input impedance. Another example is that developers took the advantage of bipolar junction transistor (BJT)'s high power density and MOSFET's fast switching to create an insulated-gate bipolar transistor (IGBT) which is a high-power, fast-switching device used in many applications. [25] Other parameters about power electronic devices such as actions described by quadrants are outside the scope of this study.

Table 2-3 Performance parameters of different types of semiconductor devices[1]

Device type	Full name	Voltage (V)	Current (A)	Switching Frequency (kHz)	Controllability
Diode	Diode/Power Diode	>10000	5000	not available	uncontrollable
SCR	Silicon controlled rectifier [4]	6000	5000	0.5	Semi-controlled
GTO	Gate turn-off thyristor	4500	2000	1	Controlled
BJT	Bipolar junction transistor	1200	500	80	Controlled
MOSFET	Metal oxide field effect transistor	1000	300	1000	Controlled
IGBT	Insulated gate Bipolar transistor	2500	600	100	Controlled

[4] SCR is thyristor- based device

2.2.4 Rectifier

2.2.4.1 Current rectifier technologies

Currently, there are three main types of rectifiers which are diode rectifiers, SCR (line-commutated converter) and Pulse Width Modulation (PWM) rectifiers (or force-commutated converter rectifier). A diode rectifier is uncontrolled meaning it is always on, and the only way to turn it off is to cut off the AC supply. This uncontrollability results in no control over its output DC voltage. On the other hand, a SCR can be turned on by a control signal, the gate delay of which signal is called firing angle α (from 0 to180º). Such a feature gives the SCR the ability of quickly regulate voltage output in the short term via the adjustment of firing angle which could increase reactive power dramatically, operating in inverter mode (90 º <α<180 º) and cutting off power. A PWM rectifier has more control over voltage output, power direction and power factor with less harmonic distortion due to its fast switching. However, this technology is current limited by the losses and power rating [1] in terms of applications in HVDC system. Since the station service power level needed in all nuclear power plant application is much lower compared to HVDC projects, the power rating should not be a problem, but overcurrent protection may post some regulatory concerns as it relies on the switch to stop the current. Only the operating principle of the SCR will be discussed in this section because it is the most widely used technologies in distribution systems.

2.2.4.2 Rectifier converter basic calculation

In a full-wave six-pulse rectifier system, the basic circuit diagram is shown in Figure 2-2Figure 2-2 basic S, and the AC current waveform is shown in Figure 2-3. Here, the rectifier is an ideal rectifier where the commutation angle μ is ignored, and the DC output voltage is given by Equation 2.1. [1] Since the power factor of the system is $\cos\alpha$, there is a considerable amount of reactive power that needs to be compensated for by correction devices such as capacitor banks. [26]

$$V_{DC} = \frac{V_{AC-peak}}{\frac{\pi}{3}} \int_{-\frac{\pi}{6+\alpha}}^{\frac{\pi}{6+\alpha}} cos\, \omega t * d(\omega t) = V_{AC-peak} * \frac{sin\frac{\pi}{6}}{\frac{\pi}{6}} * cos\, \alpha \qquad \textit{(2-1)}$$

where,

V_{DC} is the output DC voltage

$V_{AC-peak}$ is the peak voltage of AC voltage

α is the firing angle

V_{DC} is approximately equal to $1.35\ \mathrm{V_{ac}} * \cos\alpha$.

2.2.4.3 HVDC system rectifier

In the last section the basic principle of a rectifier is presented. In order to have a functional system, a converter transformer placed between the AC terminal and the rectifier has several functionalities.

1. The converter transformer is designed to have a ratio for desirable DC voltage since the DC voltage output of the rectifier is directly proportional to its AC voltage input. [2]
2. The transformers have different configurations for various converter design such as a 12-pulse converter unit which needs two-windings for each phase. [26]
3. The converter transformers are designed to withstand DC-voltage stresses and a harmonic current. [1]
4. The transformer usually has a high leakage impedance in its neutral ground [1] which is to address the neutral voltage switch issue with a DC system. [27]

In a high power HVDC system, hundreds of thyristors are connected in series with a balancing, protection, cooling and control module to achieve greater voltage output, which is termed a “valve”. A 6-pulse full-wave system needs 6 valves while a 12-pulse system needs 12 valves. The symbol usually represents one valve in a circuit diagram such as show in Figure 2-2.

After the rectifier, the DC waveform is still not smooth, so DC filters and a high frequency filter are added to reduce DC harmonics. Traditional filters only filter out specific frequency harmonics, but modern active filter using a PE device is able to filter a wide range of harmonics so that only one device is sufficient. [1] In addition, there is a DC smoothing reactor which is to smooth the DC current and protect the DC system from surges.

As mentioned above, this type of converter requires considerable amount of reactive power and some harmonics can pass through the transformer to the AC side. Therefore, capacitors or a static VAR system for the purpose of reactive power composition, and AC filter for reducing harmonics are necessary. [1] Otherwise, the system may introduce stress to the AC system or increase loss.

Overall, HVDC transmission system is relatively complicated compared to an AC system. However, the power level in HVDC system is much greater than that in NPP. Those system functions (e.g. reactive power compensation) are still needed, but they can be built in much smaller size with much less specialization due to the lower voltage and lower power. The choice of configuration (e.g. 6-pulses or 12-pulses) should depend on the actual needs. A 12-puluse system which is two 6-pulses system connected in series and can reduce harmonics may be needed for a larger power NPP application where small filtering devices or low harmonic interference are required.

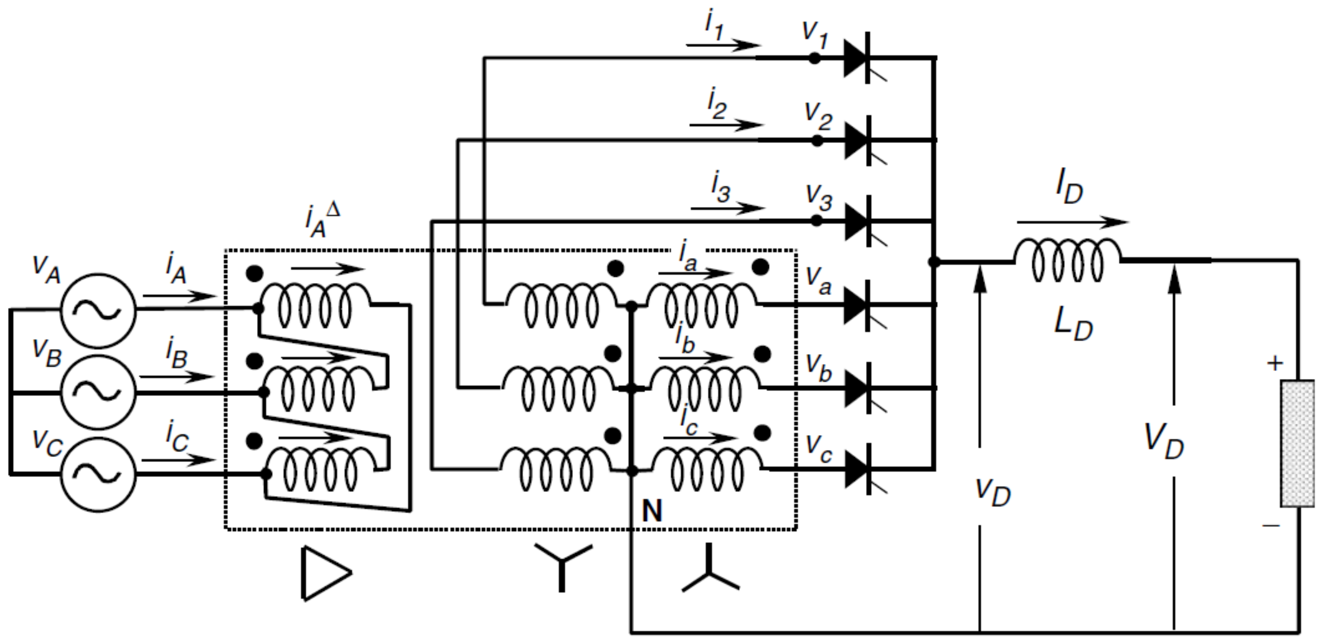
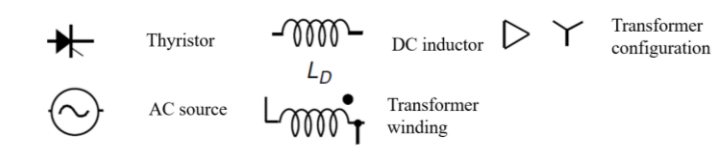
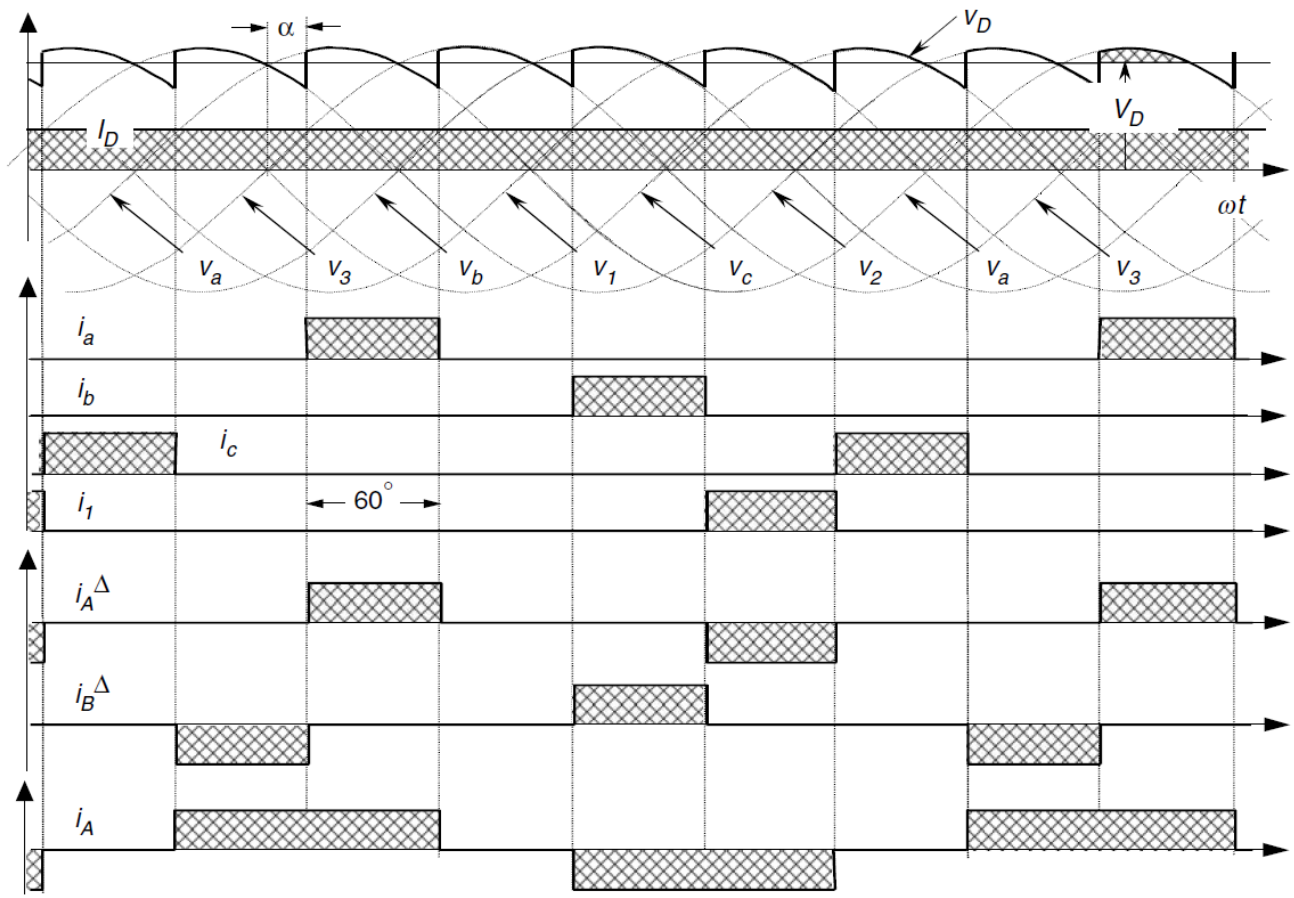


Figure 2-2 basic Silicon Control Rectifier circuit layout [1]





Va, Vb, Vc, V1, V2, V3	AC voltage
Ia, ib, ic, i1, i2, i3	AC current
VD	DC output voltage
ID	DC current

Figure 2-3 AC current waveforms for the six-pulse rectifier [1]

(V_a, V_b, V_c, V_1, V_2, V_3 is the AC voltage ; i_a, i_b, i_c, i_1, i_2, i_3 are the AC current; V_D and I_D are DC voltage and current; The DC voltage is actually the highest AC voltage when the switch is on)

2.2.4.4 VSC-HVDC

A Voltage Source Converter (VSC) HVDC system utilizing force-commutated transistors such as IGBT and GTO is able to control both active power and reactive power positively or negatively as well as the harmonics. That greatly reduces the need of AC filters, DC filters, and a reactive power source and, hence, lowers the space requirement, delivery time and cost. [28] This technology can be attractive compared to a traditional DC system, especially in a SMR where space and delivery time can play a critical role in the project. The power capacity of such a system has already reached GW level [29], so there is no power limit concern for a NPP application. However, the major concern is that the system is less protected to short-circuited current which could be a problem in a NPP where safety and reliability are important. [30]

In a VSC-HVDC system, the rectifier is a PWM rectifier and its layout is similar to a SCR illustrated in Figure 2-2, but instead of using thyristors, the switches are all of forward blocking capability (e.g. IGBT or GTO). Details about how a PWM device operates are in the inverter section. The inverter of a VSC-HVDC system is almost identical to a VSC-HVDC rectifier.

2.2.5 DC-DC converter

With the rise of electric vehicles, renewable energy and local micro grid technologies, DC-DC converter has become more common than ever. The classic DC-DC converter can be modified for a two-quadrant operation which means positive and negative voltage and four-quadrant operation which means adding bi-directional operation to the two-quadrant one. [1] In frequent stop situations like vehicles, this is essential since energy can be recovered via regenerative braking, or the energy cannot pass through the DC-DC converter and back into the battery. DC-DC converters are more commonly found in a small distribution area such as space stations and airliners as these applications usually have Uninterruptible Power Supplies, batteries or photovoltaic panels [1] which may also have a DC distribution system.

The DC-DC converter has two main divisions which are hard-switching (PWM) converters and resonant soft-switching converters. The former is well studied and commercially used for decades (e.g. bulk converter). [1] It is able to achieve high efficiency, high conversion ratio, and relatively simple control. However, the major drawbacks are the switching losses in the semi-conductor devices and the electromagnetic interference. A soft-switching device, on the other hand, has no switching losses problem which helps achieve very high efficiency, and low harmonics and electromagnetic interference. However, the converter is much more complex to build and control which may lead to higher costs. [1]

In this section, the basic principle of operation and system parameters are illustrated by using a classic step-down DC-DC converter and its transformer version as an example. This type of DC-DC converter is also used in this work as it is well described in literature and relatively mature.

2.2.5.1 Step-down DC-DC converter

The basic principle of operation of a classic DC-DC converter (also referred as a DC chopper) is discussed in this section. A Step-down DC-DC converter (commonly known as buck converter) and step-up DC-DC converter (also known as a boost converter) are similar. There is only information about voltage step-down function since the later design and analysis only utilize this converter. Figure 2-4 shows the basic circuit diagram of a buck converter. The switch S is usually implemented with devices such as IGBTs, BJTs, power MOSFETs, GTOs, and MCTs depending on the design requirements [1], while d is a freewheel diode (or flyback diode), L for DC inductor and C for capacitor. The voltage and current of the inductor, capacitor, and switch waveforms are shown Figure 2-5.

When the switch is in the on state, both the capacitor and inductor are being charged and voltage applied to the inductor is the voltage of the source minus the voltage of output. When the switch is off, both the capacitor and inductor are providing energy to the load whereas the capacitor is also smoothing the system output voltage.

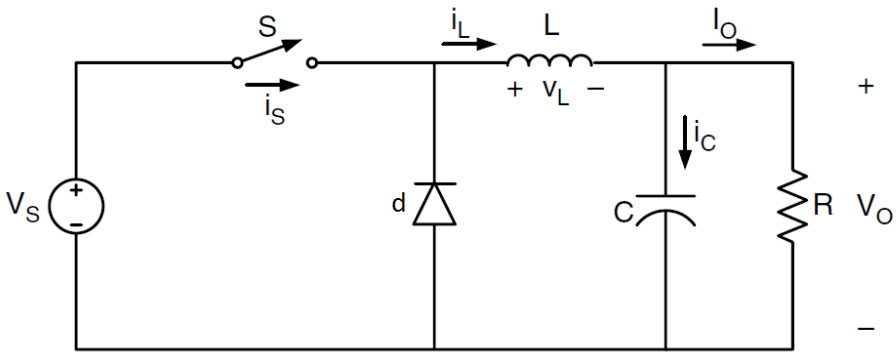


Figure 2-4 Circuit Diagram of a buck converter[1]

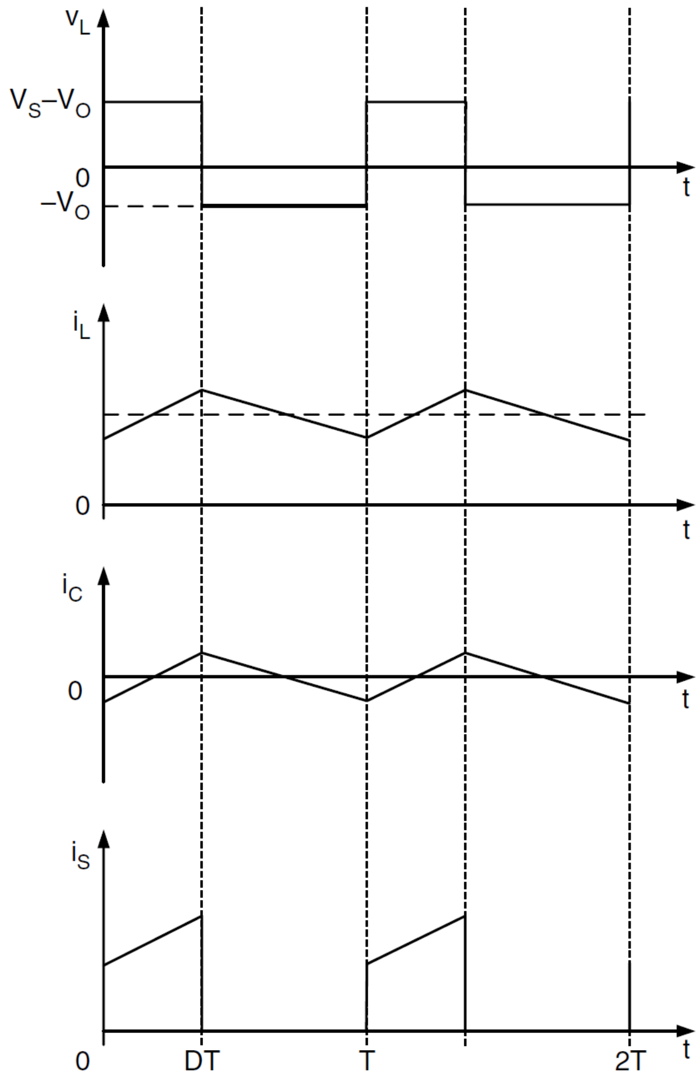


Figure 2-5 Waveforms of buck converter[1]

The input and output voltage has the following relationship

$$V_o = DV_s \tag{2-2}$$

Where D is the duty ratio.

$$D \equiv \frac{t_{on}}{t_{on}+t_{off}} = \frac{t_{on}}{T} \tag{2-3}$$

T is the period of the switching frequency f. [24]

The voltage transfer function—Equation (2-4) which is similar to the AC transformer is the ratio of the output and input voltage.

$$M_V \equiv \frac{V_o}{V_s} = D \tag{2-4}$$

2.2.5.2 Transformer-type buck converter

In some applications where electric isolation between input and output is required and/or there is a need of very large voltage conversion ratio which cannot be achieved by the buck converter, an additional high-frequency transformer is added into the converter to address those requirements. The high-frequency transformer which is small in size and light in weight has higher efficiency than an AC transformer. [1] There are four common types of transformer-type buck converters which are forward converter, full-bridge converter, half-bridge converter and push-pull converter [1], the different designs of which result in different performance parameters and is suitable for different applications. Here, the forward converter is explained as an example since it has the simplest layout and relevant to the design section.

As Figure 2-6 demonstrates, this type of converter is basically a buck converter with a transformer implemented. The third winding in the transformer is added to balance its magnetizing current. The transfer function of this DC-DC converter is

$$M_V = \frac{D}{n} \tag{2-5}$$

where n is the turn ratio of the transformer primary winding turns (N_1) and the secondary winding turns (N_2); D, M_V, same as above.

It should be mentioned that different converters have different transformer functions.

2.2.5.3 Soft-switching DC-DC converter

Much effort has been put into the development of soft-switching converters which utilize resonance to reduce losses in the 1980's and 1990's. [1] There are three main groups: zero-current-switching, zero-voltage-switching and zero-transition, while some converter may implement both zero-current-switching and zero-voltage-switching. Figure 2-7 and Figure 2-8 illustrate zero-current-switching and zero-voltage-switching switch layouts respectively. In zero-current-switching switches for example, when the switch is turned on, the current rises and then oscillates because of the resonance between the inductor and capacitor. By carefully controlling the timing, the switch can be turned off when the current reaches zero. [31] Since the switch turns when the current or voltage is zero, the switching losses is much reduced resulting in a high power density and high transfer efficiency. There is another type of converter—the multi-element resonant power converter, which has even higher power and can be found at several MW level. [24] This technology seems to solve many of the DC-DC converter even rectifier and inverter problems associated with hard-switching technologies (e.g. PWM). There are several researches achieve converter efficiency overall 99%. [32-34] In summary, it is technologically feasible to build a DC-DC converter with efficiency competitive to traditional AC transformer.

2.2.5.4 DC-DC converter versus AC transformer and application in NPP

A traditional AC transformer is very much different from a DC-DC converter in almost every respect. Figure 2-6 is a summary of the technological comparison between these two technologies. It is clear that a DC-DC converter has many advantage (e.g. weight) over a traditional AC transformer except for the power limit and overload capacity. Currently, there is no accessible literature demonstrating the existence of large power DC-DC converter (>10MW). Therefore, this could be problem for larger plant such as CANDU 6 which has station power demand of 48MW. [21] However, if the high-power converter is accessible, then the higher controllability will bring flexibility to plant designer and may improve plant safety and reliability, and the small size and light-weight makes it easier to work with and less requirement on the structure which also offers more room for designers. A comparative summary is shown in Table 2-4.

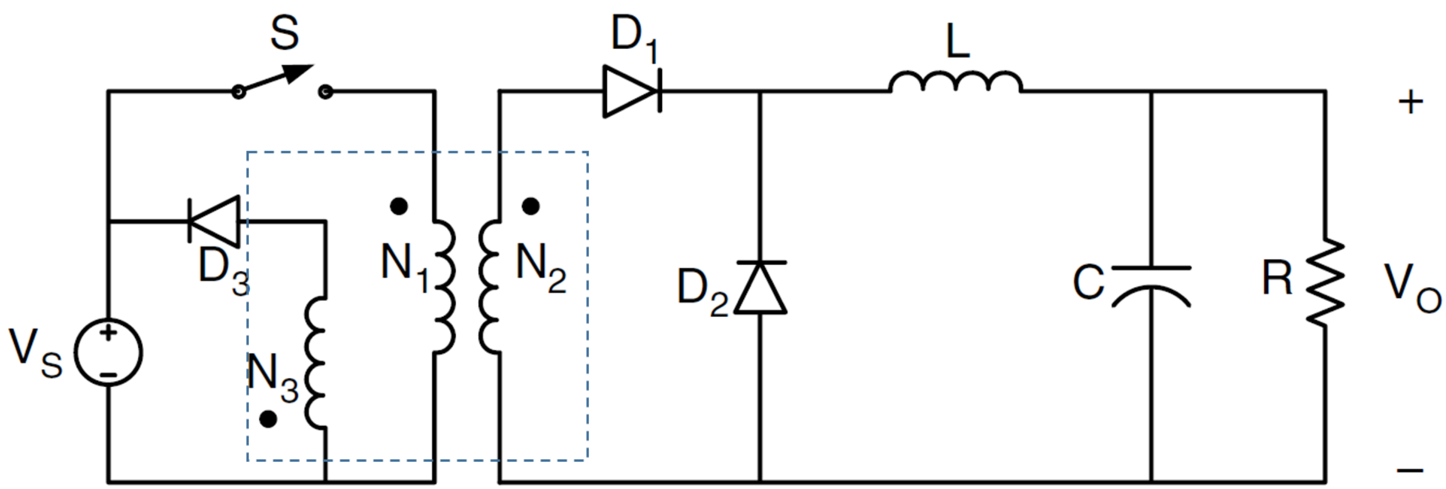


Figure 2-6 Circuit diagram of forward converter [1]

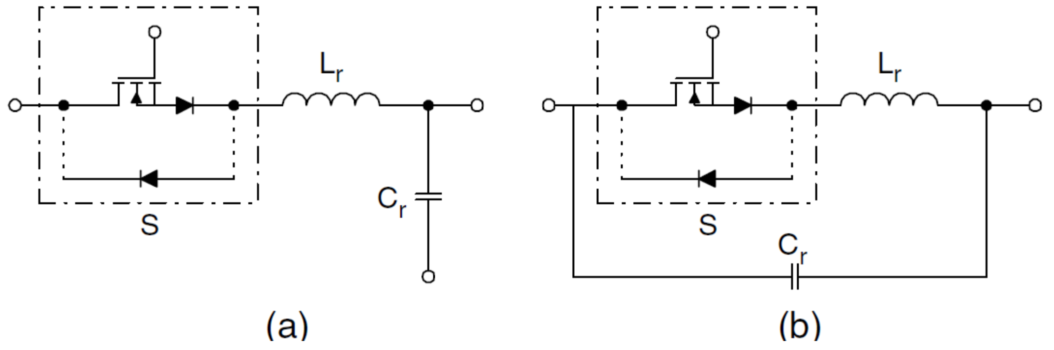


Figure 2-7 Two layouts of Zero-current resonant switch [1]

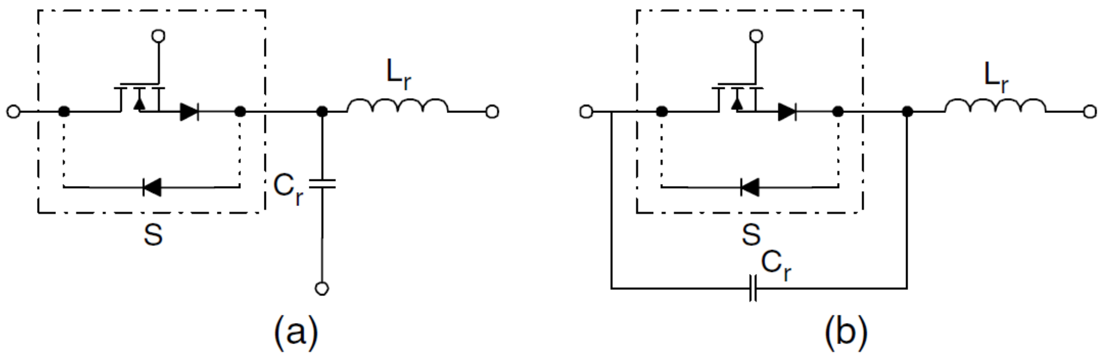


Figure 2-8 Two layouts of Zero-voltage resonant switch [1]

Table 2-4 Technological difference between AC transformer and DC-DC converter

	DC-DC converter	AC transformer	Note
Operating principle	PWM	Electromagnetism	
Key component	semiconductor switch	copper winding and icon core	
Voltage regulation	Available	N/A	except w/ on load tap changer
Responding time	<1ms	N/A	3-10s for a load tap changer [35]
Turn-off ability	Yes	No	
Efficiency	94-99.5%	97-99%	[7, 32-34, 36-38]
Overload capability	Low	High	
Power limit	Medium	Very high	
Size	Small	Large	
Weight	Light	Heavy	
Reliability	High	High	Both reliable

2.2.6 Inverter

An inverter is a device to convert DC power to AC power which is necessary to connect a DC system to an AC system or to supply an AC load in a DC system. A Voltage-Source Inverter (VSI) is a necessity for achieving an independent AC output since there is no AC source to commutate the switches in a Line-commuted-converter. Additionally, the independent inverter can output electricity in various voltage, frequency and even harmonics.

Most VSIs, today, uses PWM technology for DC to AC conversion. The simple half-bridge single-phase VSI demonstrates the operation principle of a PWM inverter. Figure 2-9 shows the basic circuit of a PWM inverter. There are two capacitors connected in series which are to create a virtual neutral point and to filter the current harmonics from the switches. The voltage of each capacitor is $V_i/2$. In Figure 2-10, it illustrates the waveform of the triangular carrier signal V_Δ and the modulating signal V_c which is in the desired AC shape. When $V_c > V_\Delta$, the S_+ switch is turned on and S_- is turned off, and vice versa. The ratio of $\frac{Vc}{V\Delta}$ is called the amplitude-modulation ratio. Such creates an output waveform as shown in Figure 2-10 the chopped rectangle waveform can be smoothed by capacitor to be close to sinusoidal shape. The three-phase PWM inverter is operating with the almost identical principle, the circuit diagram of which is shown in Figure 2-11. [1, 39]

Figure 2-12 shows three operation regions of a PWM inverter. In region where the modulating signal is always smaller than the carrier signal, then it is operating in a linear region where the voltage is increased linearly and all PWM features (e.g. harmonics control) are available. If the modulating signal increases to a point where its peak is higher than the carrier signal, then the switch keeps on over several carrier signal cycles. In this case, the system is in an over-modulation region where low-order harmonics appears in the AC output. The output voltage reaches its maximum value when the modulating signal is always greater than the carrier signal. [1] The output is square which may cause even higher harmonics and losses in the loads.

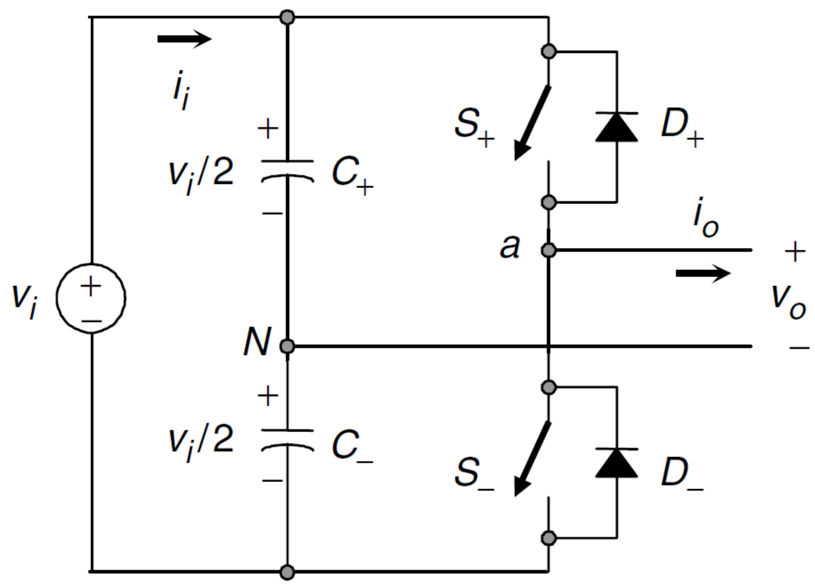


Figure 2-9 Circuit Diagram of a Single-phase half-bridge VSI [1]

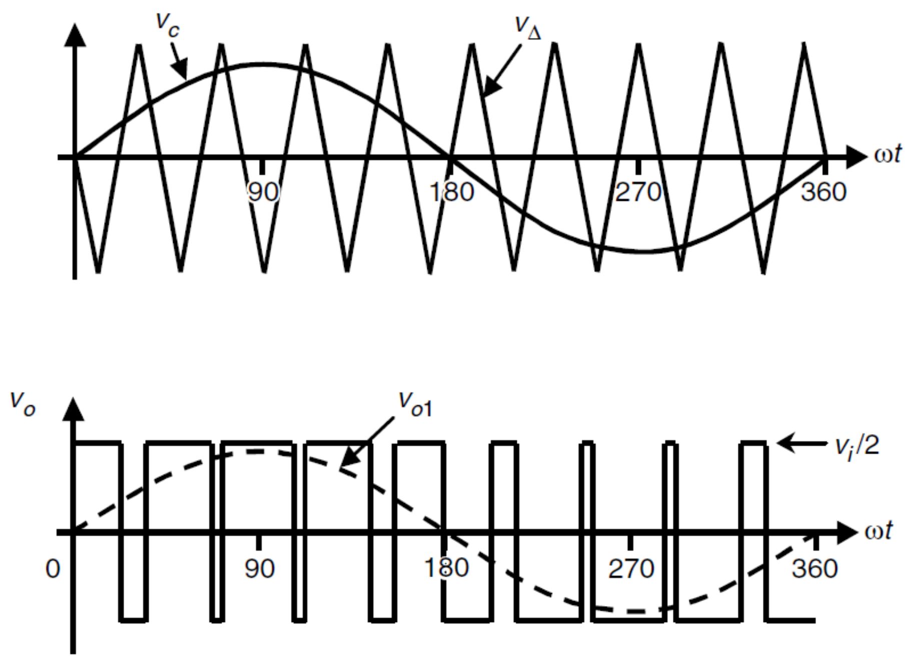


Figure 2-10 Waveforms of Carrier, modulating signals and waveform of the AC output [1]

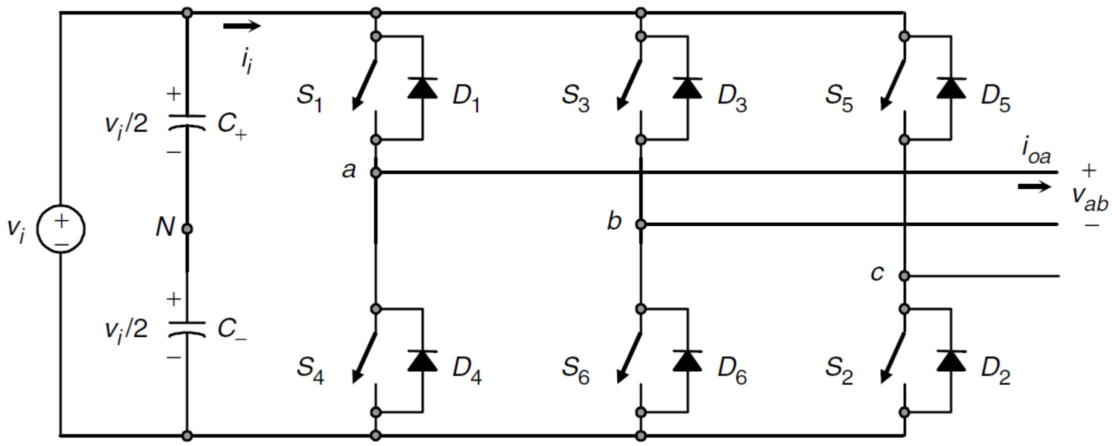


Figure 2-11 Circuit Diagram of a three-phase PWM inverter [1]

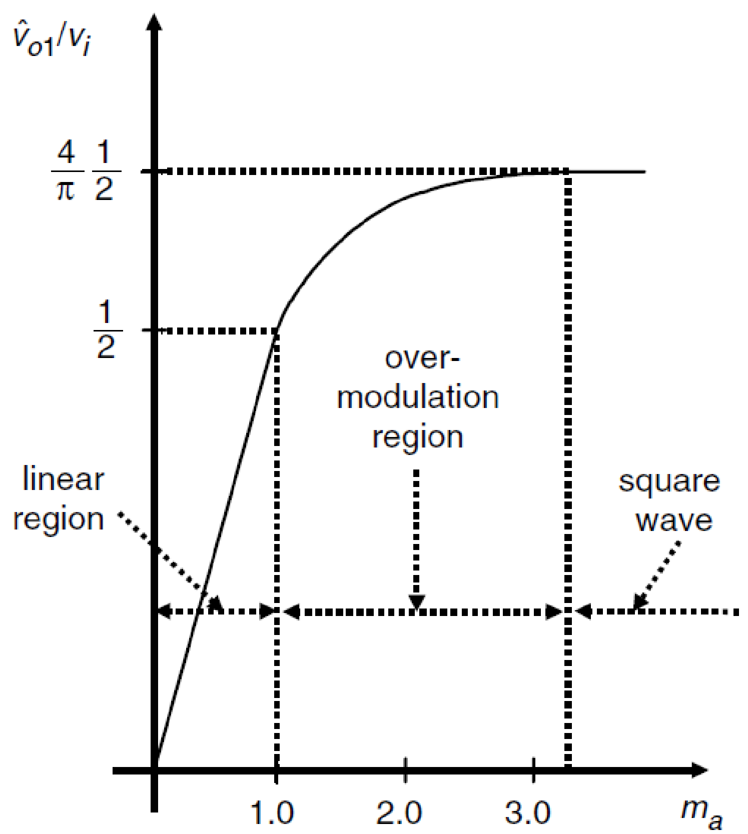


Figure 2-12 Operation region of a PWM inverter [1]

2.2.7 Variable speed drive

2.2.7.1 Types of Variable Speed Drives

There is surely a great demand for Variable Speed Drives (VSDs) in a wide range of industries (e.g. the rapidly growing electric vehicle needs both motor speed and torque control, a VSD can provide considerable energy saving on Heating Venting Air-Conditioning system in building. [39]) There are different approaches to achieve variable speed control of a motor based on various principles, as follows:

- A mechanical VSD uses a belt and chain drive with adjustable diameter sheaves, the layout of which system is similar to a Continuously Variable Transmission in automobiles, and some of mechanical VSDs utilize metallic friction drives. [39]
- A hydraulic VSD uses a hydraulic box or fluid coupling to control the speed, and there is also a hydrostatic type. [39]
- A electric VSD has the largest number of solutions including electromagnetic coupling ('Eddy Current' coupling), Variable voltage DC converter (often referred to as a DC drive) with DC motor, variable voltage variable frequency drive (often referred as Variable Frequency Drive or AC drive)with AC motor, etc. [39]

Since this study is about a DC system and power electronics in NPP, only the DC drive and the AC drive is discussed in the following section, and it is natural to pair these types of drives with a DC system which have many advantages over the others. For example, there is considerable losses associated with a hydraulic box (hydraulic losses), a metallic friction drive (friction losses) or an eddy current coupling due to their principles of operation. [39] Even belt and chain drives may have less losses, but the system is complicated and of high maintenance requirement due to the hydraulic system that operates the gear change. [40] An AC drive or DC drive, on the other hand, is relatively simple, small, and reliable, and has a lower maintenance requirement, because it is a static state device.[39]

2.2.7.2 AC induction motor and AC Variable Speed Drives (AC drive)

Before the development of an AC VSD, the Ward-Leonard system which is an AC motor coupled with a DC generator and then a DC motor is the primary option of VSD. However, the DC motor and DC generator inherently require more maintenance and is less resistant to humid environment due to the mechanical commutator--brushes which also cause higher losses. Later, a DC motor with a SCR DC drive is implemented with better performance and less complexity, but the problems associated with brushes still exists. The advances in both power electronics and fast digital control lead to the development of AC drives. AC drive with variable voltage variable frequency capability is meant to implement accurate speed and torque control in the most commonly used and widely available 3-phase AC induction motor, its flux-vector control method, in addition, makes it match or exceed all performance parameters compared to any other drive. [39]

In an AC induction motor, current passes through the sequentially arranged windings in the stator creating a rotating magnetic field which inducts current in the rotor which is either a squirrel cage rotor comprising a set of copper or aluminum bars or a wound rotor comprising 3 sets of insulated windings. If there is only one winding for one phase, then it is a 2-pole (p) motor. From Equation (2.6) and Equation (2.7), the motor rotation rate is directly proportional to the frequency, assuming slip (s, the speed difference between electromagnetic field and the rotor) does not change. Since the number of poles cannot be changed, the only way to control motor speed is by changing the frequency. The torque, as another important motor parameter, can also be controlled through the variation of voltage and the torque is proportional to the square of the voltage. What is more, controlling voltage can also enable the motor to operate over the base speed. The motor can be further accelerated by reducing its torque output via lowering the voltage. This region, shown in Figure 2-13, is known as the field weakening speed range where the motor power stays constant. Therefore, most modern AC drives come with V/f vector control. [39]

$$N_0 = \frac{f * 120}{p} \tag{2-6}$$

$$N = N_0 * (1 - s) \tag{2-7}$$

$$s = \frac{N_0 - N}{N_0} \tag{2-8}$$

where f is frequency,

p is pole,

s is slip. (Slip increase as load of the motor increases and the higher the slip, the lower the efficiency.)

N_0 is the rotational speed of the electromagnetic field,

and N is the rational speed of the rotor. [39]

The AC VSD layout is similar to a back-to-back HVDC system used to connect two different-frequency/different-voltage power grid, which is mentioned in the AC system versus DC system section. An AC drive for an AC system has similar layout with a rectifier (Diode or SCR), a DC link and an inverter (PWM) as shown in Figure 2-14. In terms of the rectifier, it is common to see an AC drive with a diode rectifier and less common with a thyristor or PWM rectifier for its simplicity and cost, and the controllability of PWM inverters is sufficient for most applications. [39] The inverters, in many AC drives, are using PWM technology as it is mature and commercialized. The operating principles of the rectifier and inverter are the same as those discussed in previous sections.

There are four main areas in the control circuit: the inverter control system; the speed feedback and control system; the current feedback and control system; and the external interface including human interface, digital Input/output to other control system. The control system can be open-loop, closed-loop or cascade closed-loop with control over speed, torque, and current. A modern VSD usually uses Vector Control which varies V/f (voltage and frequency) separately according to motor operating condition (e.g. speed and load) to achieve better performance (e.g. higher torque and accurate speed).

If an AC VSD is to be connected to a DC distribution system where the drive input power is DC instead of AC (as is in the DC system in this work), some modification needs to be done which is discussed in the methodology section. In this thesis, VSD for a DC system is referred to as a DC VSD for convenience. The fundamental difference between an AC VSD and a DC VSD is that there is only the inverter in a DC VSD rather than having all rectifier, DC link and an inverter for the AC VSD. A DC VSD may have the following advantages over an AC VSD relative to this work.

- Cost may be reduced as there are fewer components in a DC VSD.
- Electric breaking can be done by just controlling the PWM inverter in the DC VSD. The AC VSD, on the other hand, must have an active front end (usually a PWM rectifier) in order to gain electric breaking functionality.
- There is no control issue with a diode rectifier such as a delay in turn-off due to the free charges in the PN junction. [39]

This is a concept discussed in several literature about DC distribution systems [22, 41], there is no apparent evidence showing the existence of a DC VSD in an industrial application or commercial products. However, there does not seem to be a technological challenge with this kind of products.

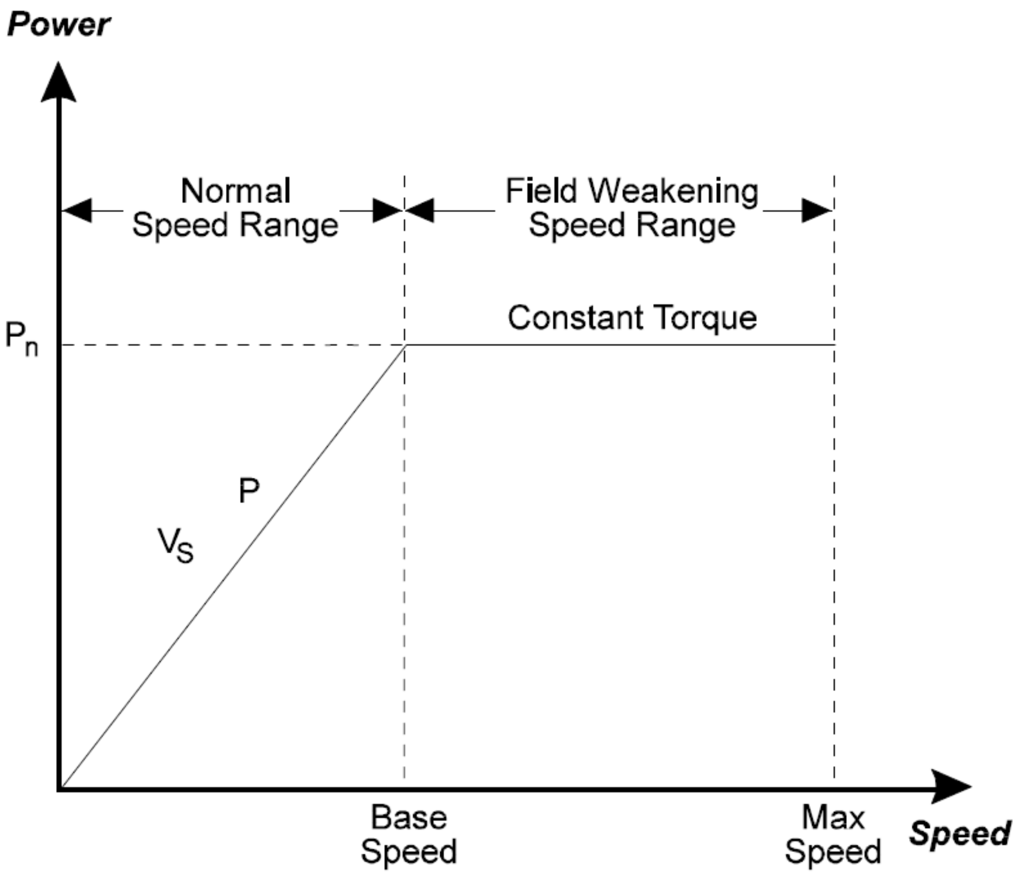


Figure 2-13 Power of an AC drive over the speed range [39]

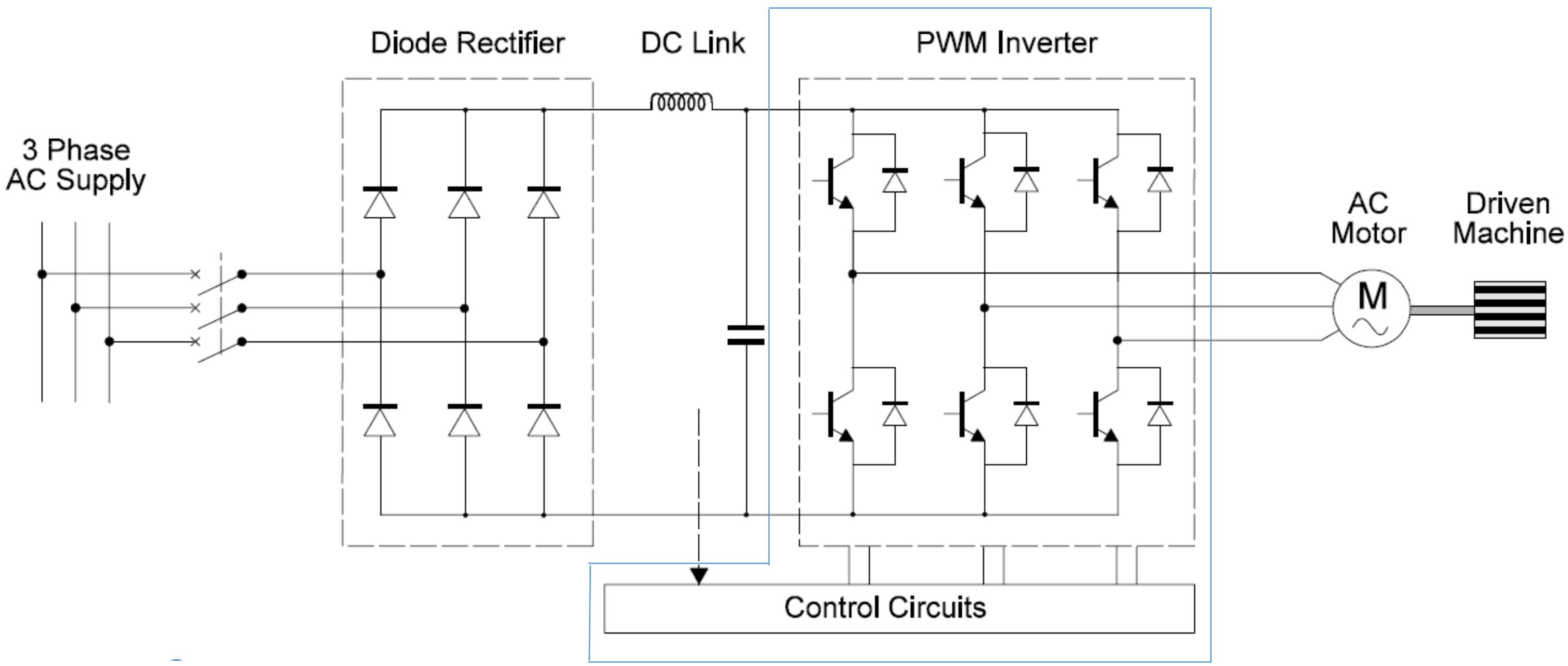


Figure 2-14 Layout of AC Drive for AC system [39][5]

[5] Circled in blue are the components required in a DC VSD.

2.2.7.3 DC Drive

A DC drive still has its place in some industries where fast dynamic response, and separate control over torque and speed are needed such as the sectional drives for paper cutting machines. [39] The control of a DC motor is relatively simple. Here, the shunt wound DC motor is used as an example to explain the basics of its control, the basic diagram of which is shown in Figure 2-15. A shunt wound DC motor is that having the field windings shunted to (connected in parallel to) the armature winding. The motor speed is directly proportional to an armature back electromagnetic force V_E which can be adjusted by armature voltage and indirectly proportional to the field flux Φ which can also be controlled through the field excitation current I_E, while the torque is proportional to the armature current I_A and the field flux (Φ). [39]

In the industrial application, the flux is usually kept constant if no control mechanism is placed before the field winding. The speed control is done by controlling the armature input voltage. If it is required to run the motor at a higher speed then its rated speed where the armature voltage reaches maximum, reducing the flux is able to get the motor into its field weakening range to enable higher operating speed, but the torque output is reduced. The control of its drive output is done either by DC-DC converter adjusting voltage and current in the armature or by a thyristor rectifier at the terminal connected to the AC system. The more traditional thyristor method has a power factor issue as this converter consumes considerable reactive power. [1, 39]

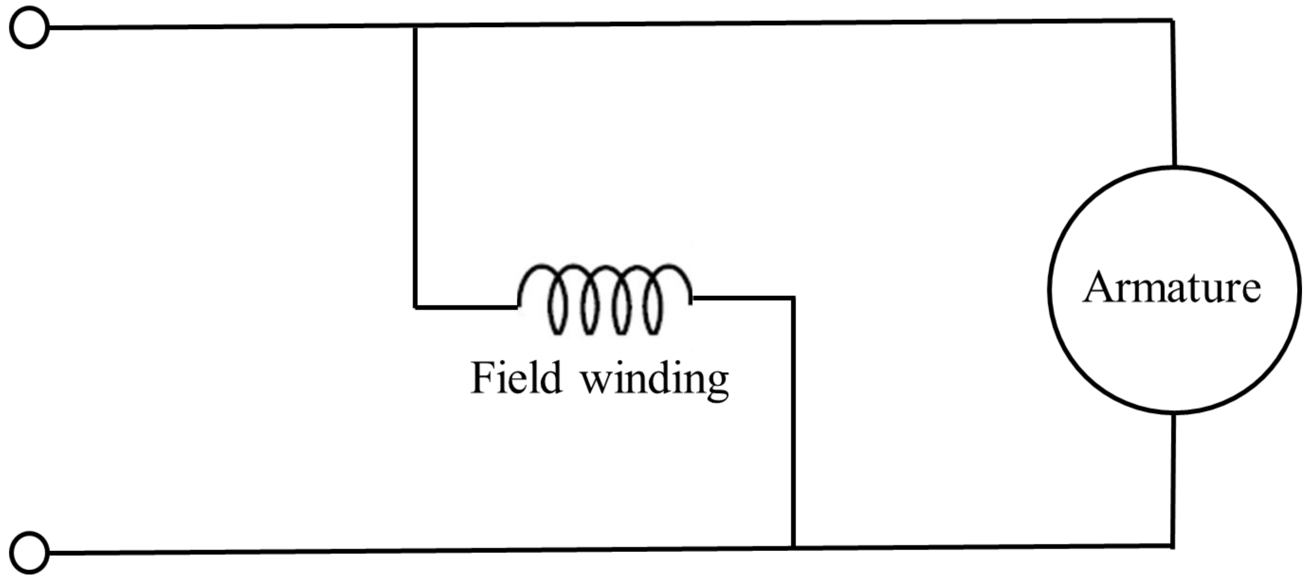


Figure 2-15 Shunt wound DC motor layout

Even a DC motor has good performance, but there are technological challenges limiting their application which include:

- Ambient condition (humidity and temperature) may pose some arc issues to the mechanical commutator.
- Maximum motor speed is restricted to ensure a complete commutation.
- High losses and heat.
- Periodic maintenance to the brushes and the commutators. [39]

The Permanent Magnet Brushless DC motor is briefly mentioned as another possible solution to the above challenges. This type of motor has permanent magnet in the rotor which can be 12 poles or higher, and the drive is a power electronic commutator similar to a PWM inverter but outputting a square waveform to each phase on the stator. The speed control is proportional to the frequency of the drive. The advantage over a DC motor is that it has no mechanical commutator and it is easy to reverse direction, and the main advantage over an AC motor is its flat (continuous and constant) torque output. Despite its superior performance, a Permanent Magnet Brushless DC motor is very expensive for high power application due to the hazardous installation and high cost of strong magnets. [42]

2.3 Electromagnetic pump basics

2.3.1 Pros and cons of electromagnetic pumps

An electromagnetic pump (EMP) is equipment that can induct an electromagnetic force onto electric-conducted fluid and complete the pumping movement. [43] Compared to an EMP, conventional mechanical pump has many engineering challenges. For example, it is almost impossible to make a mechanical pump inside the reactor vessel or submerged into liquid sodium, and the chopping action of the impeller at the high viscosity liquid sodium posts difficulties on impeller design. [43, 44] An EMP, on the other hand, has many advantages in this application which includes:

1. A static EMP has no moving parts which has no wearing issue with bearing, impeller, etc., and hence has a higher reliability and lower maintenance requirement than a mechanical pump. [44]

2. An EMP can be immersed in and cooled by sodium in the reactor vessel which means there is no need for penetration of the reactor vessel reducing the chance of leakage. [43] A mechanical pump, on the contrary, must be placed outside the vessel with a shaft connecting the impeller inside which is due to the inability of a mechanical pump rotating in sodium or withstanding the high temperature.
3. Due to the sodium-immersed design, the heat generated by an EMP can be recovered as the heat is rejected into the sodium and then into the steam cycle. This effect also applies to the EMP in the intermediate loop. [45]
4. The EMP system design is simpler than a mechanical one as there is no reduction gear, no mechanical seals, no lubricating oil system nor a pump over-flow system to recover sodium leakage on the rotating shaft. [46]
5. The control of EMP is simpler and smooth with range from zero to full capacity which also eliminates the need for a high-temperature throttle valve. [47]
6. In the event of sodium solidification, it is possible for the EMP to use its heat to melt the sodium inside the pump duct for easier start-up whereas solving the same problem in mechanical pumps is much harder.

The major drawback of an EMP is its limited efficiency and heavy weight. [46] Also, it can be challenging for electrical engineering to design a supply that meets its power requirement and power factor (depending on type of EMP). [43]

2.3.2 Basics Principle of EMP Operation

The most fundamental principle of EMP is the same as a mechanical pump which is a Lorentz force described by Fleming's left-hand rule. The filament is perpendicular to the direction of the magnetic field, the expression of such force is

$$F = BLI \qquad \text{--- (2. 9)}$$

where B is the magnetic flux strength,

L is the length of the filament,

and I is the current in the filament.

In a DC EMP, the field can be provided by a permanent magnet, field coil or both. If the field coil method is used, the winding and the electrodes are usually connected in series to increase the voltage. [47] The duct is usually fabricated from 304 or 316 stainless steel and the bus bar is of oxygen-free and high-conductivity with nickel- or silver-cladding copper. [43] The flow rate can be controlled by varying the current of the pump and/or the magnetic flux.

2.3.3 Types of EMPs

There are two main types of EMP---the induction pumps where the current is inducted into the metal and the conduction pumps in which current is conducted through electrodes. For example, the basic DC EMP is one of the conduction pumps. In the conduction pump family, there are AC conduction pumps and the DC conduction pumps which can be further separated into the PM type and the electromagnet-type. In the induction pump family, the sub-classification is based on how the magnet structure is setup. There are stationary structure and rotating structure. Since rotating structure defeats the purpose of EMP in the reactor, it is not considered in this application. There are further classifications of induction pumps which are shown in Figure 2-16.

Both conduction and induction EMP technologies have advantages and disadvantages. A DC conduction EMP[6] has better efficiency, lower weight and smaller size, lower isolation requirements than induction EMPs and can be used in a wide range of metal across a wide range of power level, but it posts difficulties in the drive system where kilo-amperes of current is at a undesirably low voltage. An induction pump, on the other hand, has the advantages of high power density, but it can only be practical in high power application due to the large size and low efficiency in low power range. [45, 47] However, the power range of a NPP application is considered high-power. Therefore, the DC conduction and induction pumps can be used in a NPP. In fact, both technologies are considered in this work (Section 4.8.5).

[6] An AC conduction EMP is restricted to small power applications, since eddy-current losses increase rapidly with size, and it has poor power factor.

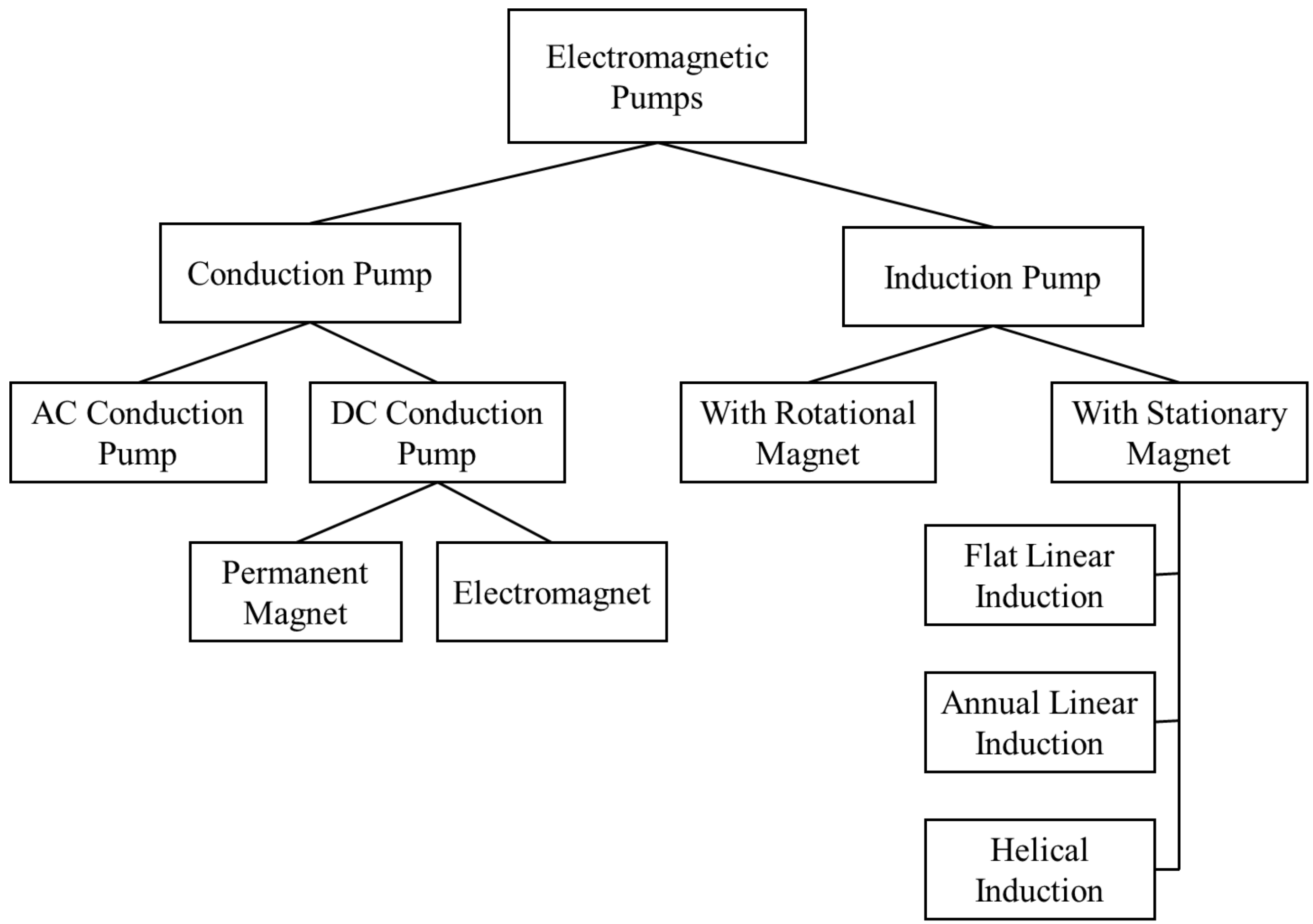


Figure 2-16 Electromagnetic pump classification [43]

2.3.4 Power source

The power supply and controller (often referred as the drive) of an EMP is a power electronic device. Depending on the system and EMPs, the drive can be a rectifier, AC-AC converter (alternating voltage and frequency), or DC-DC converter. [45, 47] A recent EMP design for ASTRID and Toshiba 4S, for example, is an Annular Linear Induction Pump which is a type of induction EMP supplied through a rectifier and a PWM inverter at the frequency of 20 Hz. [46, 48] Table 2-5 shows the necessary converter for different EMPs in a different electrical system. In this study, a DC conduction EMP is used in the base model (Section 4.1.2), but the induction EMP are also considered in sensitivity analysis (Section 4.8.5).

Table 2-5 Converter for different EMP applications [45, 47]

	Electrical system	
	DC	AC
DC conduction EMP	DC-DC converter	low-voltage rectifier
AC conduction EMP	Inverter	N/A or Rectifier - inverter
Induction EMP	Inverter	Rectifier - inverter

2.4 DC electrical system literature review

2.4.1 Overview

The AC system won the “War of Currents” in the late 1880s and early 1890s with the invention of a simple voltage altering transformer and the poly-phase motor resulting in today’s mostly AC power grid with generation, transmission and distribution. [49] However, advances in power electronics have made voltage regulation possible in a DC system with the invention of the DC-DC converter and have provided a solution comparable with AC generation (the rectifier), the AC grid and AC loads (the inverter). Although DC power applications can still be seen in many places across a wide range of power levels (e.g. computers, variable speed Heating, Ventilation and Air Conditioning systems[50], DC electric arc furnaces in the steel industry[51], data centres[52], etc.), the AC power is dominant in power distribution.

The attractiveness or necessity of a DC distribution system is increasing as the rising of renewable energy and electric vehicles makes the DC electrical system more practical. Many renewable energy systems such as solar, wind and energy storage can operate more efficiently with a DC system due to their non-standard output. The power generated by a solar panel is DC with varying voltage and unstable wind makes a wind turbine difficult to produce the standard 50/60 Hz AC power. Hence, converting the renewable energy power into DC and transmitting it through a DC electrical system could be a more reasonable solution. Also, electric vehicles can potentially improve the grid efficiency by a vehicle-to-grid strategy at peak-hours reducing power back-up and spin-reserve. [53] Although it is unclear how a sufficient number of electric vehicles will be charged in the future or how they will influence the grid, the number of electric vehicles and DC-powered charging stations will certainly increase. Additionally, ship and airplane manufacturers are also requesting electrical distribution system that is flexible enough to provide power to various loads which require electricity in different forms—different voltages, different frequencies and variable frequencies. [22]

Power Electronics also advances quickly under these demands. By implementing several types of PE devices including rectifiers, inverters, DC-DC converters together and designing a control system that coordinate these units at a system level, a DC distribution system is designed. Since it utilizes mostly power electronics devices, it is also referred to as Power Electronic Distribution System. In this work, it is simply called DC electrical system or DC system. Such system currently is able to achieve several hundred kW which is mostly constrained by the power of DC-DC converter (rectifiers and inverters have achieved much higher power).

2.4.2 Existing DC electrical system design

There are studies on small scale DC systems (focusing on renewable energy) [54-56] and in-site plant electrical systems [41]. In terms of industrial distribution system, there are two projects including a U.S. Navy shipboard zonal distribution system [22] and a data centre [41] These two projects have similarities with a NPP as summarised below:

1. The reliability requirements of these systems are extremely high.
   The loss in power can result in the inability to survive in combat for a Navy ship, the loss of critical customer data in a data centre, or a fuel meltdown in a NPP.
2. The loads of these systems are categorized.
   A naval ship, a data centre and a NPP, for example, have non-critical loads (e.g. normal lighting) and critical loads such as combat systems, fire-fighting resources and cooling systems.
3. There are multiple short-term or long-term backup systems.
   Similar to a NPP backup strategy, a data center has battery banks for short-term emergencies and diesel generators for long-term backup.
4. The loads involve both AC and DC.
   A data centre comprises both DC electronic loads and AC HVAC loads. The shipboard loads may include motor driven pumps, electronic control systems and an electromagnetic gun and an electromagnetic launcher which demand several MWs of DC charging power (assuming tens of seconds of charging time). [57]

In both Figure 2-17 and Figure 2-18, the generation is done by AC generator (s) with a rectifier. The reason of using an AC generator instead of a DC one is that in the classic DC generator, the commutation is done by the brushes (also known as a mechanical commutator) which is problematic due to their arc and wearing, while with power electronics the commutation is done electrically by a rectifier which means higher reliability and high power. [42]

After the rectifier, the power is transmitted to DC buses where other power sources and loads are connected. The DC loads can be powered directly or through DC-DC converters for the desired voltage, and the AC loads are powered through inverters. In the shipboard system design, it is clear that the vital loads are able to draw power from two DC buses for better reliability. [22]

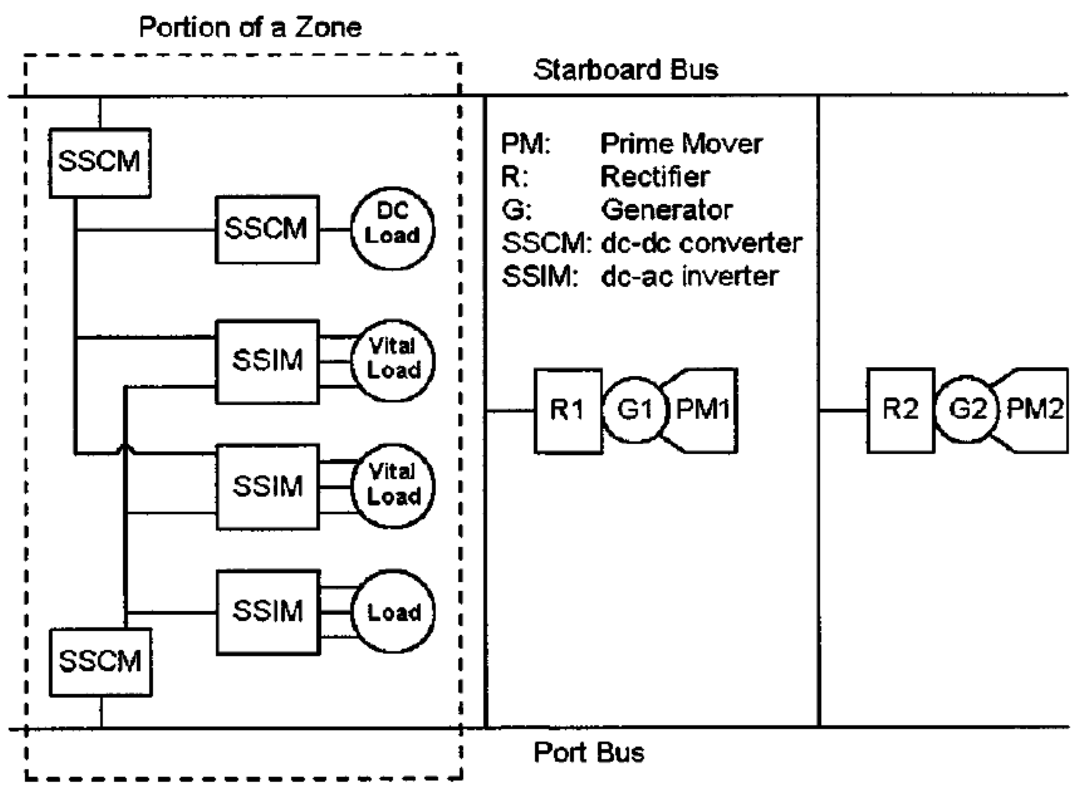


Figure 2-17 Navy shipboard DC electrical system layout [22]

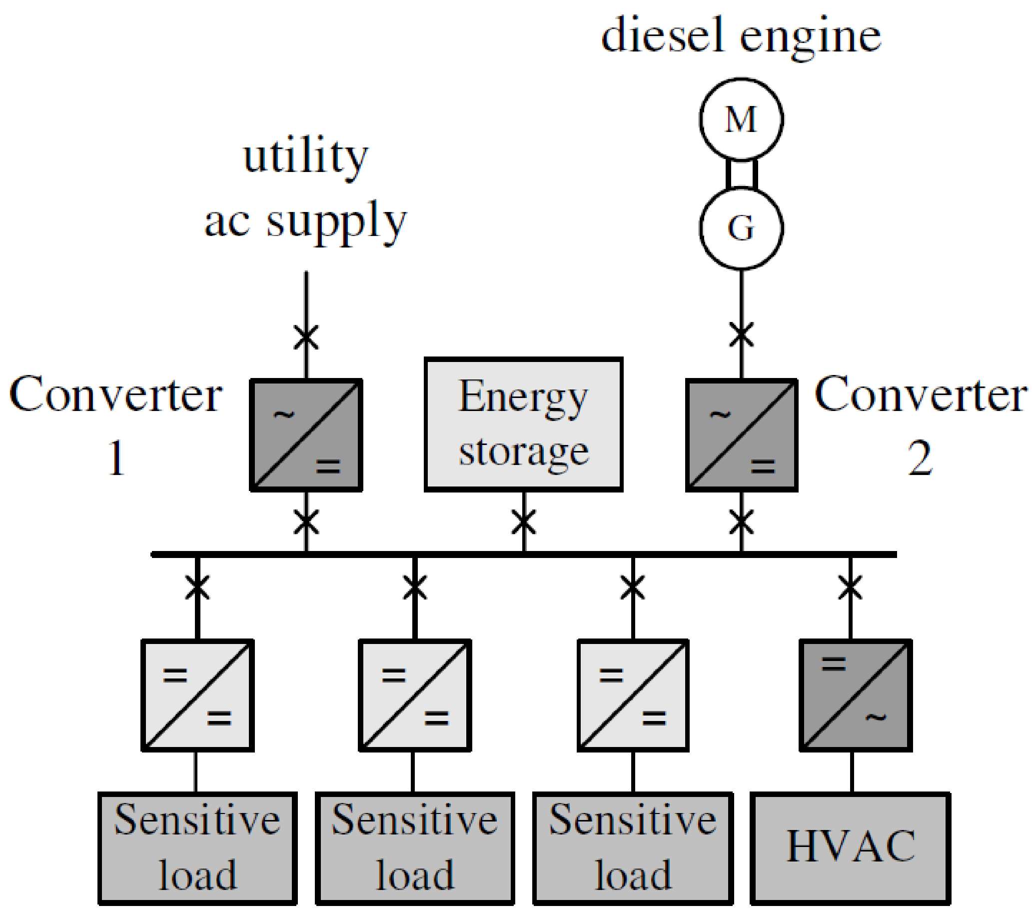


Figure 2-18 Data centre DC electrical system configuration [41]

2.4.3 Residential and industrial application and challenges

Several studies [3, 58, 59] have investigated the feasibility of DC distribution system for residential area. Instead of discussing the technological challenge of DC distribution systems, the cost seems to be the focal point. The debate is mostly on cable cost and losses since cable length is significant in this type of distribution system. Those with a more sophisticated cable loss calculation or an actual cost of DC cables (e.g. 5-wire design) seem to favour implementing a DC distribution system that is able to cut cost or increase system capacity.

In industrial applications, researchers have some concerns with the DC system stability including that a DC converter can yield a negative input resistance which may leads to system oscillation [60], the DC fed induction motors and Permanent Magnet Synchronous Motors may cause system instability [61, 62], and neutral voltage shift phenomena in a DC system. [27] However, with today's digital technology, all these problem can be addressed by proper designs and control techniques and the solutions are also proposed in the same references. All proposals about industrial DC distribution (e.g. commercial buildings with sensitive electronic loads, shipboard, etc.) are nowhere near the power level in a typical power plant or a chemical plant. The reason could be the high-power DC-DC converter has not yet been well studied in terms of their losses, reliability and cost. There are studies about circuit designs to achieve more functionalities (e.g. higher conversion ratio) [63] and about using new technologies to improve efficiency [33, 64, 65] or to rise the power level. [7, 66] There is less interest in reliability study. There seems to be no evidence demonstrating a DC-DC converter that can achieve all these goals. These could be one of the determining factor of whether this DC system concept can be applied to a NPP or not.

Another major challenge is the overcurrent protection system which is absolute for an electrical system. Cutting off DC current is a challenge since DC current does not have natural zero crossing, and many solutions are proposed in literature such as artificial neutral point with AC breaker, power electronic solid state breaker, solid state/mechanical hybrid breakers[67, 68], using thyristor rectifier to eliminate fault current on DC buses[69], etc.

2.4.4 Standardization

One of the biggest problems with DC electrical systems may be the lack of standardization. According to author's research in 2017, there is no existing standard of DC distribution system, neither possible system layout, nor how the primary or secondary systems should be designed, nor what voltage should be used. The reasons may be the quick advancing of power electronics which may make the standard outdated quickly, or DC is still in the position of supporting AC systems, or engineering experience is still limited.

There are many standards regarding the AC electric system from equipment (e.g. transformers [70]) to the whole system (e.g. reactive power [71]). Also, there are voltage levels widely accepted which is convenient for designers, manufacturers and regulators. DC, on the contrary, only has the pieces for other applications, mostly, regarding to batteries (e.g. effort on standardizing EV charging station, battery related application such as UPS [72]).

2.5 Cost engineering basics

In this section, several cost estimation techniques used in this study are introduced, along with some terminologies.

2.5.1 Classification of capital cost estimates

The classification of cost estimates proposed by the American Association of Cost Engineering (AACE) with increasing order of accuracy is: "Order of magnitude" which has the accuracy of -30% to +50%; "Budget" which is of -15% to +30% accuracy; "Definitive" having -5% to +15% accuracy [73].

This work aims to achieve the accuracy of the class "order of magnitude", due to the fact that the electrical design in this work is conceptual where not all the loads are considered. Also, the cost data of many components in this study heavily relies on historical data which is adjusted according to numerous cost indices (e.g. Producer Price Index [74]). Additionally, it is common to face the situation where the size of the component differs from that desired, and an exponential factor or scaling factor is used to calculate the estimated cost. The actual scaling factor also varies according to equipment. [73] For example, squirrel motors have an exponent value somewhere around 0.8, while pumps have an exponent value about 0.6.

2.5.2 Scaling factor estimation

In this study, the method of scaling factor is used to estimate the cost of a component having a different capacity from the data found, or to estimate the cost of the up/down-scaled version of a component or a plant. This calculation uses Equation 2-9 which is commonly used in other industries such as chemical plants. [73]

$$C_x = C_k * (\frac{E_x}{E_k})^n \tag{2-9}$$

Where,

n is the scaling factor

C_x is the cost of the plant and/or equipment item of size E_x

C_k is the known cost of the plant and/or equipment item of size E_k

2.5.3 Present value analysis

Present value analysis (PV, or Present worth analysis) is a method that calculates the value of future cost or benefits over a period of time (usually the usable time or the life time) to the point of reference (usually the time when the analysis is performed). For example, all the cash flows of a power plant over its 50 years' life time are converted into the equivalent value in 2017 in order to determine whether it should be built or not. This method involves several simplifying assumptions keeping the problems manageable. [75]

- End-of-year: most economic analysis is based on end-of-period assumption which assumes that all payment is done by the end of the period/year.
- Sunk cost: It is assumed that past costs have no bearing on cost unless the past costs affect the present or future costs.

- Zero inflation and deflation: the price is assumed to be stable in present value analysis which means the equipment or labour costs the same amount of money as present over the studied period.
- Income tax: income taxes are not introduced in PV since it is outside of the scope. [75]

The PV calculation equation is

$$PV\ (i,\ n) = \sum_{t=1}^{n} F\ (^{P}/_{F}, i, t) \qquad (2\text{-}10)$$

where i is the annual interest rate,

n is the analysis period in year,

PV (i, n) is the present value at interest rate i over analysis period n,

F is the future sum of money at the end of the t-th year interest period,

P is the present sum of money which is calculated by

$$P = F/(1+i)^n \qquad \textit{(2-11)}$$

and $F(^{P}/_{F}, i, n)$ is the notation of calculating P by given F at interest rate i and interest period t. [76]

2.5.4 Levelized cost of electricity

Levelized cost of electricity (LCOE) is used to compare unit cost of generation of different generation technologies over their life time. This method focuses on the technology instead of a specific project, and it is widely used in energy industries and governments for decision making. This method is used for relatively stable and regulated markets, and it is highly influenced by discount rates. Equation 2-12 is a generic equation used to calculate LCOE. [77]

$$LCOE = \frac{\sum[(Capital_t + O\&M_t + Fuel_t + Carbon_t * (1+r)^{-t}]}{\sum[MWh * (1+r)^{-t}]} \qquad \textit{(2-12)}$$

Where

MWh is the amount of electricity produced in MWh, assumed constant;

$(1+r)^{-t}$ is the discount factor for year t (reflecting payments to capital);

$Capital_t$ is Total capital construction costs in year t;

$O\&M_t$ is Operation and maintenance costs in year t;

$Fuel_t$ is Fuel costs in year t;

$Carbon_t$ is Carbon costs in year t;

Dt is Decommissioning and waste management costs in year t.

2.5.5 Sensitivity analysis

The purpose of the sensitivity analysis is to help determine how one variation influences the estimated result as many factors (e.g. design change, inaccuracy with estimation method, regulatory impact, etc.) including uncertainty can greatly influence the result positively or negatively. It is critical to understand how a variation impacts the result, which helps quantify the uncertainty and minimize the risk. [76]

Since the time and resources are limited, sensitivity analysis is done on the variations that may have a larger impact. The attention is paid to the components that occupy a significant amount of total cost, the components with higher uncertainty such as those using new technology, and important parameter such as interest rate which may bring a profitable project to bankruptcy.

2.5.6 Generic analysis

Generic analysis is a kind of analysis using the average or the sum of a group having similar characteristics as a reference of study which constructs a behaviour of the studied group. In this thesis, instead of studying every individual load, those serving the same functionality at the same position (e.g. PHTS circulation pumps) will be grouped together, and there is one load (e.g. one pump) that has the power of the sum of all PHTS circulation pumps. This process significantly reduces the work load. Like the data gathering method, the result of estimation is highly influenced by other factors (e.g. regulation and vendors). The inaccuracy and uncertainty it introduces is addressed by sensitivity analyses.

2.5.7 Terminology

In this section, terminology that may be used in this study is presented. [73]

- Capital cost, direct: cost of all material and labor involved in the process of fabrication, installation and erection of facilities.
- Cash flow: the net flow of dollars into or out of the proposed project. The algebraic sum, in any time period, of all cash receipts, expenses and investments.
- Discount rate: the minimum acceptable rate of return used in converting benefits and cost occurring at different time to their equivalent values at common time.
- Interest rate: the ratio of the interest payment to the principal for a given unit of time and is usually expressed as a percentage of the principal.
- Labour cost: in construction, normally refers to field personnel other than craftsmen and includes field administration and field engineering.
- Present value: the discounted value of a series of cash flows at an arbitrary point in time.
- Profitability: a measure of the excess of income over expenditure during a given period of time.
- Project life or life time: total years of operation for any facility.
- Sensitivity analysis: a technique for measuring the impact on project outcomes of changing one or more key input vales about which there is uncertainty.

3 Methodology

In order to investigate the feasibility, some of the technological improvements and the financial impact of implementing DC electrical systems in a NPP, a DC electrical system is designed at a conceptual level along with its reference AC system, both of which are based on the basic requirements from relative standards and the selected plant design. The details of various techniques to estimate the financial impact are also described in this chapter.

3.1 Reference Reactor Design

To achieve a design with strong representation of a practical NPP electrical system for carrying out further analysis, a reactor design is selected by choosing a reactor type and then a specific reactor design. In each step, several criteria are used to find the design that best fits this analysis. The Canadian 4-class electrical system is used as a reference model to determine the type and power of the typical loads in a NPP (see Table 8-1) and the reason for choosing this type of electrical system over others is its available information in literature and the clearness in classification. If specific loads in the reference model are not suitable in the study model, then the characteristics of those loads are determined from other literature.

3.1.1 Selecting a reference plant design

There are two steps in selecting a reference plant design. In the first step, a type of reactor is chosen. Secondly, a specific design is selected within the type of reactor from the first step.

The following describes the criteria used to examine the existing reactor types --maturity, scaling ability and design with large non-AC loads.

Maturity: The adequate reactor type should have the existence of various designs for selection, which implies that the idea of its design principle is widely accepted by the academy, the industry and the regulation agencies. Improvements in terms of efficiency and operation to those designs can help the technologies become more attractive. However, after long term evolution, most commercial reactors are very well developed.

Major changes to systems such as electrical system or the fuel are unlikely. A commercial plant that has been designed to meet very high safety standards in nuclear industry, and the already developed regulatory experience to that plant design may find difficulty to adopt to new technology.

Scaling ability: Facing the environmental and economical challenge in recent years, the nuclear industry has been trying to meet more customers' needs, one attempt of which is providing variety of plant power level or load follows. Many Small/Medium Modular Reactors (SMRs, <300MW [78]) based on various reactor types have been designed. Therefore, it is important for a reactor type to have potential for a wide range of scale to meet different commercial needs in the future energy market. [78]

Previous design consideration with large non-AC loads: It is common to find some loads in a NPP are supplied by battery banks though DC buses, but most of them are not in a large power level and are emergency related loads. What this criterion actually means is that a reactor type includes one or more electric load which demands a larger quantity of electricity and requires power incompatible with the AC buses running on a 50/60Hz. The reason is that if the reactor needs such an electrical load, then a DC electrical system seems to be a better solution as the PE devices of such loads usually require a DC bridge. In some cases, DC power can be used directly for loads such as a DC motor. Details about different reactor types and how they score against the criteria are listed in Table 3-1, Table 3-2 and Table 3-3.

The Sodium Fast Reactor is chosen as a result since it meets all criteria mentioned above. It is at stage of early commercialization demonstration [11] and it could be easier for it to adopt and take advantage of newer technologies. The SFR has many specific designs across the power range such as BN series reactor-BN600, BN800, BN1200, Phénix and Superphénix, Power Reactor Inherently Safe Module (PRISM), Toshiba 4s. [11] Additionally, many SFR designs require non-standard electricity due to the use of EMPs. [13]

Table 3-1 Gathered reactor information regarding to maturity

Type of Reactor	Facts regarding to Criteria--Maturity
Sodium Fast Reactor (SFR)	Widely accepted concept with numerous designs, but not commercialized; Doors are open for improvement [13, 79, 80]
Boiling Water Reactor (BWR)	Highly developed with many years of commercial operation experience; only little room for improvement to be executed.
Pressurised Water Reactor (PWR)	Same as BWR
Pressurised Heavy Water Reactor (PHWR)	Same as BWR
Supercritical Water Reactor (SCWR)	It is based on BWR and in early design phase with many technical challenges to be solved. [81, 82]
Molten Salt Reactor (MSR)	MSR is still in early design stage with many technical issues to be solved; MSR has some designs in conceptual level. [79]
Gas Cooled Reactor (GCR)	Same as MSR
Lead Fast Reactor (LFR)	There are debates about the concept experiences regarding to corrosion. [83] Only few designs available.

Table 3-2 Gathered reactor information regarding to scaling ability

Type of Reactor	Facts regarding to Criteria—scaling ability
Sodium Fast Reactor (SFR)	Various designs from 10MWe (Toshiba 4S) to 1220 MWe (BN1200) with similarities in plant layout. [13, 78]
Light Water Reactor including BWR and PWR	Various designs from 25MWe or lower (CAREM) to 1356MWe in Kashiwazaki-Kariwa. [84]
Pressurised Heavy Water Reactor (PHWR)	A few available designs ranged from 102MWe (CANDU 80) to 1200MWe (ACR-1000).
Supercritical Water Reactor (SCWR)	The number of designs is limited. (FY-03) [85]
Molten Salt Reactor (MSR)	There are a number of designs ranging from 10MWe (mini Fuji) to 550MWe (Transatomic TAP); the design layouts differ widely. [78]
Gas Cooled Reactor (GCR)	There are a number of designs ranged from 10MWe (Urenco UBattery) to 240MWe (EM2, General Atomics); The design layouts differentiated widely. [78]
Lead Fast Reactor (LFR)	Very few options available from 3MWe (SEALER) to 300MWe (BREST300) [78]

Table 3-3 Gathered reactor information regarding to non-AC loads

Type of Reactor	Previous design consideration with large non-AC loads
Sodium Fast Reactor (SFR)	Electromagnetic pumps are using electricity in neither 50 nor 60 Hz. In fact, DC induction pump is using DC while AC conduction or AC induction pump is using AC, the frequency of which varies based on the demanded power. [12, 13, 43, 46, 80]
Pressurised Heavy Water Reactor (PHWR)	None of the large loads requires electricity in the form other than standard 50 or 60 Hz. [10]
Boiling Water Reactor (BWR) and Pressurised Water Reactor (PWR)	Same as PHWR
Supercritical Water Reactor (SCWR)	Same as PHWR
Molten Salt Reactor (MSR)	Same as PHWR
Gas Cooled Reactor (GCR)	Same as PHWR
Lead Fast Reactor (LFR)	There is literature proposing EMPs for LFR, so here it is considered the same as SFR. [43, 45]

Afterwards, the following criteria are used to select a specific design in the SFR category. There are more than a dozen SFR designs from all over the world, some of which are designed to close the fuel cycle or breeding while some of which are designed to lower the cost[11]. There are also various designs in different stages. BN600 which is designed in Russia, for example, is operating while BN800 (considered to be a final step of commercialization) is under construction. Also, ASTRID from France and PRISM from the United States are in licensing and R&D stages respectively[11, 14]. The following criteria help narrow down to specific designs suitable for this analysis.

Criterion 1: Pool design configuration

Pool type configuration is chosen for the following reasons.

1. A pool type design is better from the safety viewpoint. Experience from many previous experiments and reactor operation shows a pool type design can withstand more severe accident scenario due to the large amount of sodium in the vessel providing heat sink. [12]
2. There is considerable heat loss in the primary heat circulating pumps which sometimes need to be cooled by water such as those in CANDU 9[10]. In a pool type SFR, the waste heat from the submerged EMPs can be ejected to the coolant and then recovered in the steam cycle which leads to an overall increase in plant efficiency. This can be significant as an EMP has lower efficiency (about 50%) compared to motor driven centrifugal pumps. [45]
3. Many mature SFR designs use pool type designs resulting in a wider range of information and choices available. From reference [13], the more mature designs tend to use the pool design.

Criterion 2: Steam Cycle

Most SFR designs are running with a steam cycle coupling with an intermediate sodium loop. [11] With numerous designs and operating information available for steam cycle (e.g., PRISM, BN-600) [13, 86], only those using a steam cycle will be considered in this analysis. Even though supercritical carbon dioxide is proposed to be a better working fluid for SFR power generation due to its superiority in cycle efficiency and potential solution to the sodium-water reaction issues, however, insufficient information is found to support an analysis on the electrical supply system. [87]

Criterion 3: Design with EMPs operating experience

The best scenario for this analysis is that the design itself includes EMPs or an EMP is being considered as an option when the reactors are designed (e.g. Toshiba 4S [16]). In this case, there is no need to modify one of the major loads, the PHTS pumps. Additionally, PE devices are required in the original designs.

Judging according to these criteria, the PRISM reactor design is chosen as the primary reference reactor design as it is a pool type design with steam cycle and uses EMPs as both primary heat transport circulating pump and intermediate circulating pump. It is important to know that PRISM and Integrated Fast Reactor have a similar design as they are both based on the EBR I and EBR II. [12, 88]

3.1.2 Determination of load characteristics

3.1.2.1 Downscale loads from CANDU 6

The basic reactor layout is based on the design chosen in the last section, but the loads characteristics are not yet determined. The approach to determining the loads characteristics is using the data from PWR or PHWR for balance of plant loads due to the fact that balance of plant loads in SFR are similar to that of PWR or PHWR [80], the reason of which is the capacity and power of the balance of plant components are similar in SFR and PWR/PHWR. For example, a SFR having 100 MW thermal output uses almost the same balance of plant components (e.g. fluid pumps, etc.) as a water reactor. [13, 19] Based on the information available in the literature [10, 18, 19, 21], the loads in the study SFR in terms of their types and power consumption are based on the CANDU NPP, particularly, the CANDU 6. For example, boiler feed pump is a motor driven pump in the CANDU 6, which means the boiler feed pump in the SFR is also driven by a motor. However, the power consumption is scaled down according to the size of the design which is discussed below. The major loads in each class are well documented in the literature. [10, 20, 89] However, CANDU 6 is a very large design with an output at about 700MWe or 2134MWth (steam cycle efficiency at about 33%) [10], while the reactor in this study is 300MWth, for which reason a downscale is performed. The method of achieving the desired scale is by calculate the product of the power output ratio between the two plants and the power of those loads to get the power requirements for the reference reactor. In the design of CANDU 80 which is a downscaled version of the CANDU 6, the station service power is about 7MWe and ratio between thermal power of CANDU 80 and CANDU 6 is the same as the ratio of station service power between CANDU 80 and CANDU 6. This method is also used in Reference [20], and it seems to be reliable.

$$P_{300MWth} = Load\ of\ CANDU\ 6 * \frac{300MWth}{2134MWth} \tag{3-1}$$

Where $P_{300MWth}$ is the estimated power of loads in 300MWth reactor.

The calculation result of the major loads[7] for the reference reactor is listed in Table 3-4.

[7] Major loads are either large in power or important to plant safety, see Section 2.1.4.

Table 3-4 Power of major loads in CANDU 6 and the down-scaled version for reference SFR reactor

Class	Loads	Power(kW) in CANDU 6	Power(kW) of Down-scaled components
IV	Main boiler feed pump	3700	520
IV	Main heat transport circulation pump	6700	942
IV	Condenser cooling water pump	2600	366
IV	Condenser extraction	1900	267
III	Moderator circulation pumps	750	105
III	Heat transport feed pumps	1675	235
III	Auxiliary boiler feed pump	260	37
III	Auxiliary condensation extraction pump	56	8
III	Shutdown system cooling pump	220	31
III	Service water pumps	410	58
II	Digital control computer	Unknown	
II	Reactor regulation instrumentation	Unknown	
II	Electrical operated process valves	Unknown	
II	Emergency lighting	Unknown	
II	Auxiliary oil pumps for turbine and generator	Unknown	
II	Total power of Class II	150	150
I	Emergency seal oil pumps	7.5	7.5
I	Turbine lube oil emergency pump	55	55
I	Emergency stator water cooling pumps	Unknown	
I	Protective relay	Unknown	
I	Logic command circuit control	Unknown	
I	Circuit breaker control	Unknown	

3.1.2.2 Assumptions for Class I and Class II loads

In the case of Class I and Class II, it is assumed the electronic devices of the control system and pumping loads (mainly emergency load) consume similar power across different plants. This assumption does not affect the accuracy significantly because the power demand in both classes is relatively small when compared to Class III and Class IV loads and some of them are operating only during emergency.

Also, all power data is missing for Class II loads and most of the Class I is also missing, some assumptions are made in order for further analysis to be carried out.

a. It is assumed that the total power of Class II loads is 150kW with a power factor of 1.0 which comes from the fact that the capacity of inverter supplying Class II from Class I is 0.15MVA. [10]
b. The total power of Class I loads (not included the inverter for Class II power) is assumed to be the same as Class II which is 150kW. The reason why the inverter is excluded is that devices that alter electricity form in terms of either voltage or frequency, or both, are not considered a load in any class, instead, they are categorized/referred to as electricity converters which also includes traditional AC transformers.
c. Within both Class I and Class II, some loads are pumps (some are instrumentation and control devices) with an uncertain portion. Hence, it is assumed that 130kW of 150kW is motor driven loads using one pump of 130kW to represent, and others are assumed to be electronic related devices using lower voltage power. This is not important to this work as the work focuses on the power distribution, and the electronic devices usually use much less power than devices such as a boiler feed pump.

3.1.2.3 EMPs characteristics calculation

The information in CANDU relative literature about the main heat transport circulation pump in Class IV and Moderator circulation pumps in Class III is not suitable for further analysis since the reference reactor is a SFR which has no moderator and uses sodium as coolant. Hence, the type of loads and power differ from that of the CANDU 6.

Additionally, it needs another set of pumps for the IHTS. Therefore, a calculation on the power of main heat transport circulation pump is done as the following.

The power of the main heat transport circulation pump in the reference reactor is calculated using the following approach. Toshiba designed a large electromagnetic pump for an intermediate sodium loop application in the Advanced Sodium Technological Reactor for Industrial Demonstration (ASTRID) sodium-cooled fast reactor for France, based on the company's experience in developing pumps for the Toshiba 4S. [46, 48] There are 4 pumps for ASTRID. Each of them is capable of pumping sodium at the flow rate of 1.98 $m^{3*}s^{-1}$ or 1916.64 $kg*s^{-1}$, and power of ASTRID is 1500 MWth or 600 MWe with a EMP power requirement of 1.74MW. Therefore, the flow rate requirement is calculated to be:

$$1916.64\ kg \cdot s^{-1} * 4 \div 1500\ \text{MWth} = 5.11k\ g \cdot s^{-1}/MWth$$

(This number is verified by the PRISM design which is $5.25\frac{kg}{s*MWth}$ [13].);

and power demand requirement is calculated to be:

$$\frac{1.74\ MW * 1000\ kW/MW}{1916.64\ kg/s} = 0.907\ \ kW/kg \cdot s^{-1}$$

Based on the above calculation of flowrate requirement, the reference reactor, which has the power of 300 MWth, requires sodium flowrate of 1533 kg/s. Based on the above calculation of power, the total power requirement of the intermediate heat transport circulation pump is 1.39 MW. Additionally, the PHTS requires an 8% higher flow rate than the IHTS [13], so the power of the main heat transport circulation pump is 1.50MW.

Forced circulation of the sodium in the PHTS and the IHTS during shutdown is enabled to remove decay heat as a safety feature which also gives more control to designers and operators[8] [11, 12, 80]. In most SFRs, decay heat removal capacity is less than 5% (e.g. EBR-II 0.56%, Phénix and Super-Phénix 2.1%, BN-600 3%) of its rated thermal power [13]. Thus, in this study, the EMPs in PHTS and IHTS are also connected to a Class III

[8] The PRISM and many other SFRs does not need force sodium circulation for decay heat removals due to their passive decay heat removal feature.

bus through a switch gear. They draw power from the Class III bus during occasions such as Loss of Class IV and shutdown. The power requirement is 5% of the rated full power of the pumps.

The complete list of loads for the reference reactor is in Table 4-1 in the result section. This study focus on the concept of using a DC electrical system for power distribution. Thus, most attention is paid to the larger power equipment and how the power is delivered from the power source to those loads through the system.

3.2 AC reference system

3.2.1 Basic system requirements

This section outlines the key requirements for a NPP electrical system and some design assumptions helping focus on the objective, both of which apply to both AC and DC system.

Assumptions

The following assumptions are made to address some common but less significant requirements in the electrical system.

1. It is assumed that automatic switch mechanisms with control logic and adequate switching performance for loads to alter between supplying buses without triggering other protection are in place in the electrical system.

   Justification: This mechanism has been well developed and used for many years [10].

2. It is assumed that the backup is sufficient for the system to meet the safety standard. The total capacity of the battery is enough for Class I and Class II to operate for 60 minus, and each generator has the capacity to power the loads as required and the fuel sufficient for 5 days' operation. [10, 18]
3. It is assumed that there is sufficient compensation to achieve a power factor greater than 0.8 and a DC distribution system is considered to always have the

power factor as unity (1.0). That is an advantage of DC, which will be discussed in later sections.

4. It is assumed that there are sufficient monitoring and protective devices for instrumentation and control purpose.

Justification: An electrical system is not working safely without the related protection such as a relay system or fuses. This study focuses on the primary equipment such as transformers, I&C devices of AC and DC system is out of the scope.

Requirements

The requirements presented in this section are critical to plant safety and operation which also have a significant effect on further designs and analysis.

1. The loads shall be separated into classes regarding to their importance to plant safety, and the electrical system shall also be designed into classes accordingly.

Justification: All IEEE standards [90] and IAEA safety standards [9] require categorizations of the electrical loads to improve the safety and economy of a power plant.

2. The tolerance to interruption in each class is infinity for Class IV, 5 minutes for Class III, 6(six) milliseconds for Class II and null for Class I.

Justification: This requirement follows the one in N290.5-06 from Canadian Standard Association [18]. A system with a better performance (quicker recovery) is acceptable.

3. The electrical system shall be able to supply sufficient electricity to the loads.

Justification: The electrical system shall be able to distribute sufficient power to the loads required for heat removals. Nuclear power safety is guaranteed by making sure the energy generated by the reactor core is under control, and safely and sufficiently removed from the core and other components and the electrical system shall provide enough power to devices which are able to provide sufficient coolant flow.

Specifically, the devises transmitting power from the main generator or the switch yard shall have the ability to power all Class IV loads, loads necessary for normal operation in Class III, all loads in Class II and Class I. Devices transmitting power from Class IV to Class III shall be able to provide power for Class III itself, Class II and Class I. Devices getting power from Class III and powering Class I and Class II shall have the capacity for Class I and Class II load.

4. An electrical system shall have the ability to provide adequate electricity (voltages, AC or DC, etc.) to the loads, and the voltage shall follow the widely accepted standards.

Justification: There are numerous kinds of loads in the system requiring a wide range of electricity depending on their needs, some of which require high power at a higher voltage level (e.g. the high power main boiler feed pump which needs a higher voltage level in order to lower the current and the loss), and some of which need much lower voltage (e.g. electronic devices like a processor in digital control computer can only withstand several volts).

In order to avoid the extra cost of highly customized components for better plant economy, the voltage shall be selected according to the regional standards so that price-competitive products with various choices from different manufacturers can be compared and implemented. This study uses North America standards. [91].

5. The sub-systems in each class shall be able to operate separately from each other.

Justification: Sub-systems within each class shall be able to operate by itself as long as they have the power. For example, Class III can maintain a quality supply for its loads whenever power sources such as transformers from Class IV or standby generators are available. Additionally, the voltage in the sub-system can be controlled and maintained by itself.

6. The redundancy of the main buses shall meet the IEEE and IAEA standards.

Justification: IEEE standard [90] and IAEA safety standard [9] all require redundant buses for critical loads and they shall be physically and electrically separated.

7. The electrical system shall be able to withstand a sudden load increase or decrease on the buses.

Justification: In the event of a sudden increase or decrease of loads, the voltage of the buses may fluctuate or the current may not be sufficient if the electric convertor is not responding. Therefore, it is required for the system to respond to theses change automatically and quickly to maintain a quality power supply.

8. An electrical system shall be able to isolate malfunctioned devices.

Justification: The detailed requirement is that the system shall be able to isolate every load listed in Table 4-1and all electricity converters.

Whenever there is a device malfunctioning, it shall be isolated while the rest of the system shall remain operational to prevent the plant to shut down or experiencing safety crisis. The isolation should be as electrically close to the malfunction device as possible in order to keep the spread of malfunctioning as a minimum[9]. For example, one of the cooling water circulation pumps (Class IV load), for example, is short-circuiting due to the isolation failure in the stator, the much higher current of which may trigger the connected bus protective relay and result in a loss of the Class IV power. However, the Class IV can remain functional if the pump can be isolated immediately at its terminal, and the plant can still be operating.

9. The electrical distribution system shall have over current protection.

Justification: The distribution system shall have the ability to detect and cut off unusual large current, and the extreme case is short circuiting on buses. [2]

10. The electrical system shall be able to start by itself.

---

[9] The response time is also critical for controlling the incident such as voltage drop and short-circuit current. A comment will be given, but detail analysis of responsiveness is out the scope of this study.

Justification: Components in distribution system and loads shall be able to start up when it gets energized. In the case of Station Black-Out or before the standby generators start up, the system except for Class II and Class I may experience a loss of power and it shall return to operation automatically, when the power becomes available.

3.2.2 System design

In order to design the system effectively, the following steps from the conceptual to specific level are used, which are concept layout, classification details, and finalization.

1. In the step of concept layout, the system is conceptualized by following the power flow. The number of energy sources and energy paths are determined.
2. In the step of classification, the voltages of each bus are determined. Electricity converters are also added to the paths where the change in electricity forms is necessary.
3. In the final step, more design details are finalized to meet some specific requirements.

3.2.2.1 Concept layout

The design concept is illustrated in Figure 3-1 where there are two main energy sources, two long-term backup energy sources and two short-term energy sources. There are two main energy paths which are independent (A and B) with interconnections.

This design is similar to Canadian 4-Class system where non-critical loads are on Class IV, and critical loads are separated into Class III, Class II and Class I with long-term backup source being the diesel generator and short-term backup being the battery banks.

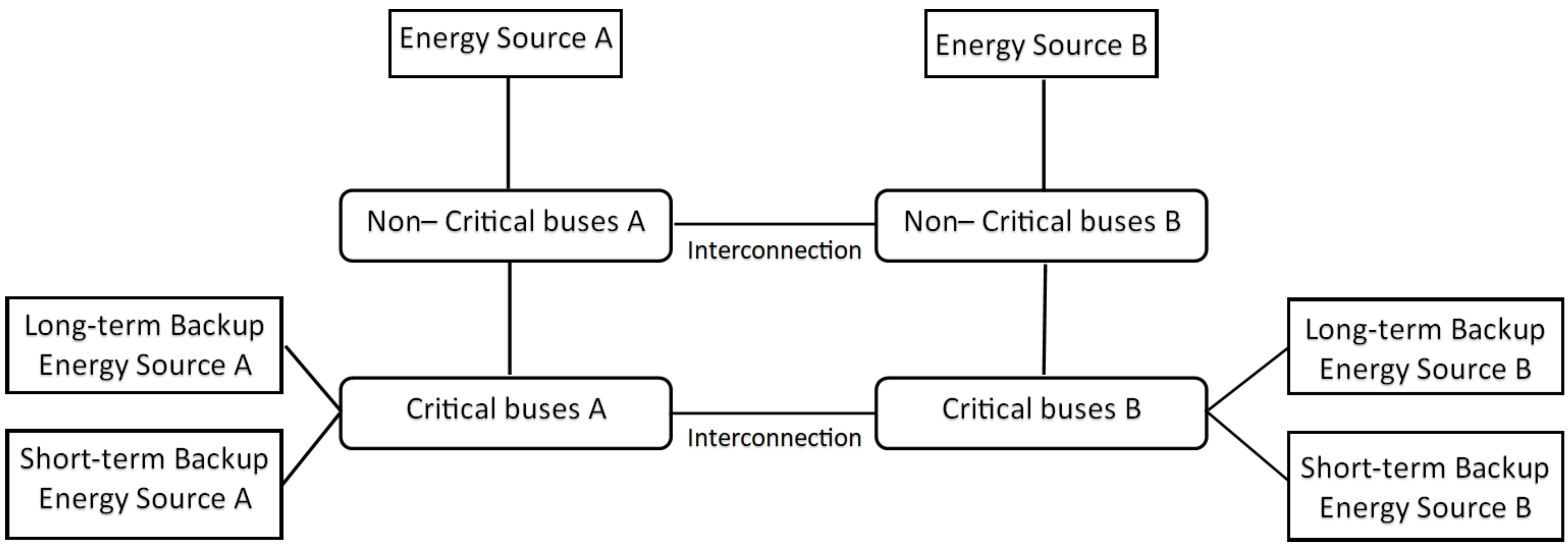


Figure 3-1 Design concept

3.2.2.2 Classification details

Class IV

In Class IV, there are two levels of voltage serving different power level loads. The following describes the determination of voltage. The standard voltage levels for 3-phase system are 240, 480, 600, 2400, 4160, 4800, 6000 and so on, and the current in this work is less than 2000A which meets the IEEE standard. [91] Therefore, the largest power for each standard voltage level is 240kW (240V), 480kW (480V), 600kW (600V), 2.4MW (2400V), 4.16MW (4160V), 4.8MW (4800V), 6MW (6000V), etc. According to list of loads in Section 3.1.2, 480VAC is chosen for the loads demanding power less than 480kW as this is most widely used voltage for industrial applications and 2400VAC for those having higher power demands. [91]

The capacities of the unit service transformer (UST) and station service transformer (SST) are the same and sufficient for supplying all loads for power generation operation. The maximum power required is calculated by summing all loads in Class IV (that is 4043kW) plus service water pump(58kW) plus all loads in Class I and Class II (300kW total) which gives an estimation of total electric loads for UST or SST for 4410kW. Therefore, the capacity of each transformer is chosen to be 4.5MW. The uncertainty associated with power of excluded load and possible design margin is addressed by equipment cost sensitivity analysis. So are the other classes.

There are two voltage levels in Class IV, for which there are two transformers for supplying those loads that are not connected to the 2400VAC buses. The capacity of each transformer is calculated by summing all loads required under normal operation except for those on 2400VAC which is 991kW. Therefore, the 1000kW transformer is chosen. The uncertainty associated with power of excluded load and possible design margin is also addressed by equipment cost sensitivity analysis.

Class III

In Class III, 480V is chosen because there are a large number of industrial devices using this voltage and it is the same voltage as the lower voltage of Class IV which avoids additional transformer in between and thus improves economy. The standby generators are connected to 480V buses as well.

Converting AC in Class III into DC for Class I is done by two sets of transformers and rectifiers (referred as a rectifier system). The transformer used to supply desired voltage to the rectifier is a converter transformer, and the capacity of the rectifier system is 300kW which is sufficient for both Class I and Class II.

Class II

In terms of voltage in Class II, it is 480VAC as Class II draws power from Class III directly in the case of an inverter failure. There is only one voltage level in Class II. The power source is Class I inverters with converter transformers for desired voltage, and the capacity of which is 150kW.

Class I

In Class I, there are two voltage levels, the 120VDC of which is for pumps and the 48VDC for electronic devices. To provide continued power to Class I, battery banks are connected to the 120VDC buses. In terms of the 48VDC, an existing method is used to achieve this different voltage which is a DC-AC-DC link, this is for comparison to the other type of DC-DC converters discussed in the DC system design section. Specifically, an inverter is used to convert DC to AC with a transformer designed to supply desired voltage to rectifier which provides the final 48VDC.

3.2.2.3 Finalization

This section discusses small aspects in the design which is important to meet the stated design requirements.

- Two backup generators are connected to Class III with the power sufficient for shutdown operation which means it is able to supply Class III, Class II and Class I loads, and the capacity of each generator is 600kW.
- There is a switch gear for each load to switch between buses A and B.
- The design is examined against the rule "failure on any of two components cannot trip the system".
- EMPs drive is a rectifier system, and centrifugal pump is powered by motors which is connected to buses via a breaker.
- Flowrate control is done by control valves.

The system diagram with description and requirement fulfillment is in result section.

3.3 Design of the DC electrical system

3.3.1 Criteria for determining the feasibility of the DC system

During the design process, the following criteria determines whether the DC system is unfeasible or unsuitable for a NPP application.

- If any component necessary in the DC system to function is not feasible, then the system will be called unfeasible and comments will be given about whether it is theoretically impossible or it is impossible for the current technology to achieve in the short term. The way to determine whether a component is feasible is by searching for existing a commercial product or a research oriented prototype. The components can come from any industry as long as it can technologically prove the DC electrical system and comment of suitability will be provided which describes possible solution to make it suited in a NPP.
- If the interfaces between two components are not ready (e.g. the DC VSD and the DC-DC converters cannot work with each other), then the system will be called unfeasible and comments about the problems will be given.
- If the whole system cannot function for some inherit problems, then the system will be called unfeasible. It will be determined whether it is due to the inability of using the AC configuration for DC system, and a further modification or system redesign will be performed. If it is only an engineering problem, a possible solution will be presented.
- If the system cannot meet any of the stated requirements, then the system will be called unfeasible, and possible solution will be provided if applicable.

In the case where the DC system is feasible in concept, a comparison between DC and AC electrical system in the NPP application will be performed. The method is to compare the key performance of components serving the same functionality, then a comparison of both systems as a whole.

This is to determine whether the DC system concept is feasible in a NPP and the potential technological benefit and challenge which could have contributions to the research direction of this NPP application of Power Electronics Distribution System.

Furthermore, the design result is used for a financial comparison determining the impact of such system.

3.3.2 System Design

3.3.2.1 Concept layout

The design of the DC electrical system is based on the identical requirements and same design concept in Figure 3-1 as the AC system, and it will be designed closely to the AC system. The reasons are:

1. It is more accurate to do comparison between similar systems with the key difference being the technology itself to prevent an inaccurate result.
2. The ideas and principles of distributing energy through the plant according to the needs of loads in a NPP remains the same. The classification and operation of the AC system for maximum plant safety, efficiency, cost-effectiveness, etc. should be inherited by the DC electrical system.

The DC system has the same physical layout as the designed AC system with the same number of buses and power source, the inter-connections, and the same power requirements. What is changed is the electricity converters necessary to enable DC power, and some aspects the classification (details below).

3.3.2.2 Classification details

The physical layout and design concept is the same as that of the AC system, but the classification of the electrical system differs from the AC system. Specifically, the Class II in the DC system is treated as Class I in a “Combined Class I and Class II” or “Class I&II” in short. Class I has zero tolerance to interruption (Class II is 6 millisecond) with battery backup, the Class II loads, now, in DC system can be treated as Class I for the following reasons:

1. It is technologically possible to combine Class I and Class II in the DC system since there is no problem finding a pumping solution for the power and type of loads in Class II (e.g. DC motors) and the battery banks can be connected directly to the Class II buses which gives the same degree of availability as Class I.

2. It is not necessary to separate Class I and Class II loads in the DC system, since both classes are DC-powered with the same availability. In comparison to the AC system where Class II is allowed and may experience milliseconds of interruption, the combined Class I and Class II in the DC system is an improvement.
3. It is possible to keep the existing separation between Class I and Class II as that in the AC system, but this configuration may require a different type of DC-DC converters. This may have negative impacts to plant economy.

Voltage determination

There are three major types of loads (EMP, induction motor and electronic devices) and only the AC induction motors are both power demanding and standardized in term of voltage and frequency (see next section for the reasons of choosing AC induction motors). The PWM inverters (see Section 2.2.6 and Section 2.2.7) used in most commercial VSDs has maximum AC voltage output related to the DC input in linear control region (over-modulation operation is not considered). Therefore, the DC buses voltage shall be decided according to the motors and the PWM VSDs.

$$V_{peak-AC} = \frac{V_{DC}}{2} \tag{3-2}$$

Where $V_{peak-AC}$ is the peak voltage value of one phase to neutral in an AC system.

$\frac{V_{DC}}{2}$ is the voltage between DC bus and an artificial neutral point.

$$V_{line-to-neutral\ AC} = V_{peak-AC}/\sqrt{2} \tag{3-3}$$

$$V_{line-to-line\ AC} = V_{line-to-neutral\ AC} * \sqrt{3} \tag{3-4}$$

$V_{line-to-line\ AC}$ is the number described in the standards.

Hence,

$$V_{DC} = \frac{2\sqrt{2}}{\sqrt{3}} * V_{line-to-line\ AC} \tag{3-5}$$

The chosen voltages in the DC system is slightly higher than the calculated which can be justified by that the inverted AC voltages at VSDs output do not exceed the standards limit. [91] Table 3-5 summarizes the result of voltage determination in the DC system.

Table 3-5 Voltage selecting result summary

Class	AC system voltage	Calculated DC voltage	Chosen DC voltage	Maximum VSD terminal AC voltage[10]	Upper voltage limit in IEEE standard [91]
IV	2400 VAC	3919 VDC	4000 VDC	2449 VAC	2520 VAC
IV	480 VAC	784 VDC	800 VDC	490 VAC	504 VAC
III	480 VAC	784 VDC	800 VDC	490 VAC	504 VAC
II	480 VAC	784 VDC	800 VDC	490 VAC	504 VAC
I	120 VDC	120 VDC	120 VDC	N/A	N/A
I	48 VDC	48 VDC	48 VDC	N/A	N/A

[10] The VSDs are capable of controlling both the output voltage and frequency, hence, they can be tuned to output voltages suitable for the motors and their operation conditions.

3.3.2.3 Selection of technologies

There are currently many types of converter technologies available for each component since much effort is put into the relevant research. Rectifier, for example, has two main categories—Line Commutated Converter running on semi-controlled thyristors and Voltage-source converters (VSC) running on fully-controlled IGBT or GTO. In this section, specific technologies are chosen for the system component.

Rectifier

A Line Commutated Converter rectifier using thyristors is relatively mature and has been operated for many years, but it requires many accessories in order to reach a desired performance. The system is usually complicated and large in size due to its need of a large converter transformer, compensation devices and other filtering devices (see Section 2.2.4).

A Voltage Source Converter rectifier using fully controlled (or self-commutated) devices such as IGBTs, GTOs and power MOSFETs which were mostly used in PWM inverters are brought to the HVDC transmission in recent years. Since it consumes little or no reactive power and generates much less harmonics compared to Line Commutated Converter rectifier, this technology has become attractive for limited space area [29].

Since traditional mechanical circuit breaker has trouble cutting off constant voltage DC power and solid-state circuit breaker could be very expensive [67], Line Commutated Converter technology is chosen in this study to address the overcurrent protection concern. Proper design in relay system logics along with Line Commutated Converter ability of quick-responding reverse direction operation (sucking out remaining energy in the system) enables a high-performance overcurrent protection system. [69] More specifically, a monopole 6-pulse system is used in this study because the power level in the system is relatively low.

The capacity of each set of the converter transformer and rectifier is 4.5MW same as the AC reference system. This system is feasible because the technology has been implemented in HVDC transmission system for a long time with power level up to several GWe at the voltage of 1000kV (e.g. the “Réseau multiterminal à courant continu” project –2 GWe [92]).

DC-DC converter

Many efforts have been put into the development of high power DC-DC converters in terms of circuits, and many designs have been proposed including the bulk type converter, the booster type converter, the buck/boost type converter, the Zero Voltage Switching or Zero Current Switching DC-DC converter, etc. [1, 33, 93] In fact, smaller power DC-DC converters can be found in changers used in daily life. Although many DC-DC converter designs are capable of operating for both level-up and level-down voltage, in this application where only the step-down function is needed, there is no advantage of using these advanced designs which are usually more complex and expensive due to the increased number of switches. The traditional bulk type converter is chosen for this application. Compared to most other deigns, bulk type converter only uses one IGBT which gives a simple and relatively cost-efficient solution. The concern of having different types of DC-DC converters and the financial impact in terms of equipment and O&M cost is addressed in sensitivity analysis. [1, 7]

Motor solution

For motor technologies used to pump water in the plant, there are three main solutions to implement motors in a DC system which are an AC induction motor with an inverter, a brush DC motor with a controller and a brushless DC motor with a controller. These three candidates have their own advantages and disadvantages, which are provided in Section 2.2.7. Table 3-6 outlines the pros and cons of these drives. Overall, the AC drive control is mature, responsive and precise, while the driven induction motor has the same level of power and torque as DC motor but is superior in cost and maintenance requirement. Additionally, this solution also keeps the motor unchanged from the AC system with an additional VSD controller placed in front of motors which reduces the complexity of the financial analysis. Therefore, the AC VSD is chosen as solution for water pumping loads. [39]

Electronic devices

As mentioned above, most electronic devices are considered one unit with its own power converter inside. The discussion of the technologies used in the AC and DC systems to supply those devices is out of the scope of this study.

Table 3-6 Comparison of several drive technologies(based on [39])

	AC induction motor	Brushed DC motor	Permanent Magnet Brushless DC motor
Efficiency	High	Moderate	High
Specific cost	Moderate	Low	Very high
Resistance to humidity	High	Low	High
Maintenance requirement	Low	Moderate	Low

3.4 Financial analysis

3.4.1 General methodology

3.4.1.1 Objective and simplification

The objective is to determine the financial impact of implementing the DC electrical system, which means the premium paid or saving gained from this AC to DC transformation. To achieve that objective, the components from the AC and DC conceptual designs will be compared to figure out division between these two systems, based on which further analyses will be carried out. The DC and AC systems are designed to be similar which allows a parallel comparison of system components. As a result, it produces a list of changed equipment for calculating the financial impact.

There are some assumptions to keep the scope manageable with adequate accuracy.

1. The labour cost of installation of the parallel component in AC and DC system is assumed to be the same.
2. The operation cost is assumed to be energy used by the equipment since the components in both systems do not require fuel or periodic change of parts and the majority of cost is from energy usage. For example, many researchers consider the operation cost as the energy consumption plus the maintenance cost or the cost of loss alone in a transformer life-cycle analysis, and since the maintenance cost is considered separately in this study, the operation cost is considered the cost of energy consumption. [94, 95]

This analysis focuses on calculating the present worth (PW) of cost from two aspects which are the equipment cost and O&M cost. [75] In this analysis, equipment cost means the financial impact on purchasing the equipment caused by using DC electrical system rather than AC, while O&M cost means the expense differences when operating and maintaining the DC electrical system rather than AC. This is achieved by calculating the equipment cost and O&M cost of both the AC and the DC system.

In terms of the loads, the method of generic analysis discussed in background section is used [96], as the focus rests on the differences between AC and DC components and the accuracy is set to be in the order of magnitude. Specifically, the quantities of all load components are set to be one even though this may not be true in reality due to regulation (e.g. redundancy), efficiency concern (e.g. one of several parallel pumps is operating when the plant is operating at lower power). [10] The data and calculation is based on the requirements (e.g. power and cost) of one component instead of two or more. The introduced uncertainty is addressed by sensitivity analysis. Noticed that number of the components in the distribution system is two which matches the number in the design layouts.

3.4.1.2 Coverage and justification

In this analysis, only major components that can influences the result the most will be covered. The reasons are:

1. The largest components (assuming they are costliest) have the biggest impact of the total cost.
2. Other components are assumed to experience the same impact in percentage as these large components. For example, a small transformer serving, say, the vacuum pumps for the vacuum building, will experience a 20% (assumed) increase in cost from converting to DC just like those larger transformers studied in the work. Hence, the impact expressed in percentage is meaningful and can be used to estimate an actual plant.
3. Some of the components are hard to determine the cost due to insufficient commercial data of the components (e.g. PE devices) or the confidentiality of some NPP data.

3.4.1.3 Data gathering methods

Several approaches are used in this work to help obtain a more accurate basis for estimation.

1. Data from actual engineering projects that have been built for demonstration or commercial purpose is preferred as the numbers from projects are usually more comprehensive in estimation process.
2. The second-best option is to gather the purchasing price of the studied components plus additional cost of necessary accessories.

3. The alternative for estimating components (e.g. DC-DC converter) missing purchasing price is to find a relatively comprehensive design and the costs for its sub-components, and use the sum as the cost of the components (e.g. transistors and controller). This method usually underestimates the actual cost for the missing labour cost and profit margin.
4. If there are more sources available, an additional verification is performed via comparing similar projects in literature or consulting people in the industry, etc. The issue of inaccuracy in costs is addressed by sensitivity analysis.

In terms of operating cost, the focus, as stated above, is on the usage of energy when it is operating. There are several ways to calculate the losses of those components, including:

- Collecting and calculating the average loss from manufacturers.
- Literature review on studies regarding the efficiency of a component.
- Reviewing surveys on related projects about their operation cost.

The estimation of maintenance cost is similar to operation cost which is gathering information from various resources including manufacturer data, literature and project surveys. Since some of the components are newly developed or under development and the maintenance requirement may not be available, the data is based on components using similar technology or/and having similar design.

3.4.1.4 Discount rate and LCOE

In terms of the discount rate, the base model is of 7%, while 3% and 10% are used in sensitivity analysis, and there are two main reasons for this selection.

1. The "cost of capital" in U.S., Germany, Korea, U.K., Netherland, New Zealand and Switzerland ranges from 3% to 10%, and average at 7% for different power generation technologies (e.g. coal-fired power plant, hydro plant, wind farm, solar farm, etc.). The "cost of debt" is about 6% in those countries. [77]
2. It is appropriate to use 7% for electric utility investment in a regulated market. However, 3% can be used for government-owned project in counties with high bond rating. [77]

This work is about cost impact to a plant which means the LCOE may change due to the implementation of the DC system, but within the analysis, it is unavoidable use LCOE to calculate some critical cost. Therefore, it is assumed that the LCOE does not change between the AC and the DC systems in this analysis, and the value of LCOE is by referencing an average of estimations regarding to advanced nuclear technologies done by U.S. Energy Information Administration for plants which are projected to be online from 2016-2022 [97-104]. The average LCOE is about 105 USD/MWh.

3.4.1.5 Data processing and other discussions

The cost data is collected according to the AC and DC system models designed in previous section, and then is used to calculate the equipment cost as well as annual O&M cost. The processed data is presented in a data sheet in terms of cash flow, based on which PVs of these AC and DC system models over 50 years at an interest rate of 7% is calculated. There are some assumptions made during this process.

- It is assumed that the capital cost is at the beginning of Year One (also referred as Year Zero).
- The O&M cost is paid at the end of the year, starting Year One.
- The analysis period is 50 years. After 50 years of operation which is the design lifetime of many nuclear power plant, the plant may need refurbishment to extend its life-time.
- The O&M cost does not change over the plant lifetime.

This process gives an overall result in PV to compare these two systems. However, this general result may not be sufficient to understand how the PE technology actually impacts the electrical system. Therefore, the AC and DC systems are separated into two sub-systems--the distribution system and the load similar to the idea used to categorize electrical power system, which can give an in-depth vision of the causes.

A power system is usually categorized into three main sections--power generation, transmission and local distribution. Since the generation in a NPP is done by the Main Generator, only the distribution system and loads are discussed. All components of electricity converter and cabling are considered a part of the distribution system, while others such as VSDs, EMP drives are part of the loads. In either distribution system and loads, the equipment cost and O&M cost are presented separately as well as the PV comparisons.

3.4.1.6 Sensitivity analysis

The relatively high uncertainty is inherently in this study as it includes advanced technologies, new application and some missing cost data. Sensitivity analysis can help identify the main cause of the result and the major variables that influences the most, and help determine the future of this technology.

The first three section focuses on equipment cost. As some of the cost estimation may involve relatively high uncertainty, it is important to quantify how much the cost of a component affects the final result in the scenario where the actual cost is significantly over- or under-estimated. In background information section, it is mentioned that cables cost greatly influence AC and DC system cost in residential application where a large amount of cable is used to deliver power to customers. In a nuclear power plant, it is difficult to quantify the amount, types and cost of cables used in both systems, and, hence, the estimation of cable is too uncertain to be included in basic models. To address the cable cost estimation, a calculation is conducted in sensitivity analysis.

Since operation cost plays the most significant role in overall cost (see Section 4.7), it is critical to investigate the performance of both systems under different configurations (different level or PE device implementation). These configuration includes 1) AC system with VSDs installed which is the most common application (see section 2.2.7); 2) much lower losses in DC system component which uses Silicon Carbide transistors [105]; 3) a hybrid system where high-power classes (Class IV and Class III or the equivalent) use AC, and others use DC is analyzed to represent the nearer future of PE implementation where high-power power electronic devises (e.g. DC-DC converters) is not available.

In the last section, uncertainty regarding to economic factor is analyzed. Discount rate is uncertain depending on countries, investment environments, energy market, etc. while LCOE is also uncertain due to the risk of investment, energy market, interest rate, etc. [77, 104] Discount rate and LCOE is related. Therefore, LCOE is selected to be \$60/MWh when discount rate is 3%, \$105/MWh for 7%, and \$130/MWh for 10%. [77]

3.4.2 Equipment cost estimation details

Table 8-2 and Table 8-3 (found in Appendix I) summarize the system components in AC and DC systems which also show the variation in component.

There are total 6 types of sub-systems in both systems which are a rectifier system (a converter transformer and a silicon control rectifier), a traditional transformer (a transformer and its relative accessories), a DC-DC converter, an inverter system (a PWM inverter and a transformer), flow rate control devices (a VSD or a control valve), and cabling (cable and its foundation). These differences are the key to the following analysis and eventually result in cost difference. A summary of these sub-systems can be found in Table 3-7.

The cable cost is not included in the base model due to the fact that it is very difficult to estimate the length and types of cables are used in a NPP without the access to the detailed design. For example, an AC cable could be a 1-wire single phase cable, 3-wire 3-phase cable, 4-wire 3-phase with neutral, etc., and the purposes of these cables are different and could be implemented in different area. Another example is the radiation protection requirement may vary the cost of cables significantly. The cost of cable is analyzed in sensitivity analysis.

3.4.2.1 Transformers

A distribution transformer is a traditional AC transformer (not a converter transformer) which, in this design, has an online Continuous Monitoring System and some other monitoring devices. This is an acceptable method of reducing maintenance cost and making a distribution transformer closer to a DC-DC converter in terms of safety features. [106]

In Reference [37], cost data of transformers in a wide power range is provided. The estimation of transformer cost is based on this data and the generated trend line. Two charts are created for the lower capacity range (less than 250kVA) and the higher capacity region respectively for higher estimation accuracy. The final price of transformer is also verified by Reference [107], and then converted into price in 2017 by Producer Price Index database (PPI). [74]

On top of transformer cost, a 20% additional cost for CMS and other accessories is added. [106] The reason why CMS is included is that CMS reduces maintenance cost in long term and provides some safety feature as a DC-DC converter built with many sensors and online monitoring features.

Table 3-7 Summary of types of sub-systems used in AC and DC systems

Components	Electricity converter in AC system	Electricity converter in DC system
Electricity converters to Class IV from main generator	Traditional transformer	Converter transformer+ Silicon control rectifier
Electricity converters for Backup generator	N/A	Converter transformer+ Silicon control rectifier
Electricity converters in Class IV	Traditional transformer	DC-DC converter
Electricity converters in Class III (to Class I)	Converter transformer+ Silicon control rectifier	N/A
Electricity converters between Class I and Class II	Inverter+ converter transformer	DC-DC converter
Electricity converters inn Class I	Inverter+ converter+ rectifier	DC-DC converter
Cabling	3 sets for 3 phases	2 sets
PHTS Electromagnetic pump solution	Converter transformer+ Silicon control rectifier	DC-DC converter
IHTS Electromagnetic pump solution	Converter transformer+ Silicon control rectifier	DC-DC converter
Flow control solution	N/A[11]	Variable speed drive

[11] Flow control functionality is achieved by control valve in the AC system.

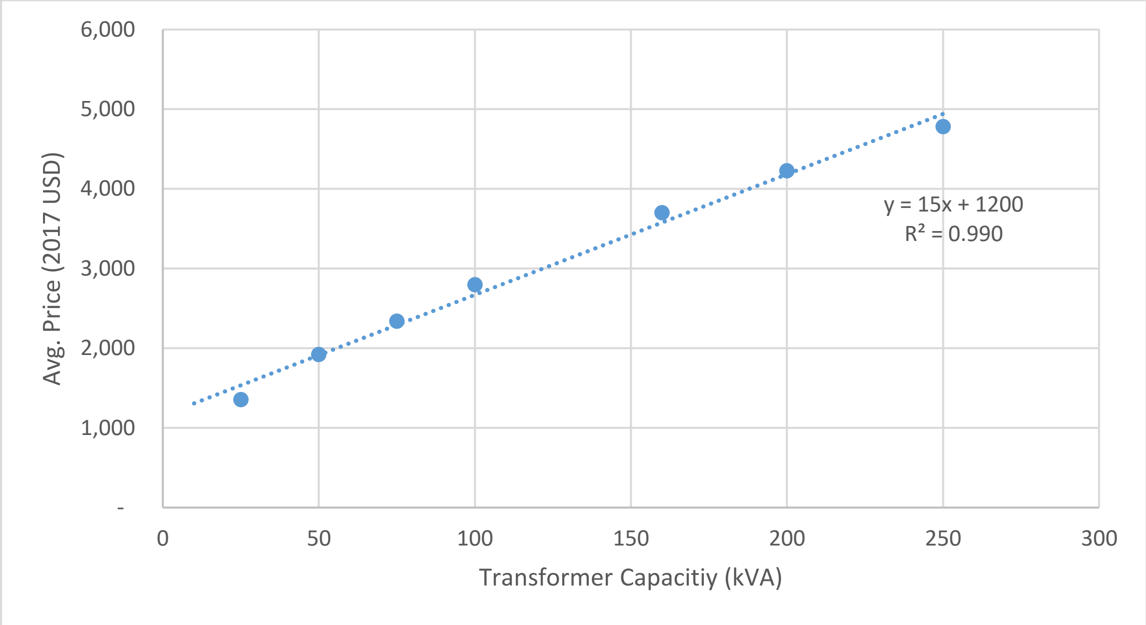


Figure 3-2 Average Price of transformer under 250kVA [37, 108]

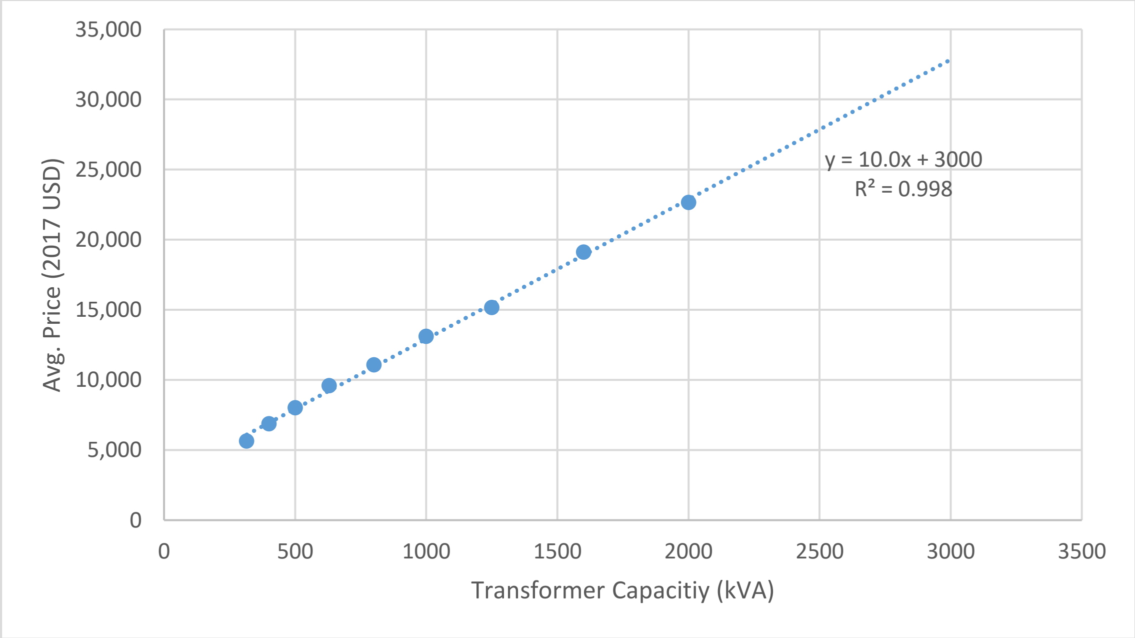


Figure 3-3 Average Price of transformer over 250kVA [37, 108]

3.4.2.2 DC-DC converter

The approach to a Buck-type DC-DC converter is gathering data of the component used to build one since cost data for a whole converter cannot be found. Valuable data for this approach is given by a reference about a 2 MW DC-DC converter of commercial data centre [7]. The DC-DC converter discussed in the reference is a 4-stage Interleaved DC-DC converter which is designed with the ability of altering voltage at wide range for buck and boost operation. This type of converter has cost and efficiency advantages over a conventional buck-boost converter at the same performance level [7]. However, only the buck function is necessary in NPP application which does not require altering the voltage in wide voltage range. Therefore, the cost estimation is based on a buck converter to lower the equipment cost. The layout diagram can be found in Chapter 2.

The following calculation determines the scaling factor for components when their costs are influence more by the material (e.g. inductor and capacitor) based on the different inductors listed in the reference. This factor is used for capacitors, cable and bus bar, water cooling system and miscellaneous, while the cost of IGBT modules, IGBT drivers, control boards and sensors are directly listed or calculated by dividing the price by the number of component sets in the 4-stage Interleaved DC-DC converter and multiplying by number of sets necessary in a Buck-type converter. The cost of enclosure remains unchanged.

The single 1000A inductor costs $9000 whilst the 600A costs $6500.

$$C_x = C_k * (\frac{E_x}{E_k})^n \qquad (3.6)$$

Where,

n is the scaling factor,

C_x is the cost of equipment item of size E_x

C_k is the known cost of equipment item of size E_k.[73]

Substituting Price x=9000, Price k=6500, Size x= 1000 and Size k=600 gives the component scaling factor of 0.64.

The estimated cost of each component and the total cost of building a 1 MW buck type DC-DC converter is listed in Table 3-8, and the cost of a Buck-type DC-DC converter is $36,600 in 2014. Adjusting this price by PPI, it costs $36,000 in 2017 [74]. Since PE technology is advancing rapidly, it is not surprising to see a decrease in price annually. This same build-one-from-component method is also used to estimate the cost of a 2MW buck type DC-DC converter which is for calculating the scaling factor for the DC-DC converters as a whole unit. The result is that the cost of a 2MW converter is $52,000 in 2014. Compared to the 1 MW converter, the calculated scaling factor for a buck type DC-DC converter is 0.51.

Since the MW-level DC-DC converter is still relatively new technology, there is uncertainty with its equipment cost. Additionally, this method only considers the material cost which also adds uncertainty to the result. These concerns are addressed in the equipment cost sensitivity analysis.

Table 3-8 Components and cost of a 1MW buck type converter

Components	Number of component[12]	Estimated cost (2014 USD)
IGBT module	1	2,700
IGBT Driver	1	700
Control board	1	1,000
DC Inductor	1	9,000
Capacitor bank	1	3,900
Cable and bus bar	1 set	3,200
Sensors	1 set	1,500
Miscellaneous	1	3,000
Cooling system	1	9,600
Enclosure	1	2,000
Total		36,600

[12] The number is based on the common buck-type DC-DC converter circuit in Reference [1] and actual converter design in Reference [7].

3.4.2.3 Rectifier and inverter

The main components of a rectifier system have thyristors and a converter transformer which is designed to work with converters for the purposes such as voltage regulation and harmonics control. The uncertainty of the cost difference between a regular transformer and a converter transformer is addressed in sensitivity analysis.

The cost estimation of a rectifier and an inverter in this study is achieved by the same method of estimating the cost of a DC-DC converter. The scaling factor is 0.59 which is the same as the DC-DC converters as they are PE devices with similar components. These components include switching devices (e.g. thyristor, IGBT), capacitors, controllers, an enclosure. Table 3-10 shows the components and estimated cost of a 300kW rectifier, which is an example of the estimation method and the costs are adjusted by PPI. [74] The same method is used for inverter which is in Table 3-11.

The cost of a rectifier or inverter system includes the cost of the converter itself and the cost of the converter transformer. For the estimation of the 20kW (120VDC to 48VDC) converter which is a combination of an inverter, a transformer and a rectifier, it cost is the sum of a 20kW rectifier, a 20kW inverter and a 20kVA converter transformer. The estimated cost of the systems are shown in Table 3-12. Similar to the estimated cost of DC-DC converter, the concern of uncertainty is addressed in sensitivity analysis. Additionally, it is possible to choose Voltage Source Converter rectifiers or inverters, which may increase the cost by 20%. [109] The impact of this design option can also be addressed by the sensitivity analysis.

Table 3-9 Cost of converter transformers [37, 108]

AC or DC system	Power (kVA)	Cost (2017 USD)
DC	4,500	53,000
DC	600	10,000
AC	300	6,600
AC	150	3,800
AC	20	1,600

Table 3-10 Components and cost of a 300kW rectifier

Components	Cost (2014 USD)
Thyristor modules	6,000
Control board	1,000
Sensors	2,300
Capacitor bank	1,800
Cable and bus bar	1,500
Miscellaneous	900
Cooling system	2,300
Enclosure	600
Total	16,400
Total in 2017	16,000

Table 3-11 Components and cost of a 150kW inverter

Components	Cost (2014 USD)
IGBT modules	6,000
IGBT Drivers	2,200
Sensors	2,300
Control board	1,000
Capacitor bank	1,200
Cable and bus bar	1,000
Miscellaneous	600
Cooling system	1,100
Enclosure	400
Total	15,800
Total in 2017	15,500

Table 3-12 Estimated cost of rectifier and inverter systems

AC or DC system	Type of converter	Power	Estimated cost (2017 USD)
AC	Rectifier	300kW	22,000
AC	Inverter	150kW	19,000
AC	Rectifier and inverter	20kW	12,000
DC	Rectifier	4,500kW	122,000
DC	Rectifier	600kW	31,000

3.4.2.4 Electromagnetic pump drive

One of the most significant characteristic of the EMP loads is the high power consumption. In fact, in this particular model, EMP loads occupy 63% of the total power. Therefore, the drives that supply power to the EMPs may have some impact of the result and a sensitivity analysis is conducted to address this concern. Another most significant characteristic of a EMP which is of DC conduction EMP that EMP requires a very high current at a low voltage. [43] This input requirement posts challenges to its drive design and rises the cost. In fact, the very high ratio of input and output voltage conversion changes the converter designs in both AC and DC systems.

A DC EMP demands DC power, the drive solutions differ between the AC and DC systems. The drive in the AC system is a rectifier system that can output the required DC power and the estimation this drive is based on the same method as other rectifier systems which is discussed in previous sections. In a DC system, the technology to achieve such output is the transformer type DC-DC converter which is capable of high conversion ratio. The high current issue is expected to raise the cost due to engineering challenges. [43, 45] However, since there is not sufficient data to determine the cost of such drives, the concern of the difference is addressed in sensitivity analysis by the equipment cost section.

Since the power difference between the EMPs in PHTS and IHTS is only 0.11MW (see section 3.1.2), it is more reasonable to have two 1.5MW system rather than customizing a 1.5MW system and a 1.39MW system separately. Thus, the cost of the EMP drive in IHTS is assumed be the same as that of PHTS.

Since the electromagnetic pump is one of the largest power and costliest components in the system, its price variation can significantly impact the capital cost of the whole system (AC or DC). Thus, the sensitivity analysis on this component is conducted regarding to other types of EMP (e.g. the induction EMP) and to the cost of the drives.

3.4.2.5 Motor driven pump

Keeping the continuity and control of heat removal capability is the key to the NPP safety and efficiency. Controlling the flow rate to the steam generator, for example, influences the water level in the steam generator which must be kept in a specific range, and, hence, maintaining a flow rate of PHTS coolant is the important to reactor safety and the plant efficiency. Traditionally, the motor is directly connected to its bus and operating near its rated output and the flow rate is altered by the opening of a control valve. [21]

With VSD (also referred as variable frequency drive or AC drive), a PE device, it is possible to operate the motor at an optimized point according to the plant operating condition. This not only reduces electricity usage, but also potentially eliminates the need of a control valve. This study focus on two scenario[13] which are:

- VSD controls the flow rate all the time without the need of a control valve.
- Control valve controls the flow rate without a VSD.

The equipment cost comparison in this analysis is the cost of purchasing VSDs versus control valves, and the operation cost focuses on the energy usage comparison.

The cost data of VSDs are from three different manufacturers across the range of 7.5kW to 597kW collected on vendor websites. [110, 111] Three manufacturers available on both vendors' websites are chosen because they provide the widest product line in terms of power level. The collected data seems to show that the rated current influences the cost the most. For example, a 600V drive can cost less than a 480 V one, even thought the 600V drive has a higher rated power output. However, the difference is not significant (about 5%) and only those that meet the requirements (e.g. voltage and power) are considered in this study.

From Figure 3-4, the relationship between cost and power level is almost linear, and the trend line is $y = 60x + 600$ with $R=0.987$. The installation cost is not considered in the model as it is assumed to be equal to AC system, even though installation of a VSD is reported to be much simpler than control valve which involves other systems (e.g. airline deployment, sealing, etc.). [112]

[13] In some cases, especially in nuclear industry, both methods are implemented in a plant at the same time for different operation conditions due to the regulations. The details and reference are found in regulatory impact section.

The VSDs in a DC system is different from that in an AC system, specifically, there is no rectifier and DC link which means the VSD is basically an inverter designed to drive (provide power to) motors, and the cost of such drive should be theoretically lower. On the other hand, this also means the customization, because commercially VSDs are built for AC systems due to the fact that DC distribution system is in conceptual stage. It is difficult to quantify the effect of these two factors. Therefore, it is assumed that the cost of a DC VSD equals to an AC VSD. The influence of a simpler DC VSD is considered in some sensitivity analysis.

Previously mentioned that the generic analysis method used for estimating the cost of the loads where the number of component in each position is assumed to be one, the inaccuracy introduced by assuming there is only one load is addressed in the sensitivity analysis.

In terms of control valves, although there are some vendors providing cost of control valve, the actual cost cannot be determined due to the unclear relationship between sizes, power and flow rate and the unavailability of detailed design data from existing plants. Additionally, the cost of control valve accessories, bypass valve, air piping, labour of installation, etc. is also difficult to verify. Therefore, this estimation relies on engineering experience regarding to the cost comparison at a system level, reported in literature. This includes experience from projects of converting existing control valve application to VSD, projects with VSDs when they are designed, detailed comparative estimation, etc. As a result, it is concluded that the cost of VSDs could be more expensive than that of control valve at high power application. Therefore, it is assumed that a control valve application is 75% of the cost of VSD application when the power is greater than 200kW, and equal to that of VSD when power is less than 200kW. The uncertainty is addressed in the sensitivity analysis. [112]

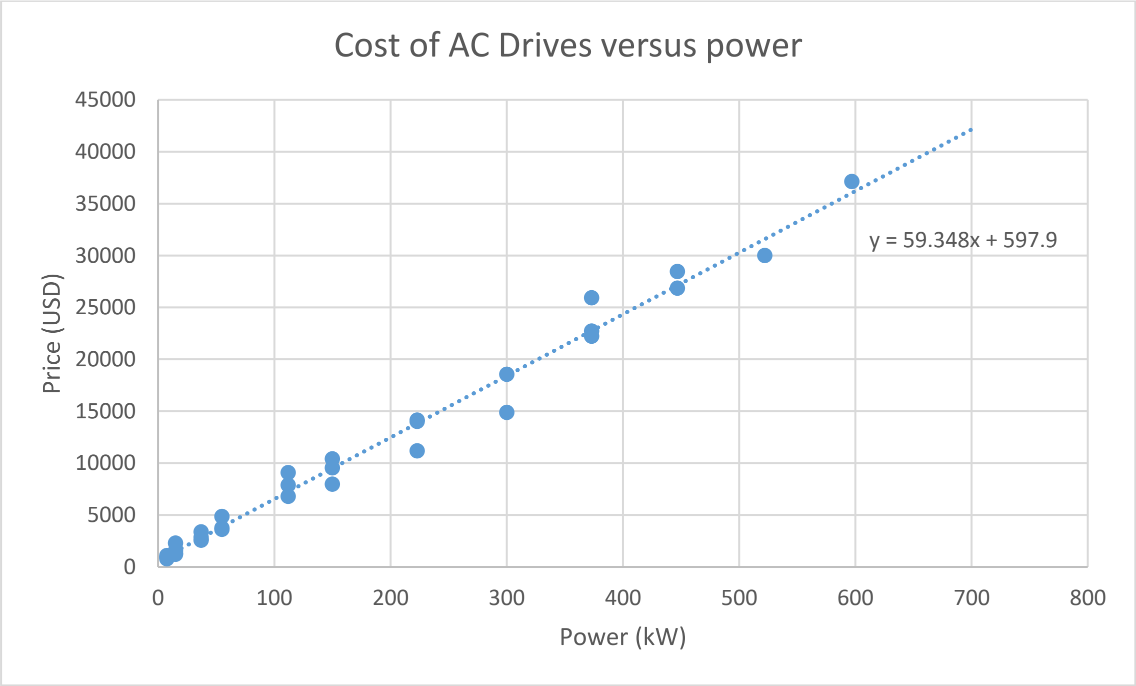


Figure 3-4 Cost of AC Drives versus power

3.4.3 O&M cost estimation details

In this section, the operation cost is estimated, which focuses on the electricity usage as stated in Section 3.4.1. In power generation industry, a more efficient plant electrical system means less station power usage and more power for sale which raises the project profitability. As for maintenance cost, it is based on historical data (presented below) from literature.

3.4.3.1 Power generation operation/normal operation mode

The definition of normal operation or power generation operation is when the power plant is generating electricity to the grid. Several assumptions are made to define this operation condition.

- It is assumed that only the main pumps of each task are operating and all auxiliary and shutdown cooling pumps are not consuming any power.
- The actual input power of pumps is adjusted by the flow rate requirement, instead of the rated power. In AC system which utilizes traditional control valve, the input power is calculated by an approximate pump power curve. In DC system which implements VSDs for flow rate control, the input power is calculated by Affinity laws. The details are provided in later sections.
- The whole electric system is also assumed to be fully functional with all electricity converters online. Each converter and bus in the same level equally shares the loads connected. For instance, each transformer in Class IV in AC system provides 1000kW power to secondary side which is consuming 2000kW.
- In fact, many power plants are not always operating at its rated power output due to either a plant design defect or the actual needs of the grid. A statistic of 402 power units shows the annual average load factor of 78.6% which has already included the offline period due to schedule maintenance. [19] Therefore, the load factor in this study is set to be 78.6% flat across its life-time which is assumed to be 50 years in this study. Assuming the reactor power and the flow rate of all coolants in the reactor are linearly proportional to load factor, the actual power input of pumps, either mechanical or electromagnetic, can be calculated. Also, power of other devices such as electronics is assumed to stay at rated power.

3.4.3.2 Power input of pumps

Although the actual power consumption of the pumps varies from reactor design to another, the electric consumptions of pumps greatly impact the operation cost of a plant due to the fact that station service power is considerable compared to the output (e.g. about 7% for CANDU, about 5% for PWRs in France [84]) and the majority of the station service power is consumed by pumping coolant according to the gather data presented in Appendix I. In this section, the power consumption of pumps in the AC and DC system is calculated.

In the AC system, the operating point of a sub- system is determined by an approximated pump curve. Although every sub-system has different system characteristics, this approximation needs to be used for systems due to limited resource the author has. This linear approximation is based on the linear region of the pump power curves reported in Reference [39, 112] and this approximation is relatively accurate within the actual flowrate range of 50% to 90% [39, 112]. The average power input for pumps with control valves at 78.6% is calculated to be 87% of its rated power and the mechanical and electrical losses of the motor is about 4.6% of the input power to the motor at 87% loading [113].

In the case of VSDs, the Affinity Law [112] describes the relationship between power (bhp), pump speed (N) and flowrate (Q) as:

$$\frac{bhp_1}{bhp_2} = \left(\frac{Q_1}{Q_2}\right)^3 = \left(\frac{N_1}{N_2}\right)^3 \tag{3.7}$$

This relationship is accurate in most real-life applications with a slight favor to VSDs due to the reduced flow velocity [112, 114]. Thereby, the actual power input of motor with VSD is $(78.6\%)^3$ which is 48.6%. Even though VSDs may increase the loss of the motor due to PWM-introduced non-perfect sinusoidal wave or harmonic distortion (0.6%-0.8% higher [113]), the reduced load and power input significantly decrease mechanical and electrical loss due to the eased operating condition and the overall energy usage. [112] The electrical and mechanical losses is about 3.4% at 48.6% loading. [113]

A VSD itself does have extra loss which is typically 1% of its full capacity plus 2% of actual load for a VSD. [112] The total losses of 3% at full power is close to counting the system as a combination of an rectifier loss (typically 0.8%) and an inverter loss (typically 2.3%) separately [39]. In DC system, however, the DC version of a VSD does not include the rectifier and the DC bridge. Since rectifier is relatively efficient, the majority (about 75%) of loss in VSD is caused by the inverter. [108, 115] To avoid double counting the rectifier loss, it is assumed that the loss of a DC VSD has 75% of the loss as the VSD for AC system which is, now, 0.75% of its full capacity plus 1.5% of actual load. Shown in Table 3-13 is the total electric losses VSD applications which is about 1% higher than the motor with control valve.

The annual energy consumption of a pump is the electricity input at its bus terminal times the time period of operation which is 51 weeks or 8592 hours per year when a one-week maintenance is assumed.

For example, the AC induction motor of the Main Boiler Feed Pump has a rated power of 520kW, but actual power demand depends on the operating condition, the flow rate requirement of which is assumed to be 78.6%. Hence, the actual power output of the motor to the impeller is the 452kW in control valve application and 253kW in the VSD application. VSD does reduces electrical and mechanical loss (from 21kW to12kW) but the converter has loss (7.7kW). Adding the losses to the systems, the control valve application power input to the motor is 473kW while the VSD application power input is 272kW which is a 42% reduction. Multiplied by annual operating hours (8,592) and LCOE ($0.105/kWh), the annual operating cost in electricity in VSD application (about 245,000 USD) still has 42% reduction over the control valve application (427,000USD). The result is summarized in Table 3-14.

Since the operation cost of the pumps is significant, the uncertainty associated with operating condition and cost of electricity is addressed in operation cost sensitivity analysis.

3.4.3.3 Transformers

The loss associated with a transformer is categorized into no-load loss and load loss. [37, 70] No-load loss (often referred as iron loss) is mainly introduced by leakage or eddy current of the magnetic field in the core of the transformer. The magnetic field is always present in the transformer as long as it is connected, which means the no-load loss appears regardless the amount of power is being transferred through the transformer. Load loss (often referred as copper loss) occurs in the winding when current passes through meaning it depends on load condition. As a matter of fact, those transformers are much below its rated capacities under normal operation and the load-loss are directly proportional to square current ($P \propto I^2$). Hence, the load-loss of a transformer is calculated by its rated load-loss time square of loading factor. [116]

$$P_{ll} = P_{rll} * n^2 \tag{3.8}$$

where P_{ll} is transformer load-loss under normal operation in kW,

P_{rll} is transformer rated load-loss provided in kW,

n is the loading percentage in %.

The total losses from a transformer times the operating hours is the energy consumed.

The data from Reference [37] is separated into two groups (below 315kVA and above 315kVA). The loss and capacity relationship is linear and the linear approximations are of R^2>0.99.

Table 3-13 Electric losses comparison of Control valve and VSD application

Systems	Motor loss	VSD loss (constant)	VSD loss (variable with load)	Total
Control valve application	4.6%	0	0	4.6%
VSD application	3.4%	0.75%	1.5%	5.65%

Table 3-14 Example of pump operating cost

	Control valve	VSD
Rated Power(kW)	520	520
Flow rate	79%	79%
Actual power output (kW)	452	253
Converter loss	0	7.7
Mechanical and electrical loss (kW)	21	12
Actual electrical input (kW)	473	272
Operating hours (hrs.)	8,592	8,592
Annual energy consumption (kWh)	4,065,824	2,335,378
Annual operating cost (2017 USD)	427,000	245,000

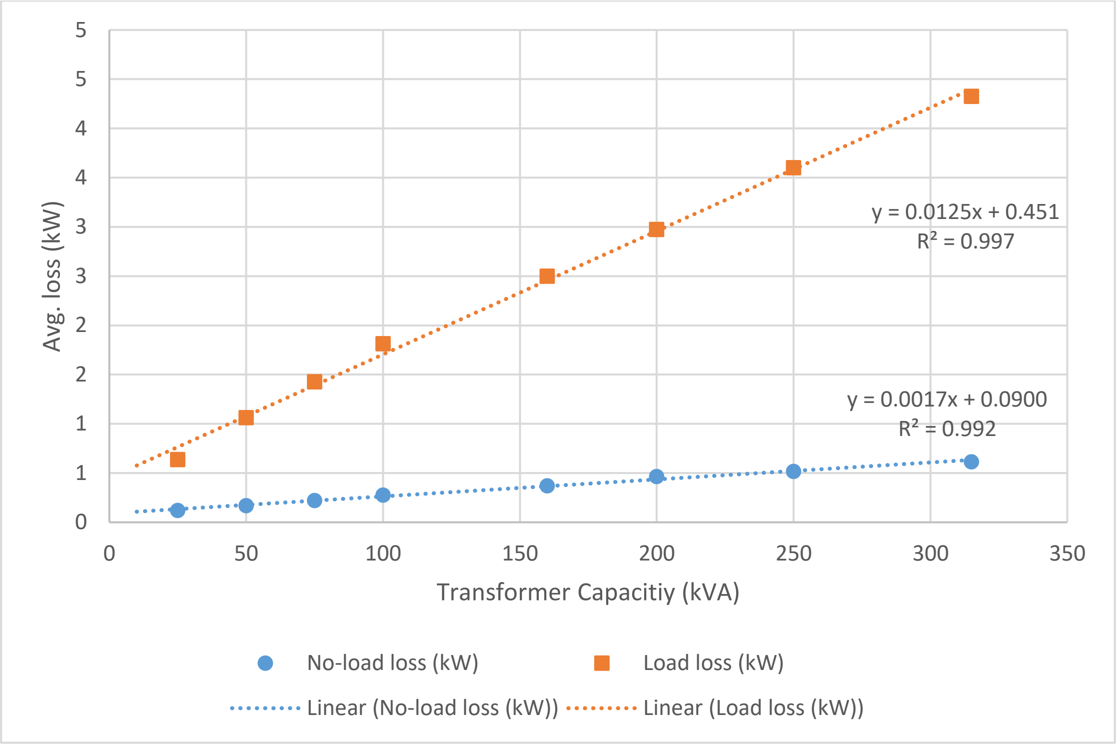


Figure 3-5 Avg. Loss (kW) of smaller transformers [37]

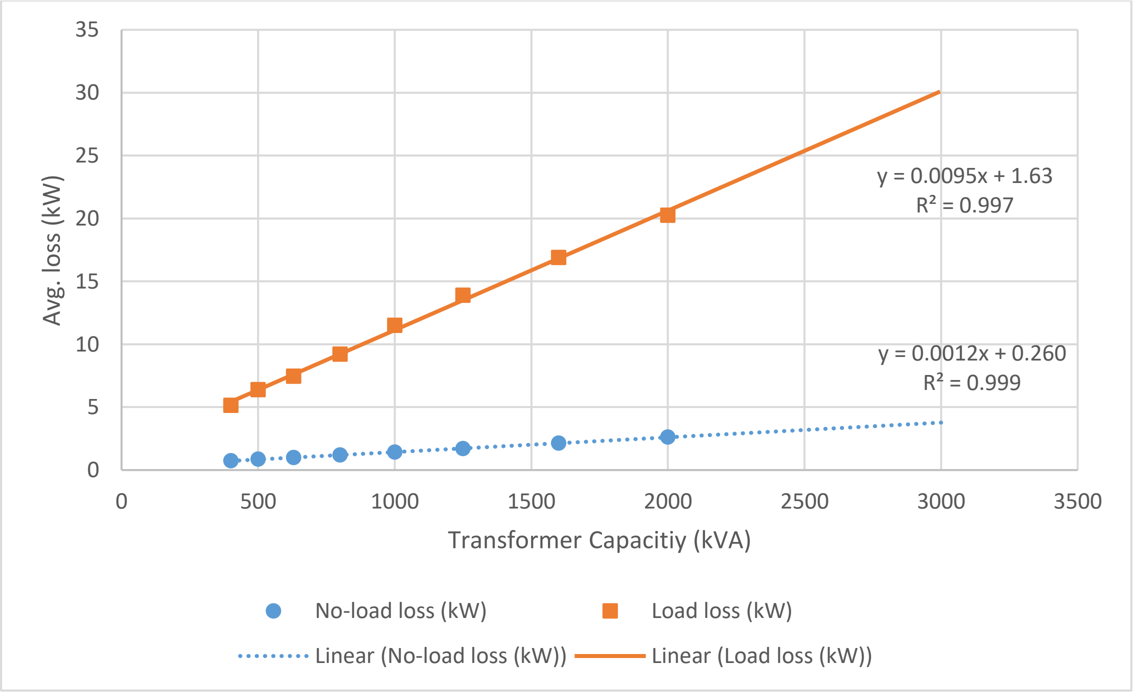


Figure 3-6 Avg. Loss (kW) of larger transformers [37]

3.4.3.4 Power electronic electricity converter (Rectifier, inverter and DC-DC converter)

The loss of PE devices is mainly due to the switching loss which occurs only when there is power passing through similar to the load loss in transformers. Unlike transformers, there is no no-load loss. Indeed, they are very efficient. A thyristor-based rectifier has loss of 0.8%, while PWM inverter losses about 2.3% at full power and the loss follow the rule of I^2R like the transformer copper loss. [108, 115]

In terms of the DC-DC converter, most of the designs based on various principle in literature are able to achieve overall converter losses of 3% to 5%. [7, 36, 93, 117, 118] Therefore, the loss of a DC-DC converter is assumed to be 4% in this study which is the median in those references. From previous section, the average total loss of an AC transformer is about 1.18% while high-frequency transformers used in DC-DC converters are more efficient. [1, 118] Therefore, it is assumed that 1% additional loss due to the presence of high-frequency transformer link In the case of transformer type DC-DC converter.

3.4.3.5 Reliability and Maintenance cost

Reliability of power electronic devices

Reliability is critical to ensuring functionality of a system. This is important for a nuclear power plant where a loss of some functionality could lead to severe accident (e.g. loss of coolant flow accident). Reliability is defined as the probability that a component continually performs the required function without failure under the stated conditions for a stated period of time[119]. There are specific program set by the regulators about how to conduct different types of maintenance in a NPP[120]. However, this is a conceptual work and estimation of maintenance is based on the components themselves. The details about how DC electrical system may impact the overall maintenance program and vice versa are considered for future work.

Since PE devices have been implemented into various industries, the reliability of widely available technologies (e.g. rectifiers, inverters, VSDs, etc.) has also been studied along with the approaches for improvement in literature [121]. Two main aspects of reliability that influences the analysis of this work are failure rate and lifetime. The typical design lifetime of PE devices varies according to the applications (e.g. 24 years or 100,000 operation hours for aircraft, 30 years or 130,000 operation hours for solar plants, over 50 years for HVDC systems, etc. [121, 122]). However, there is uncertainty with the life span of these PE devices, especially the high-power DC-DC converter as this is a relatively new technology. To address the uncertainty associated with life span of PE devices, sensitivity analysis of replacement is conducted where frequency of replacement of every 25 years, every 10 years, every 5 years, and every 1-year are considered. That is addressed in sensitivity analysis by assuming different replacement period.

For very high reliability requirement application such as NPP, one or several design approaches can be taken to reduce failure rate including redundant components, redundant assemblies, redundant configuration, and redundant sub-systems. These are considered internal or built-in redundancies which increase the cost from several percent to around 30%. [123] Additionally, reliability can also be improved by adding another unit this approach is also used in other applications in a NPP where it is common to find multiple pumps operating in parallel, which is considered external redundancies. The uncertainty associated with having multiple units in one position is addressed in equipment cost sensitivity analysis.

Maintenance cost estimation of power electronic devices

Assuming an maintenance of those devices needs 2 man-hours and each man-hour costs $133 in 2017 [124], annual maintenance cost of one electricity converter is $399. The maintenance cost is also influenced by the replacement caused the design life time (discussed in early section). The associated uncertainty is addressed in sensitivity analysis.

Maintenance cost estimation of transformers

Traditionally, transformers usually require annual one-day maintenance in the first few decades followed by major preventive and corrective maintenance such as oil regeneration, insulation regeneration, etc. [125] This maintenance approach is rather expensive and may even cause damage to a healthy transformer. Therefore, some industries, nowadays, have adopted continuous monitoring system to reduce overall maintenance cost. Although the continuous monitoring system may increase the equipment cost, a lot more can be saved by monitoring any faulty part in the transformer and giving early alert to operator, which also increases the transformer’s availability and extends its lifetime.[106, 125] Within life time of a transformer, only annual inspection is needed. Details about possible failure model and its effects on maintenance and availability is out of the scope of this study.

Maintenance cost estimation of control valves

A control valve is a device dissipating hydraulic energy which usually has many mechanical parts and air lines. Hence, the maintenance requirement is much higher than that of other components, the maintenance expenditures associated with a valve in 5 years of operation will equal its purchase price. [112]

3.4.4 Uncertainty and sensitivity analysis

3.4.4.1 Definition of uncertainty

Uncertainty is caused by the imprecise measurement of a value, or a lack of information, or the ignorance of some factors, which can be improved by additional research. [140] The primary reason why there is a considerable amount of uncertainty in this work is the lack of full information or the insufficiency of data. For example, it is impossible to survey all the loads and their operating conditions. As mentioned previously, the philosophy of this work is to investigate the large and safety related loads which determine the power level and types of loads in the electrical system. This is sufficient to the scope of determining the feasibility of the DC system in a NPP. However, the approach does introduce uncertainty when performing estimation of equipment cost as well as O&M cost. There are several main variables that contribute the most to uncertainty, and they are listed in Table 3-15, which are also separated according to the part of the estimation it influences.

3.4.4.2 Variables descriptions

Design margin

Design margin is a common practice for a designer as tolerance to ensure the safety factor of a design to encounter operation uncertainties, and it also depends on particular system components. Hence, it is hard to determine and justify the design margin of the distribution system or each component in this work. Therefore, the method to address this concern is to incorporate the uncertainty into the equipment cost. In terms of the range, a 15% to 30% power ratings capacity for overload situation is recommended in IEEE 141-

1993 standard. [126] However, the design margins in the nuclear industry could be much higher. Hence, for the purpose of this sensitivity analysis, a 500% analysis range is selected instead of the 15% to 30% stated in IEEE standard, which is followed by a calculation determining when this variable will change the conclusion drawn by the base model. Since the uncertainty of design margin affects most of the components in the design in either the AC or the DC system, this uncertainty can be and is addressed in the same analysis as the total system equipment cost. A discussion about how this variable influences the result based on the analysis is given.

Individual equipment cost

The cost estimation of some individual equipment involves a concerning amount of uncertainty because of the lack of reliable historical data. Particularly, the method used to estimate the cost of PE devices only consider the material cost of the components, which tends to underestimate the purchasing cost of such components. Also, due to the fact that some equipment such as high power DC-DC converter is not, yet, considered mature or commercialized, even though it is technologically feasible. Therefore, a 1000% analysis range is selected to address this issue which is followed by a calculation of when their cost will alter the result in terms of capital cost and overall PV. On the other end of the spectrum is a 10% cost scenario. The purpose of this analysis is to 1) investigate the influence of the individual equipment uncertainty impact upon the whole system equipment cost; 2) investigate the influence of the uncertainty of the system as a whole, which provides inputs to the next section.

Total system equipment cost

The purpose of analysing system equipment cost as a whole is to look at the final system equipment cost instead of analysing the effect of each components. The method is changing one of the system’s equipment case by multiplying the base model cost by a set factor and keeping other parameters constant. The DC system equipment cost, for example, is the variable, the base case cost of which is multiplied by a factor while the AC system equipment cost is not changed, nor the O&M cost of the AC system, nor the O&M cost of the DC system. The analysis range (10% to 6000%) is based on the former two variables—the design margin and individual equipment cost, followed by a calculation of when this variable alters the result.

Replacement of power electronic devices

As mentioned in Section 3.4.3, due to the limitation of some of the PE technologies, the lifetime of reliability may not meet the requirement in nuclear industry. If the design life time is shorter than the life time of the plant, then replacement is needed which affects the PV results. The frequency of replacement ranges from once in 50 years to once in 5 years, followed by a calculation of when the replacement cost alters the result.

LCOE and discount rate

As discussed in Section 3.4.1, Discount rate and LCOE are two of the key parameters that may impact the economy of a project, and the impact is investigated in this section. Also, these two parameters are highly related to each other. Hence, at each scenario of discount rate (3%, 7%--base case and 10%, see Section 3.4.1), there is one LCOE according to the result of the International Energy Agency (IEA) & Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA) study. [77] In the study, the LCOE for advanced nuclear power generation used in 3% discount rate scenario is \$60/MWh, and \$130/MWh for 10%. Additionally, a calculation to determine at what LCOE the result alters as LCOE could be a determining factor to the O&M cost which is usually critical to the overall system cost and some of the nuclear generation technologies or existing plant could have a lower LCOE.

Other variables

There are other parameters that highly depend on the actual system and it is hard to quantify the impacts to the result. Therefore, they are analysed qualitatively---determining the preferences to the DC or the AC systems, or no preference. These variables are the cost of cable, parallel operation of multiple pumps, use of induction EMP, and low-loss PE devices. Those parameters are discussed in result section.

Table 3-15 Main uncertainty variables

Variables	Part of result influenced	Range of analysis
Design margin	Capital cost	0 to 500%
Individual equipment cost	Capital cost	10% to 1000%
Total system equipment cost	Capital cost	10% 6000%
Reliability (replacement)	O&M cost	1 time to 4 times
LCOE and discount rate	O&M cost	\$60/MWh to \$130/MWh

4 Result

4.1. Reference Reactor Design Layout

A reactor design is selected to be the reference design, and the power plant layout of this design is used to carry out further analyses (e.g. electrical system design and loads determination).

4.1.1 Selected reactor design

GE HITACHI's Power Reactor Inherently Safe Module (PRISM) is from the U.S. Advanced Liquid Metal Reactor (ALMR) program. Its compact modular design has many advanced characteristics including factory fabrication, economical shipment, breeding capability, passive shutdown ability and passive cooling features. Each reactor module has the design output of 155MWe or 350-500MWth. [13, 127] The ALMR is commercialized into PRISM, and the approach is packing 3 smaller modules into one block and 3 blocks in one plant which has the net electric output of 1395MWe[86].

Each reactor module has its own steam generator, to which an IHTS containing non-radioactive sodium circulated by two EMPs is used to transfer thermal energy from two intermediate heat exchangers in the reactor vessel to the steam generator. The IHTS is capable of natural convection for decay heat removal. The steam generator and IHTS along with the reactor vessel compose the nuclear steam supply system. [86, 127]

Beside the intermediate heat exchangers, in the reactor vessel, there are the reactor core with its control mechanism and 4 EMPs fully submerged under the sodium. The pumps are cooled by the surrounding sodium and controlled by solid-state power supply. The primary sodium inlet and outlet temperature is 360 and 510 °C respectively while the secondary sodium temperature is 320 and 500 °C. [14, 86]

4.1.2 Reference Reactor characteristics

The reference reactor is mainly based on the selected PRISM reactor design. The configuration is the same as PRISM illustrated in Figure 4-1. The thermal energy generated by the reactor core is transferred by the sodium from the core to the intermediate heat exchangers, and then from intermediate heat exchangers to the steam generator by the IHTS filled with non-radioactive sodium. Then a steam cycle running on superheated conduction is used to generate electricity. The main difference between the reference PRISM reactor and that used for this study is the power output. The reactor in this study is a 300MWth unit with gross electricity output about 120MWe assuming the thermal efficiency is 40% which is common for a SFR. [13]

In terms of the power of loads, the CANDU 6 NPP design [10] is used as reference, and a downscaling is performed to make the load characteristics suitable for the study. Other types of loads that cannot reference the CANDU 6 model (e.g. EMP) are calculated using data from other plant designs. The resulted list of loads and their estimated power is in Table 4-1.

It is evident that most of the energy is consumed by pumping equipment, while the EMPs occupy a significant portion of power within the pumping devices due to their high power output and relatively low efficiency. Beside all those pumps, others are mostly electronic devices relating to I&C systems which are usually sensitive to interference and require the quality of electric input. This study focuses on the distribution of power to the high power loads, and the design of I&C system, harmonics analyses are out of the scope of this study.

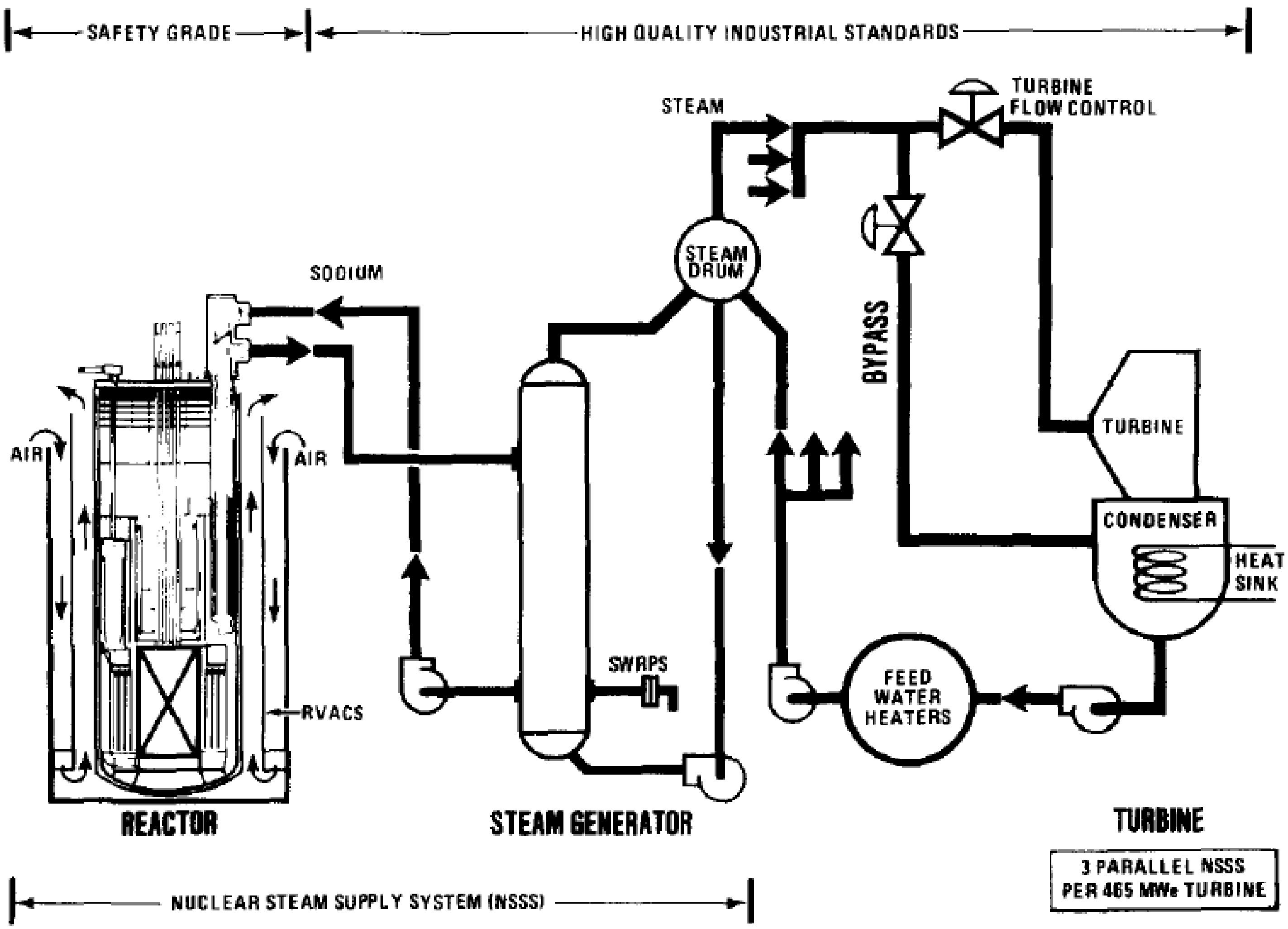


Figure 4-1 PRISM main power system layout[86]

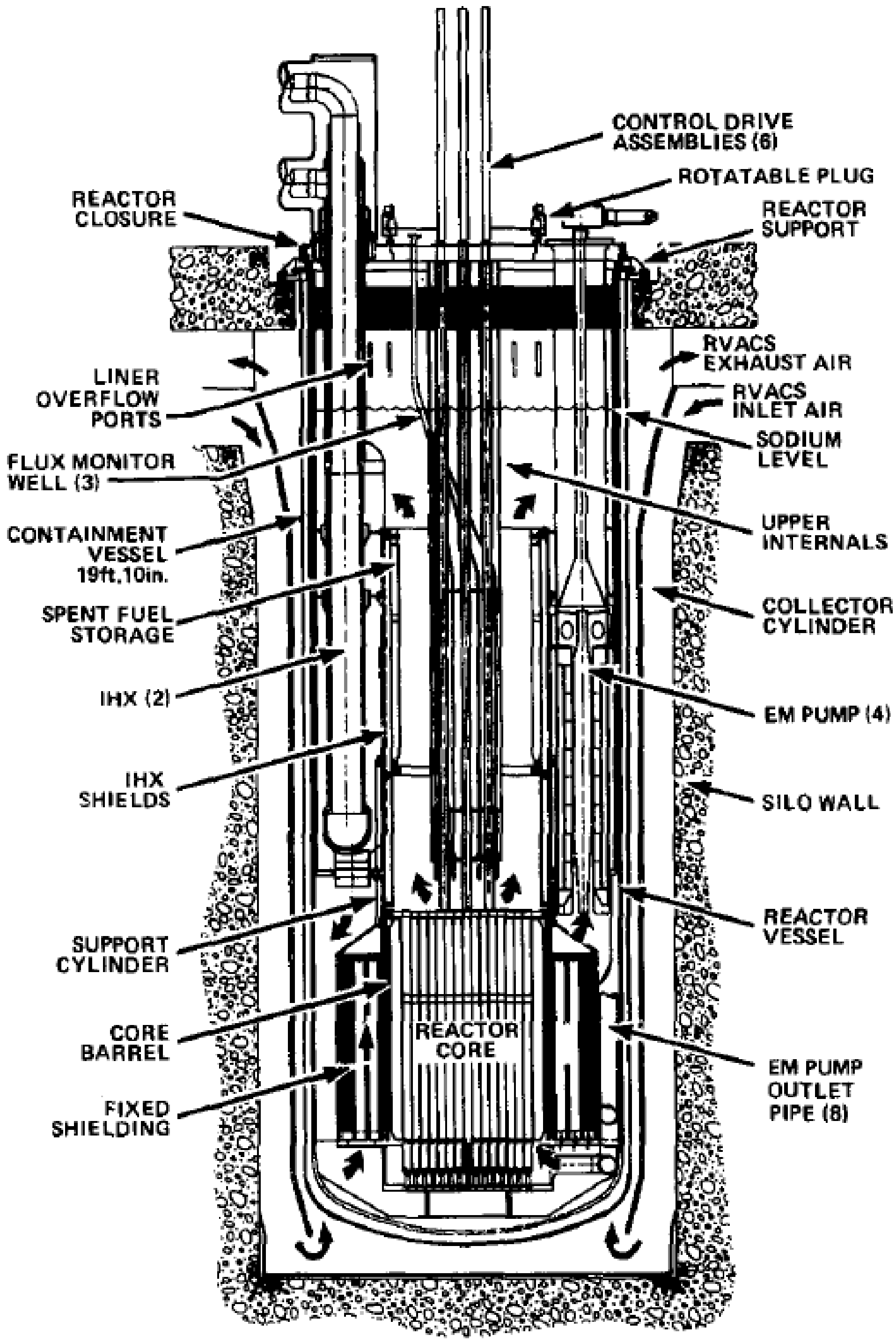


Figure 4-2 PRISM reactor Module[86]

Table 4-1 List of major loads in reference plant

Class	Loads	Reference design	Power(kW)	Note
IV	Main boiler feed pump	CANDU 6	520	Mechanical pump
IV	Main heat transport system pump	ASTRID	1,500	Electromagnetic pump
IV	Intermediate heat transport system pump	ASTRID	1390	Electromagnetic pump
IV	Condenser cooling water pump	CANDU 6	366	Mechanical pump
IV	Condenser extraction	CANDU 6	267	Mechanical pump
III	Main heat transport system pump	ASTRID	75	Electromagnetic pump
III	Intermediate heat transport system pump	ASTRID	69.5	Electromagnetic pump
III	Auxiliary boiler feed pump	CANDU 6	37	Mechanical pump
III	Auxiliary condensation extraction pump	CANDU 6	8	Mechanical pump
III	Shutdown system cooling pump	CANDU 6	31	Mechanical pump
III	Service water pumps	CANDU 6	58	Mechanical pump
II	Electronic Devices in Class II	CANDU 6	20	Electronic Devices
II	Representative pump in Class II	CANDU 6	130	Mechanical pump
I	Electronic Devices in Class I	CANDU 6	20	Electronic Devices
I	Representative pump in Class I	CANDU 6	130	Mechanical pump

4.2 AC reference system

4.2.1 System general design and description

This AC reference electrical system layout is designed to meet all the requirements (see Section 3.1). By adopting design concept and considering design requirements and relative standards, the AC reference system is designed, the layout of which is illustrated in Figure 4-3.

The electrical system has 4 classes with several sources for different operation conditions (e.g. normal generation or reactor shutdown). Under normal operation, the whole system draws power from main generator (assumed to be 10kV) through the SST and/or from switch yard through the UST. Class III draws power from Class IV, Class I from Class III and Class II from Class I (In short, IV—III—I—II). Also, if the inverters are not available, Class II can also draw power from Class III. Under shutdown operation and Class IV is offline, Class II and Class I power depend on the battery bank in Class I until the diesel generator in Class III are back online. The battery banks in Class I provides power to Class I directly and to Class II via the invertors.

In terms of loads for the SFR, the pumps remain the traditional way which is connecting 3-phase motors to the buses via breakers and the control valves varies the flowrate. The electronic devices use low voltage DC internally (power supply level) which means those devices are considered one unit with all necessary component for DC packed inside just like household appliance at home which is one unit plugged into 120VAC wall outlet but uses low voltage DC internally. The EMPs should not be considered as one unit like electronic devices in this study since the power level is relatively high which may have impacts to the analysis result by a considerable margin. The EMP solution in AC system is a rectifier system consisting of a converter transformer and a rectifier. The former provides a desired voltage and the latter provides AC/DC conversion.

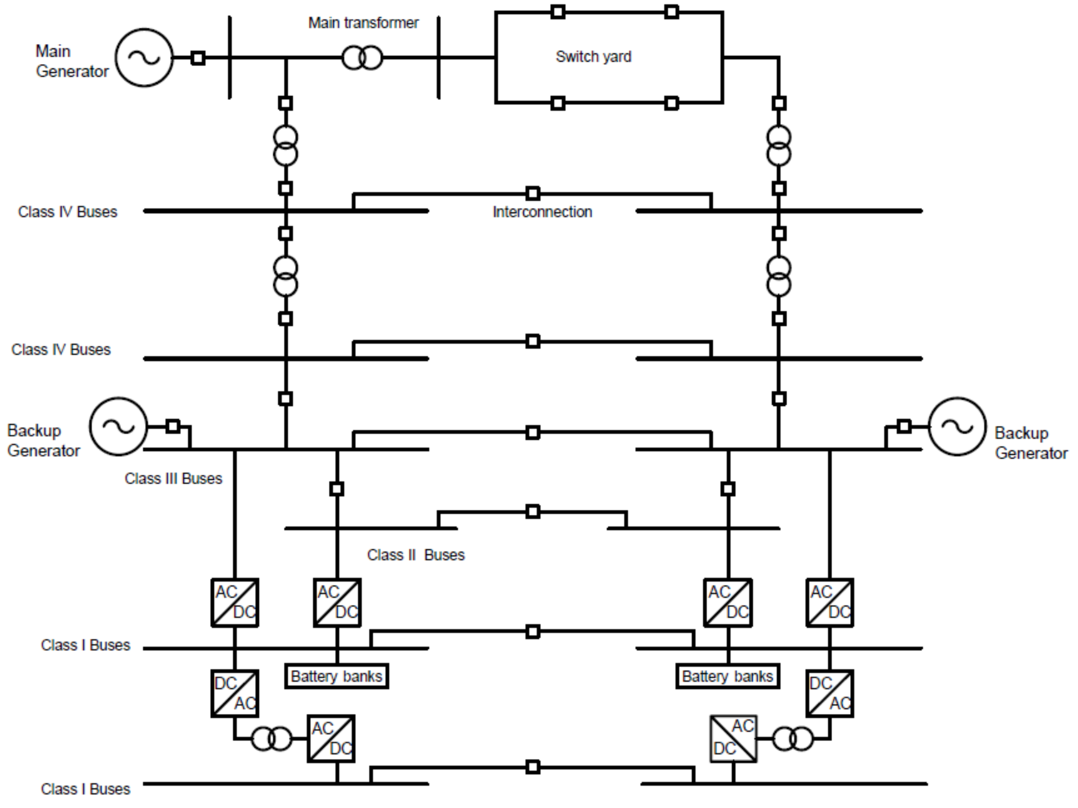


Figure 4-3 AC reference system layout

4.2.2 Requirements fulfillment

This section describe how the designed system is able to meet the design requirements provided in Chapter 3.

1. The loads shall be separated into classes regarding to their importance to plant safety, and electrical system shall also be designed into classes accordingly.

The AC reference system is designed to have 4 classes supplying loads according to their importance.

2. The tolerance to interruption in each class is infinity for Class IV, 5 minutes for Class III, 6(six) milliseconds for Class II and null for Class I.

In the AC reference system, Class IV can be interrupted infinitely for the loads are only used in power generation and not necessary under shutdown operation. The voltage drops in Class IV will trigger the start-up of the backup generators which takes less than 5 minutes and they will supply power to Class III. As Class II is powered via sets of inverters which have very quick reaction, so it can meet the 6 milliseconds requirement. [128] There are banks of battery keeping Class I power, therefore, Class I always has desired power at all time.

3. The electrical system shall be able to supply sufficient electricity to loads.

With calculated total load capacity, the transformers and converters are chosen to have sufficient capacity. The UST or SST is of 4.5MW capacity for full system functionality as the total demand of electricity in order for the plant to be fully functioning is about 4.4MW. Each rectifier from Class III to Class I which also supplies Class II is 300kW and there are two sets of 150kW inverters for Class II.

4. The electrical system shall have the ability to provide adequate electricity (voltages, AC or DC, etc.) to loads, and the voltage shall follow the widely accepted standards

As described above, every class has one or more voltage levels in order to provide adequate electricity to the loads. Class IV uses 2400VAC and 480VAC, while Class III uses 480VAC which is the same as Class II. In Class I, there are 120VDC buses and 48VDC buses serving different loads. All AC voltages are those in the standard. [91] As for the DC buses, the voltages follow those used in existing plants.

5. The sub-systems in each class shall be able to operate separately from each other.

Every class is able to be operated separately due to the breakers capable of separating transformers and buses. In the event of loss of Class IV power, for instance, breakers before Class III from Class IV are opened which separates Class IV from the remaining system. Also, there is a control mechanism on individual transformer and converter for the voltage regulation. Hence, the sub-systems can be operated separately.

6. The redundancy of main buses shall meet the standards.

In IEEE standard [90], it is required to have redundant buses which is at least two buses for each voltage level in Class 1E. In this design, there are two buses with inter-connection between them for each voltage level in each class, and either branch has the full capability of supporting all power requirements of the power generation operation.

7. The electrical system shall be able to withstand a sudden load increase on the buses.

There are several scenarios where the loads on a bus will increase such as reactor power hike which leads to raising demand on pumping capacity and the most severe case is the loss of one of the transformers in 100% reactor full power. Usually, one transformer connected to one bus is providing 50% of the power to the total loads. If one goes offline, the loads switch to the other bus posing a stress to the other branch.

In AC system, as long as the transformer is energized and operating, the response time is almost immediately as there is no functioning device controlling the power and the transformer can pass a lot more power than its rated power. This feature has been in electrical system for a long time.

8. The electrical system shall be able to isolate malfunctioned devices.

This is achieved by adding breaker with protection (automatically or manually triggered) at the terminals before loads. For example, such breaker placed before a pump can be disconnected by logic or by operator if the pump is malfunctioning. Another example is the breakers in front of and after a transformer are able to isolate that transformer and keep the rest of the system working as needed.

9. The electrical distribution system shall have over current protection.

Like most electrical system, the system must have over current protection. Even though it is not shown in the chart, there are monitoring, logic and operating devices keeping the system from over load. If a fault is detected, relay protection system will signal breakers according to the fault location or other information to shutoff the faulty part of the system.

10. The electrical system shall be able to start by itself.

As long as the transformer is energized it will start by itself and be ready to transmit power as transformer does not require additional control to start. In terms of breakers, they are controlled by logic circuit powered by Class I. With properly designed control logic, the system will be able to start up by itself.

In conclusion, the AC system successfully meets all requirements.

4.3 DC system design

The idea is to design a DC electrical system that has the same functionality and similar layout as the AC system, and it shall meet the same design requirements for electrical system. By referencing the designed AC system, following design concept, considering the requirements, standards and available technologies, the DC system is designed, the layout of which is shown in Figure 4-4.

4.3.1 System general design and description

The main generator (assumed to be 10 kV) and the connected power grid are running on AC system, same as in the AC system. Under normal operation, the whole system draws power from main generator through the SST and/or from switch yard through the UST. In the DC system, the UST and SST are converter transformers paired with rectifiers which supply DC electricity to the whole system under normal operation. There are two generators for backup power connected to Class III, each through a set of rectifier system. The DC to DC voltage conversion required is done by DC-DC converters.

The energy flow under normal operation is Class IV to Class III to Class I&II and always from the higher voltage buses to the lower voltages buses to avoid the cost of a boost-type converter. In loss of Class IV event, the standby generators provide power to Class III and from Class III to Class I&II. For example, when comparing DC loads or buses to AC Class II, it means the bus is the highest voltage bus in Class I&II. Because the Class I&II buses in DC system are DC and of same reliability, the battery banks are separated and connected to both classes. The capacities of electricity converters serving the same functionality in both systems are identical.

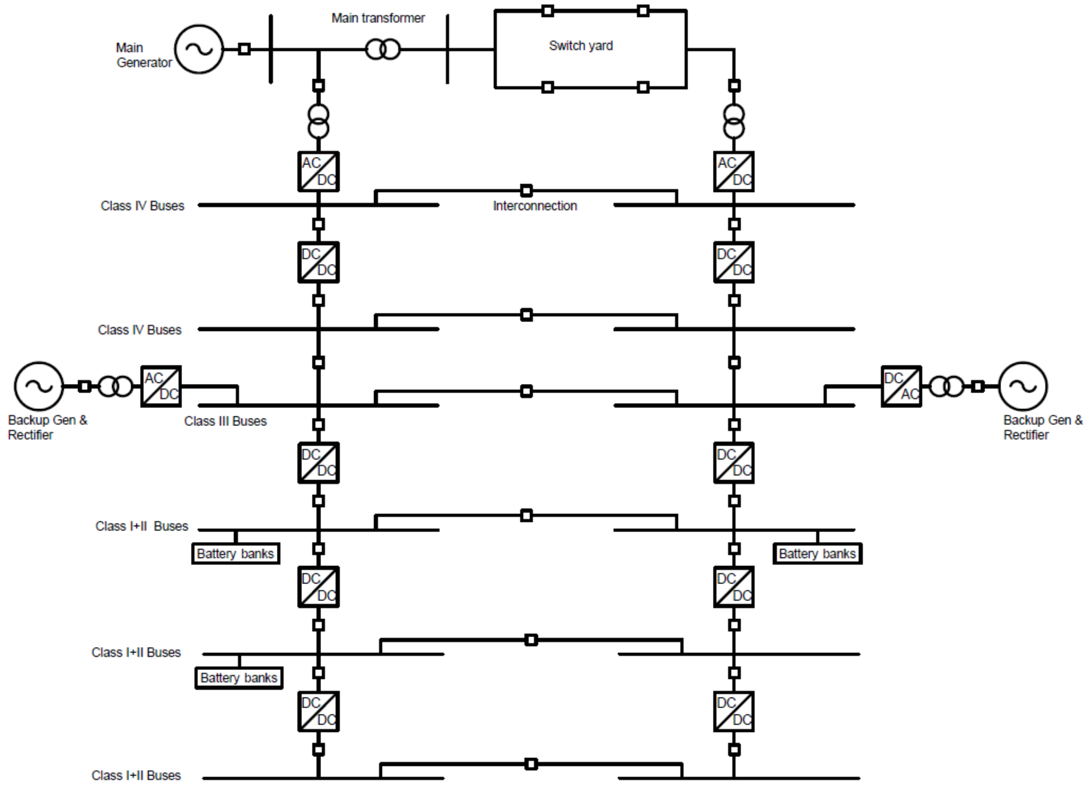


Figure 4-4 DC system layout

4.3.2 Requirements fulfillment

1. The loads shall be separated into classes regarding to their importance to plant safety, and electrical system shall also be designed into classes accordingly.

Similar to the AC reference system, the DC system is designed to have 3 classes supplying loads having different importance.

2. The tolerance to interruption in each class is infinity for Class IV, 5 minutes for Class III, 6(six) milliseconds for Class II and null for Class I.

In the DC reference system, Class IV can be interrupted infinitely for the loads are only used in power generation and not necessary under shutdown operation. The voltage drops in Class IV will trigger the backup generators connected to Class III to start up which takes less than 5 minutes. In the combined Class I and Class II, it is designed using the no-interruption requirement in AC system Class I (in AC system) which is achieved by placing battery banks in both classes. As long as the battery banks provide sufficient power, the voltages on Class I&II buses are maintained.

3. The electrical system shall be able to supply sufficient electricity to loads.

The transformers and converters are chosen with calculated power. The UST or SST with their rectifiers has the 4.5MW capacity for full system functionality as the total demand of electricity in order for the plant to operate fully is 4.4MW. The DC-DC converters between different voltage buses are also capable of supplying sufficient power.

4. The electrical system shall have the ability to provide adequate electricity (voltages, AC or DC, etc.) to the loads, and the voltage shall follow the widely accepted standards.

As described in last section, every class has one or more voltage levels providing adequate electricity according to the needs of loads. By the time this study is done, there is no standard that regulates DC distribution system (see Section 2.5.4), but the voltage level is restricted by the motor driven pump and the inverter technology. Class IV uses 4000VDC and 800VDC, while Class III uses 800VDC which is the same as the higher voltage buses in Class I&II. There are another two set of 120VDC buses and 48VDC buses serving different loads in Class I&II.

5. The sub-system in each class shall be able to operate separately from each other.

Every class is able to be operated separately due to fact that PE devices such as rectifier and DC-DC converter are highly controllable in terms of voltage and power and the overwhelming engineering and project experience have proved the PE-device-based systems have more flexibility over AC systems. [1, 26, 28, 128] Additionally, DC breakers (available in this power level from manufactures such as Schneider Electric[129] or ABB[130]) beside the DC-DC converters for additional protection and isolation provide extra control and safety to the system. Hence, the sub system can be operated separately.

6. The redundancy of main buses shall meet the standard.

In IEEE standard [90], it is required to have redundant buses which means at least two buses for each voltage level in Class 1E. In this design, there are two buses with inter-connection between them for each voltage level in each class, and each side has the capability of supporting full functionality for power generation operation.

7. The electrical system shall be able to withstand a sudden load increase on the buses.

Similar to the AC system, the maximum power change happens when one of two devices goes offline, the load of which will transfer to the other one. In switching device level, the increase of current raises the current in every switch cycle automatically, and no additional control is needed. Although extra switching loss or conduction loss introduced by the increase current resulting a voltage drop, the system controller is able to raise voltage in millisecond to compensate. [128] Overall, DC system is much more advanced over AC system in terms of control and it meets this requirement.

8. The electrical system shall be able to isolate malfunctioned devices.

PE devices used in this system such as VSD controller and DC-DC converter are operating whenever there is a correct control signal input given by higher level controller/logic. Therefore, the power supply can be withdrawn automatically by protection system or manually by operators. Also, DC breakers are added to provide additional protection against more severe faults, such as short-circuiting.

9. The electrical distribution system shall have over current protection.

Some PE devices based on IGBT or power MOSFET is less capable of stopping very large current caused by shot-circuiting on buses. [1] Therefore, DC breakers may be necessary for some location for the system to achieve adequate over current protection. PE devices have sensors in order to function, which can be used as input to relay system for faster response time.[2, 7] After cutting off large current, the breaker can be closed again and use the PE devices for isolation or it can be kept open. The system can meet the over current protection requirement even though the relay system design is out the scope of this study.

10. The electrical system shall be able to start by itself.

With properly designed control logic, the system will be able to start up by itself due to the fact that devices in DC system do not require manual or on-site action to energize the system.

In conclusion, the DC electrical system successfully meets the design requirements for a NPP. In terms of functions, individual component is able to provide such function necessary for an electrical system comparable to a NPP, and the DC system also successfully meets requirements (e.g. redundancy, backup) in a system level. In terms of performers, it seems to suggest that the DC system consisted of many PE devices has many considerable advantages over the AC system by improving responding time and how the system react to an incident (e.g. drop in voltage). Additional to meeting those requirements, the DC system can also provide more controllability (e.g. constant voltage regulation, real-time power regulation) and more functionalities (e.g. accurate power supply to motors).

4.3.3 System characteristics compared to AC system

In both systems, there is no difference in the main generator which is AC generator[14] that can be found in most thermal power plants. The output voltage may range from 10kV to 30kV depending on parameters such as power, and frequency can be 50Hz or 60Hz. The generator is connected to the power grid via the main transformer(s) and switch yard.

The divisions of system components in AC and DC systems begin from UST and SST. As the name implies, UST and SST are AC transformers altering voltage to what Class IV loads need in AC system. In DC system, on the other hand, they are rectifier system, including a converter transformer and a rectifier, used in order to convert the AC power into DC. The extra rectifiers introduce loss (around 0.8%) to the system compared to a transformer alone in the AC system. The benefit is that the rectifier is capable of quickly responding (milliseconds) to over-current and of sucking energy (reversing power direction) from the system in case of a short-circuited which is an advantage over AC system where the breaker can only turn off the power instead of reversing it. [128]

For the rest of the distribution system, the AC system seems to be more complicated due to the existence of multiple voltage levels in both AC power (Class IV, III, II) and DC power (Class I) where all transformers, rectifiers and inverters are required. The DC system, on the other hand, has only DC-DC converters, the voltages and power of which can be fast controlled in individual converters to address sudden change in loads. The stability of the DC system is inherently higher due to the fact that there is no power factor or synchronizing issue in DC system, which also has higher utilization on cables resulting in reduction in capital cost and losses. However, current DC-DC converter technology is less competitive in loss than AC transformers which may end up making the overall system less efficient. These are discussed in later sections along with the Silicon Carbide and soft-switching technology claiming to exceed efficiency of 99%. [32-34]

The voltage levels are summarized in Table 4-2 which shows the difference in voltage at the same class buses of both systems as a result of voltage output reduction of PWM

[14] Large power DC generator is not practical due to the arc and wearing issues of the mechanical commutators, and generating DC power also means the power grid must be DC which is not common.

inverters in VSDs. In order to supply power to the same induction motor for motor driven loads, the voltage in the DC buses must be higher, the principle of which is discussed in previous sections. The PWM inverters in VSDs set a minimum requirement of voltage, but they are able to work at a higher voltage but still provide a regulated power to motors as PWM inverter can regulate voltage and frequency. The highest input voltage limit depends on the transistors inside. If the buses voltages are much higher than that required by the motor, the transmission loss could be potentially lowered.

An obvious drawback of the DC system is overcurrent protection. PE devices such as IGBT are usually less tolerant to overload, and the stopping power requirement of the breakers is much higher due to the consistent voltage of DC which could be a factor limiting its application power. There are several solutions for high power DC breaker such as artificial zero-voltage point devices and solid state (thyristor-based) breaker, but the cost could be very high. [68] This limit may be more important to higher power application which is discussed in scaling discussion.

The pumps are benefited from the DC system due to the implementation of VSDs which could reduce the stress in motor bearing, pumping loss and reactive power. This PE drive is able to significantly increase pump efficiency and eliminate the need of a control valve and a lot of maintenance associated with air-line and valve body. [112] Besides, this technology can also improve the start-up conduction of a motor and reduce the start-up stress to the electrical system. [112]

Overall, the DC electrical system seems to have many technological advantages in control and stability because of its superiority in control responsiveness and control to individual system parameter. However, the DC system may be more vulnerable to overcurrent and a more sophisticated protection system is needed.

Table 4-2 Summary of electricity converters and voltages in AC and DC systems

Converter	Capacity in AC reference system	Capacity in DC system
UST or SST	4.5MW (10kVAC/2400VAC)	4.5MW (10kVAC/4000VDC)
In Class IV	1.4MW (2400VAC/480VAC)	1.4MW (4000VDC/800VDC)
From Class III to Class I	300kW (480VAC/120VDC)	N/A
To Class II or to 120V bus	150kW (120VDC/480VAC)	150kW (800VDC/120VDC)
In Class I	20kW (120VDC/48VDC)	20kW (120VDC/48VDC)

4.4 System design result summary

The 300MWth SFR based on PRISM reactor layout is the reference model of this study with key system parameters (e.g. electrical system layout and loads characteristics) referenced from various literature sources (e.g. Canadian 4-class system, ASTRID from France). A representative model of a NPP has been achieved which covers both traditional steam cycle loads (e.g. water pumping equipment) and loads that may appear in future reactor designs such as non-water coolant (in this case, sodium). The AC system and DC electrical system are based on the Canadian 4-Class electrical system which has plentiful information in literature. Both systems have identical loads, 62.5% of which is electromagnetic pump due to the low efficiency of EMPs and the intermediate sodium loop (heat ejected into sodium can be recovered and not wasted), 36.5% of which is motor driven pump, and about 1% others.

By referencing various NPP electrical system design standards from different organizations (e.g. IEEE and IAEA), the AC system and the DC system are successfully designed meeting all the design requirements. The feasibility of the DC system is checked by reviewing the availability of those essential components in literature and commercial products. The thyristor-based rectifier systems used in the DC system has been used for many years in HVDC transmission projects which usually have power from MW to GW, and they also are existing in wide range of power in various industries. There are also rectifier system using more advanced technology to achieve higher performance and smaller footprint which is technologically feasible and commercially available in high power application, but there is no evidence of their commercial availability in this specific power level.

There are some MW level DC-DC converters found as commercial products, but they are built for other applications with different voltage outputs and the technologies behind them are unclear. Research oriented high-power DC-DC converters, on the other hand, are found in literature with sufficient amount of detail about the power and voltage output. Hence, it is concluded that DC-DC converter necessary for NPP application is technologically feasible but not commercially available.

In terms of the loads, electric VSD technology has been used in numerous industries and households. There are wide range of selections for different application, which are designed to work with AC power supply. Even though the drives for DC electrical system are not found in manufacturers or literature, there shall not be a technical problem for designing a VSD for DC system, because AC VSD is an all-in-one converter with a rectifier, inverter (mostly using PWM technology) and a DC link in between which means the VSDs for DC system (not DC motor drive) is actually an inverter. Since there are lots of information and products across a wide range of power about PWM inverter, the situation of VSD for DC system is also technologically feasible but not commercially available.

When all components for making a working DC system are put together, there is no evidence suggesting that DC system is not functional or cannot meet the same requirements as AC system, and the instrumentation of DC system which is used in HVDC transmission system should not be an issue, either. However, R&D effort is needed to develop a reliable control system.

In the process of examining the DC system against the design requirements, not only does it meet all requirements, but it demonstrates many advanced features showing potential that it may outperform the traditional AC system in terms of controllability and responsiveness which can help improve plant performance and safety. The success in designing the DC electrical system and identifying its potential to improve power plant performance, maintenance and efficiency accomplishes the first two sub-objectives of this study.

4.5 Equipment Cost Estimation

4.5.1 Equipment cost result

4.5.1.1 Transformer

The cost estimation of distribution transformers is based on historical data collected by Hajipour et al. [37] with minimum modification in monitoring equipment which is to reduce maintenance to a level similar to the DC-DC converters (online monitoring). The estimated cost is verified with the data in Olivares-Galvan et al. [107] The estimated result is presented in Table 4-3.

4.5.1.2 DC-DC converter

The equipment cost estimation method of DC-DC converter is by gathering cost data of its sub-components and using reference design model (see Section 3.4.2) which generates a list of components to calculate the total cost. The DC-DC converters are estimated to cost about $36,000 per MW. There are several DC-DC converters in the system and the cost is listed in Table 4-4.

4.5.1.3 Rectifier and inverter

The same method of the DC-DC converter cost estimation is also the approach to cost estimation of a rectifier and an inverter. Since a rectifier or inverter system usually needs a converter transformer for a desirable voltage output, the system cost includes the cost of converter and transformer. The result of estimated rectifier and inverter systems cost is listed in Table 4-5.

4.5.1.4 Electromagnetic pump drives

As mentioned in Methodology section, the EMPs in the model are a DC conduction EMPs which requires high current but low voltage DC power. The drive in the AC system is a rectifier system and that in the DC system is a transformer type DC-DC converter. The result is listed below in Table 4-6 and Table 4-7.

4.5.1.5 Motor driven pump

The cost of VSDs is estimated by gathering information from several vendors and generate a trend line in Excel (as described in Section 3.4.2.5). Since it is very difficult to determine the cost of control valves which highly depends on the actual system, the cost of the control valves is estimated by engineering experience reported in literature [112], which suggests that high power VSDs tend to be more expensive in high power application while control valves is usually more costly in lower power region. Table 4-8 shows the cost of VSDs for motor driven pump loads in the system. As mentioned in Section 3.4, the cost of motor is not included in this model. Instead, the comparison is between the equipment cost of VSDs and the equipment cost of control valves.

4.5.2 Equipment cost summary and comparison

This section summaries the cost of parallel function components in the AC and DC systems which is to give a comparison between the two systems.

Figure 4-5 show the estimated cost according to the type of functions. The high power PE devices are expensive compared to traditional AC devices, which is evident in the comparison of rectifiers and transformers at UST/SST as well as the DC-DC converters in Class IV. Since the DC system has more PE devices, its equipment cost is higher than the AC system. Also, the DC system is more cost effective in low power applications in Class I and Class II due to the fact that the new technology enables simpler design which reduces the number of components. Nevertheless, the high cost of the high power PE devices still make the DC system equipment cost 50% higher than that of the AC system in Figure 4-6.

Table 4-3 Estimated costs of transformers

System	Position	Type of transformer	Power (kVA)	Estimated cost (2017 USD)
AC	UST/SST	Traditional transformer	4500	53,000
AC	Class IV	Traditional transformer	1000	14,000
AC	EMP drives	Converter transformer	1500	20,000
AC	Class III	Converter transformer	300	6,600
AC	Class I	Converter transformer	150	3,800
AC	Class I	Converter transformer	20	1,600
DC	UST/SST	Converter transformer	4500	53,000
DC	Backup gen	Converter transformer	600	10,000

Table 4-4 Estimated costs of DC-DC converters

Converter	Capacity in DC system	Estimated cost (2017 USD)
In Class IV	1MW (4000VDC/800VDC)	36,000
To Class II or to 120V bus	150kW (800VDC/120VDC)	14,000
In Class I	20kW (120VDC/48VDC)	4,900

Table 4-5 Estimated cost of rectifier systems and inverter systems

AC or DC system	Converter systems	Power (kW)	Estimated cost (2017 USD)
AC	Rectifier system	300	23,000
AC	Inverter system	150	19,000
AC	DC/AC/DC system	20	11,000
DC	Rectifier system	4500	122,000
DC	Rectifier system	600	30,000

Table 4-6 Cost of EMP drives in AC system

Functions	Sub components	Sub-components cost	Total estimated cost (2017 USD)
PHTS sodium pump	Converter transformer	20,000	53,000
	Rectifier	33,000	
IHTS sodium pump	Converter transformer	20,000	53,000
	Rectifier	33,000	

Table 4-7 Cost of EMP drives in DC system

Functions	Sub components	Sub-components cost	Total estimated cost (2017 USD)
PHTS sodium pump	DC-DC converter	N/A	64,000
IHTS sodium pump	DC-DC converter	N/A	64,000

Table 4-8 Cost of VSDs and control valves

Class	Motor driven pump loads	Power(kW)	Cost of VSD[15] (2017 USD)	Cost of control valve[16] (2017 USD)
IV	Main boiler feed pump	520	31,000	24,000
IV	Condenser cooling water pump	366	22,000	17,000
IV	Condenser extraction	267	16,000	12,000
III	Auxiliary boiler feed pump	37	2,800	2,800
III	Auxiliary condensation extraction pump	8	1,000	1,000
III	Shutdown system cooling pump	31	2,400	2,400
III	Service water pumps	58	4,000	4,000
II	Representative pump in Class II	130	8,000	8,000
I	Representative pump in Class I	130	8,000	8,000
	Total		95,200	79,200

[15] Only used in the DC system
[16] Only used in the AC system

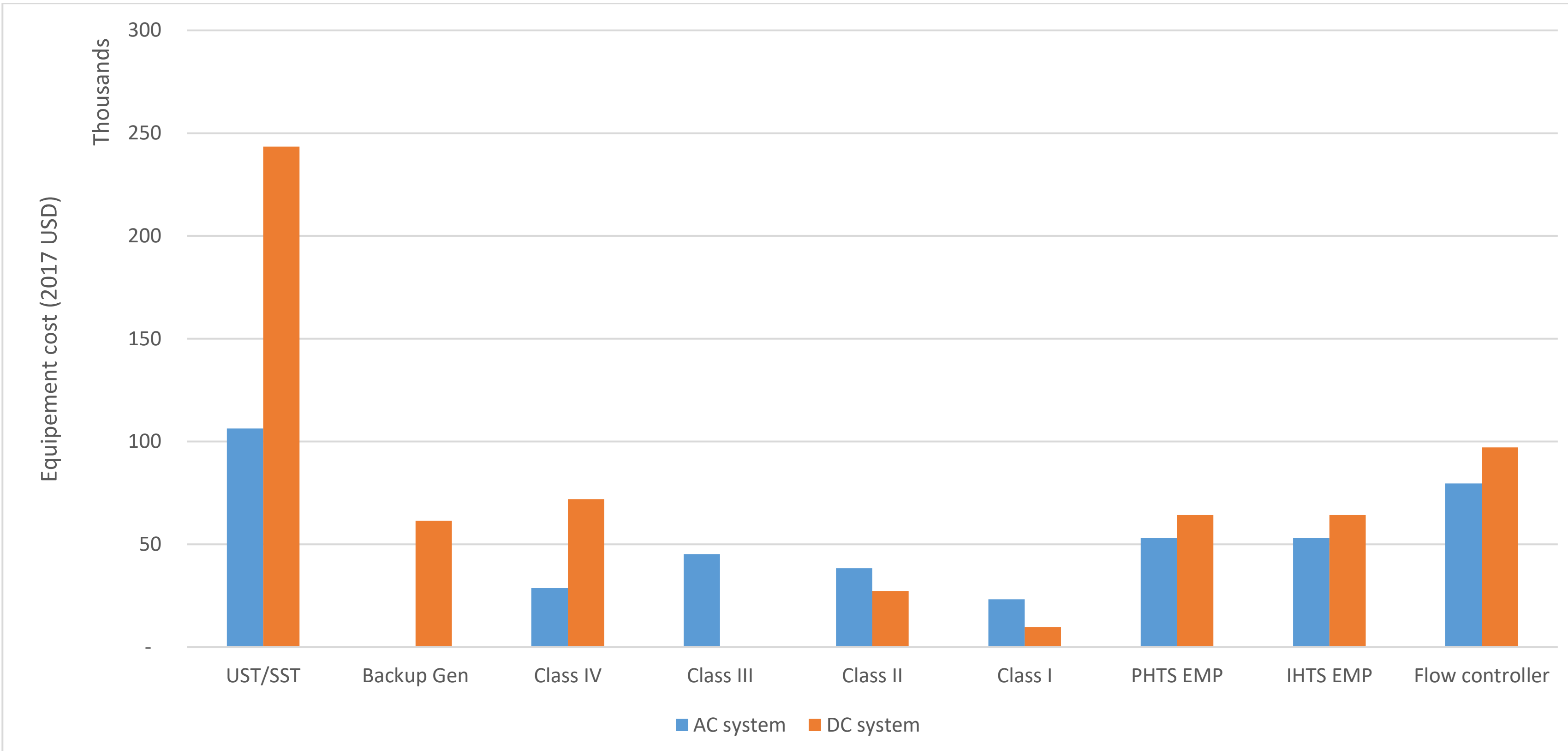


Figure 4-5 Cost by Component Type[17]

(This graph describes the equipment cost of components in each position.)

[17] Refer to Table 8-4

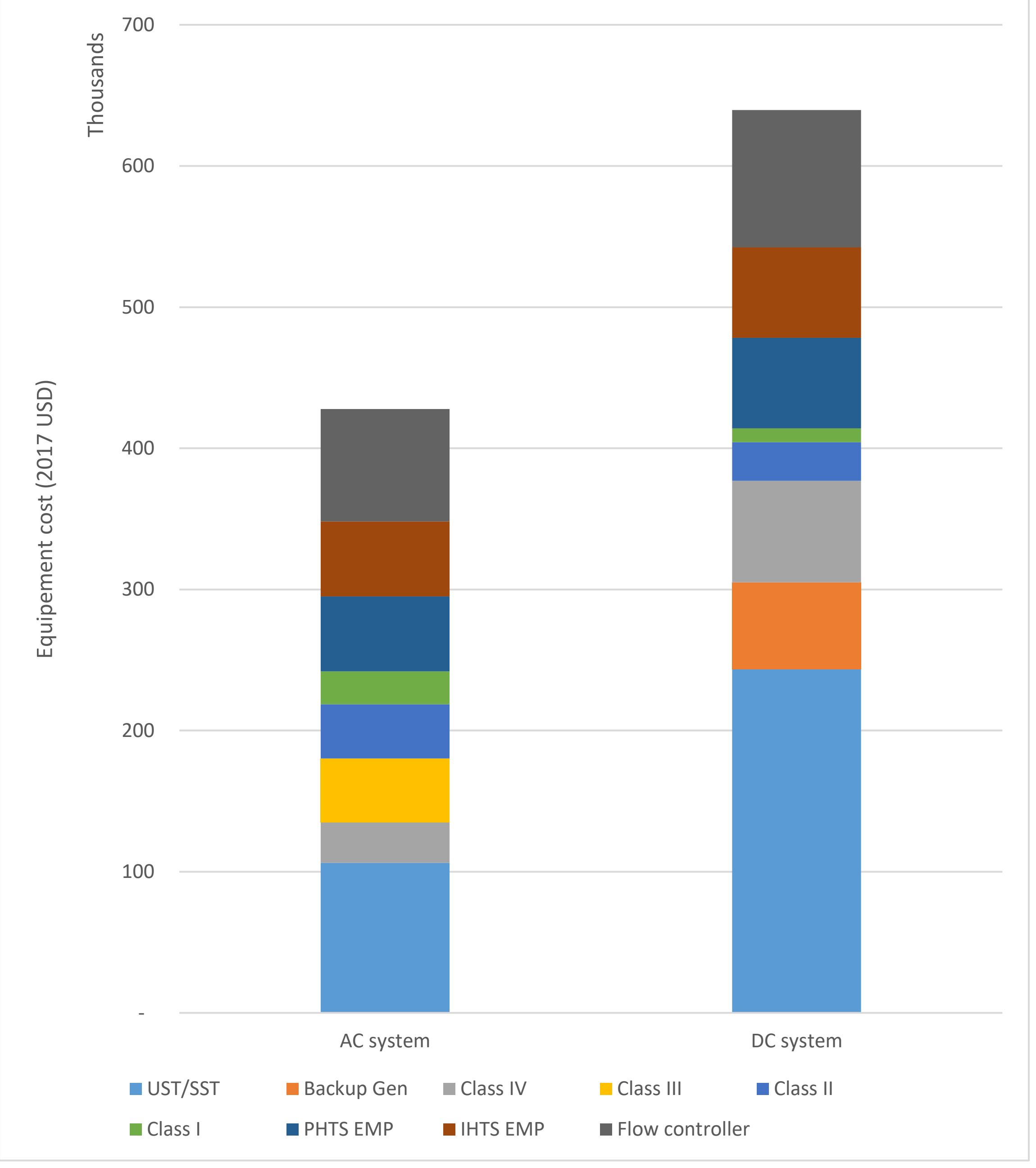


Figure 4-6 Equipment cost of AC and DC systems[18]

(This graph shows the equipment cost and its contribution to total equipment cost.)

[18] Refer to Table 8-4

4.6 Operations & Maintenance cost

This study focus on electricity usage of the listed components under normal operation (or power generation operation). The annual operating hour is assumed to be 8,592 hours and the LCOE is assumed to be $105/MWh.

4.6.1 Electricity converter operation cost

Losses of different types of electricity converters are calculated differently. For transformers, the main methodology is gathering data and processing by creating trend line in Excel and further adjustment for assumed operation condition of the power plant. Unlike transformers which have no-load loss, power electronic devices have only little no-load loss which is negligible (see Section 3.4.3). The actual loss is based on literature data and adjustment (according to the actual operation condition, as described in Section 3.4.3) for this application. The calculated result is illustrated in Figure 4-8 which shows that the DC system costs more to operate regarding to energy usage by about 45% (20,000 2017 USD) annually. This is because most large power components (e.g. electricity converters for UST/SST) in DC system have higher loss. If the loss of electricity converters in loads—EMP drives and VSDs—are taken into account, the increase is even higher (about 90%, 55,000 2017 USD) as shown in Figure 4-8, again, due to the higher losses in converter technologies in the DC system. Low power classes (Class I and Class II), on the other hand, shows preference to the DC system due to the simpler design. The details can be found in shown in Table 8-5 and Table 8-6.

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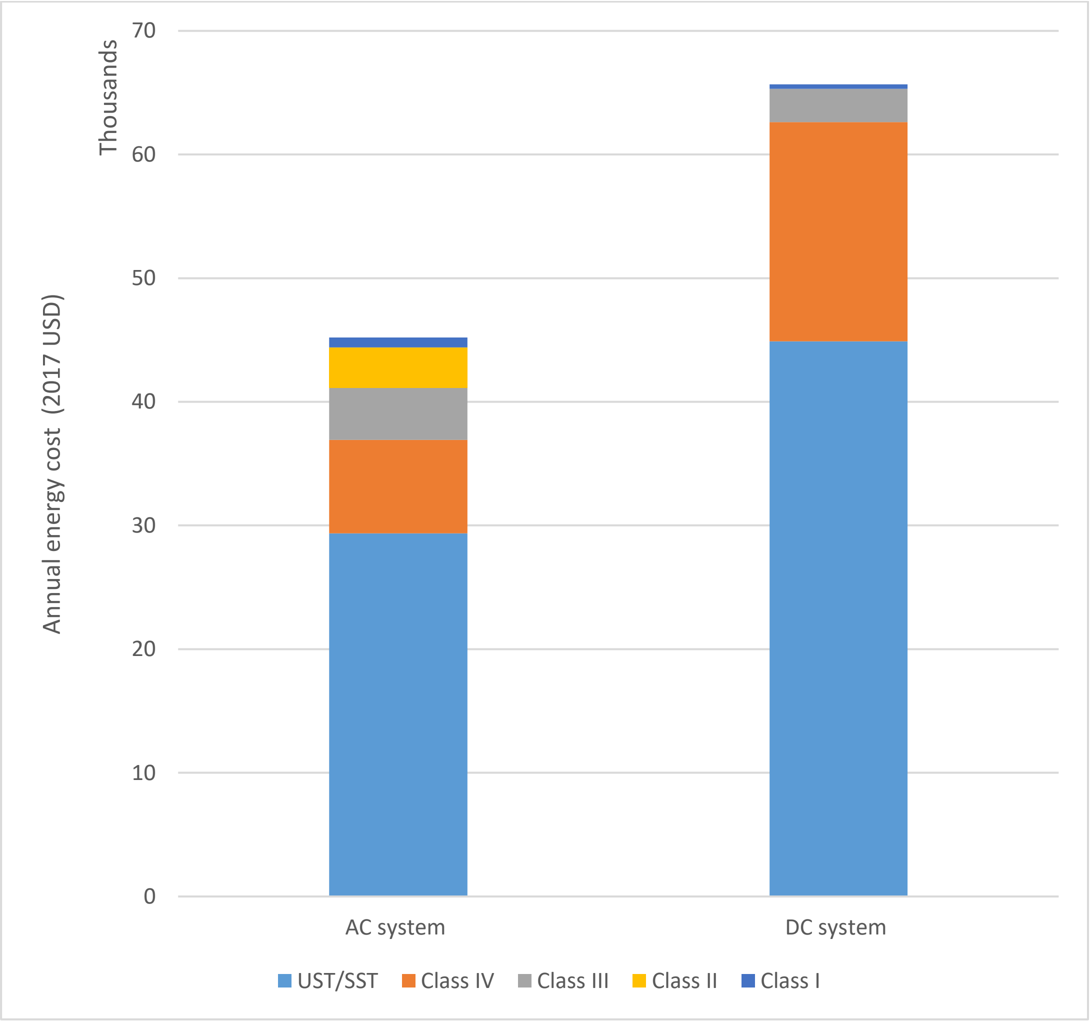


Figure 4-7 Annual operating cost (w/o considering EMP drives and VSDs)[19]

(This graph describes the energy cost associated with electricity converters in distribution system.)

[19]LCOE in this calculation is 0.105USD/kWh

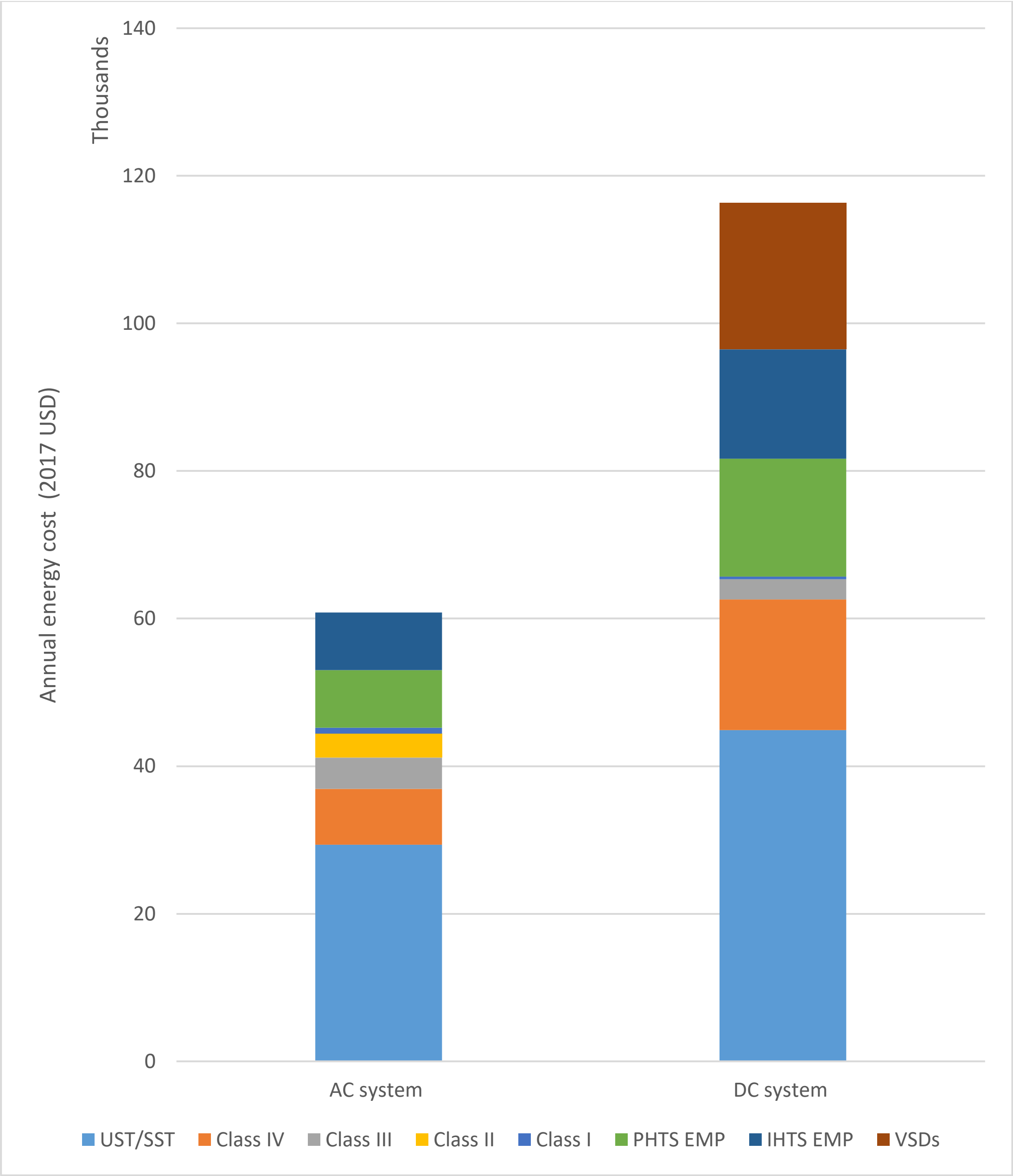


Figure 4-8 Annual operating cost (considering EMP drives and VSDs)[20]

(This graph describes cost of electricity converters in the system. Notice: the electricity cost of VSDs is only the losses in the converters)

[20] LCOE in this calculation is 0.105USD/kWh

4.6.2 Motor driven pump operation cost

The annual electricity usage which is a major part of the operation cost for motor driven pumps in the AC and DC systems is shown in Figure 4-9 (More details are found in Table 8-7 and Table 8-8 in Appendix II). The reduction in cost from control valve application in the AC system to the VSD application in the DC system is about 42% which is very significant considering the power consumption by pumps is very large. Additionally, the total cost from operating pumps are about 11.6 million USD in AC system and 6.6 million USD in DC system which are several magnitudes larger than the equipment cost and operating cost of the distribution system combined. Therefore, two sub-conclusions for this section are drawn.

1. VSDs can significantly improve pumping efficiency and hence greatly improve the power plant generating efficiency.
2. Due to the considerable reduction caused by VSDs, the following discussions should also analyze distribution system and loads separately because VSDs can also be implemented into AC systems. Also, analysis quantifying the difference between an AC system with VSDs, the reference AC system (without VSD) and the DC electrical system should be conducted in sensitivity analysis.

4.6.3 Maintenance cost

There is minimum maintenance associated with electricity converters due to their steady-state designs and usually lower-than-rated operating conditions (described in Section 4.2.2 and Section 4.3.3). The equipment that needs most maintenance is the control valves which have water and air systems along with many mechanical parts, and are operating under stress. The maintenance costs are 26,000 USD for AC system and 7,700 USD for DC system which is a 70% reduction, and the uncertainty associated is investigated in sensitivity analysis. The reason why the actual cost in USD is low is this analysis only considers the parts that differ between the two systems, which is described in general methodology section. Therefore, the actual reduction in maintenance cost could be higher if components such as pumps are considered due to the fact that VSDs drops the stress to the motor bearing and impellers. However, this effect is not considered in this study for 1) there is no quantified data found in literature, 2) it highly depends on the actual number of pumps, types of pumps and specific maintenance schedule. A summary regarding the maintenance cost is found in Table 8-9 in Appendix II.

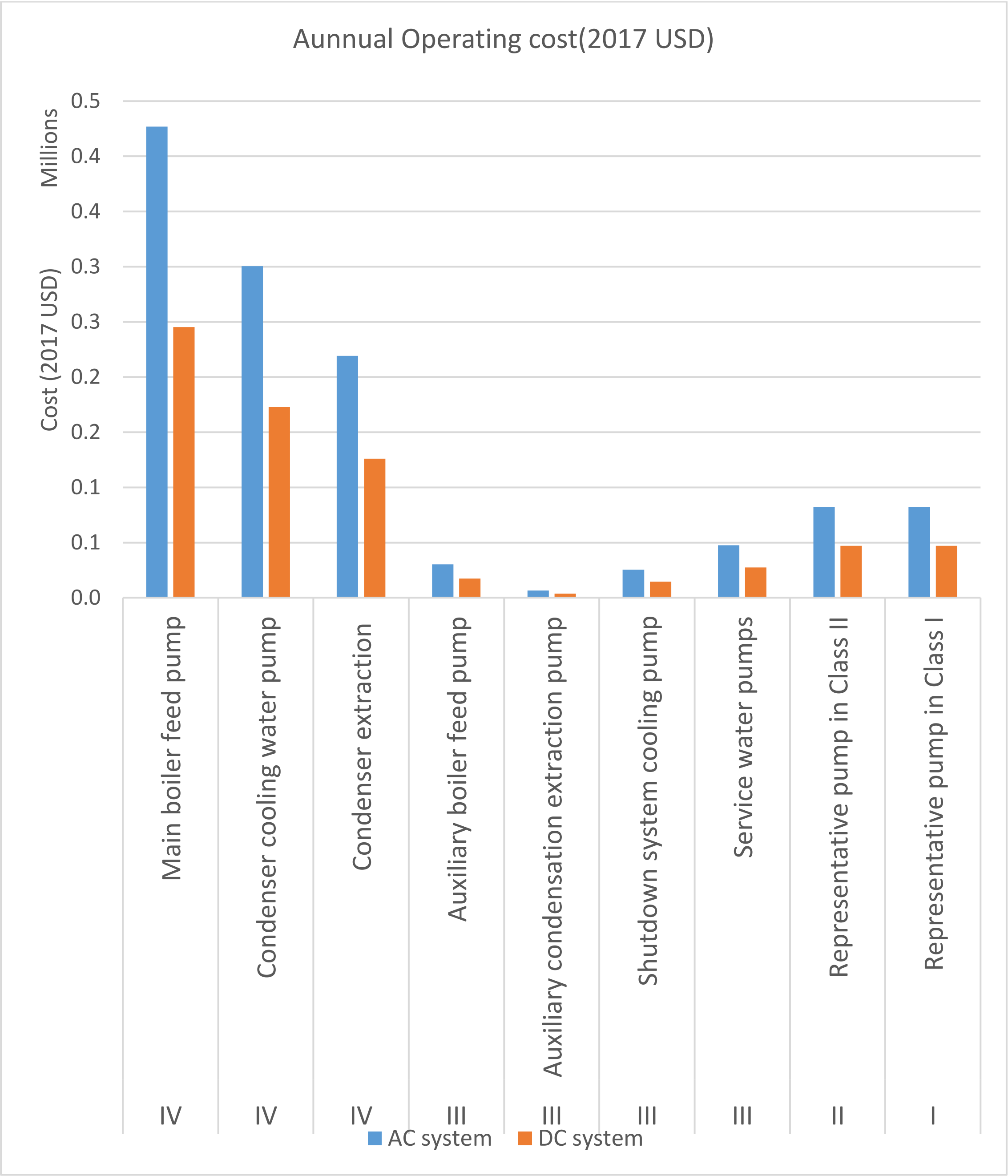


Figure 4-9 Annual operating cost of motor driven pumps[21]

[21] See Section 3.1.2 for the source of the load determination.

4.7 Cash flow and present value calculation

4.7.1 System PV calculation result

It is evident in Figure 4-10 and Figure 4-11 that there is clear financial advantage of the DC electrical system over the AC system in overall system[22]. Although it cost more for equipment (about 50%), the spending over its lifetime is significantly lower by about 36% in PV (7%, 50yr.). This is a result of high O&M cost. Indeed, the PV (7%, 50yr.) of O&M cost is 97.7% and 94.6% of the total cost the AC and DC system in PV (7%, 50yr.) respectively (shown in Figure 4-11).

Due to the fact that the operating cost of the loads occupies the majority of the cost while the cost associated with the distribution system (equipment cost and O&M cost) is a smaller portion (5% for AC system and 11% for DC system) of the total PV (7%, 50yr.), the results of the distribution system and loads are separately discussed in this sections.

In distribution part alone, the equipment cost plays a slightly more significant role in the total system cost, but the operation cost is still larger over its lifetime which is set to be 50 years (about 25% for the AC system and 27% for the DC system). Also, the DC system has a much higher (about 46%) equipment cost and higher (about 33%) O&M costs than that of the AC system. The primary reason is the high equipment cost of the DC system and higher operating loss introduced by the high power converters.

The equipment cost of DC distribution system is about $111,000 higher than that of AC system mainly because of the high-power rectifier and the expensive high-power DC-DC converter compared to AC transformers. Also, the losses of those converters contribute to the higher operation cost ($11,000 higher annually). After 50 years of operation, the PV of AC and DC distribution system is about 0.97 million USD and 1.3 million USD respectively (DC system costs 36% more). However, the cost (in PV) of the distribution system only represent 5% and 11% to AC system and DC system respectively, and the efficiency of the end loads is more significant.

[22] The first 3 years of the cash flow tables of the AC and the DC systems are given as examples in Table 8-10 and Table 8-11 in the Appendix II.

In terms of the loads, it is evident in Figure 4-12 that the annual operation costs of the loads in both system are significant (one year of operation cost could be higher than the equipment cost and operation cost of the distribution system combined).

The DC system has a significant advantage as the VSDs can significantly improve the pumps' efficiency, even though loads in the DC system has a higher equipment cost (about 20%) compared to that of the AC system. Comparing the present value over 50 years with a discount rate of 7%, DC system cost about $7,100,000 less (about 41% cheaper). Details about equipment cost and O&M cost of each component is found in Appendix. As the result suggests, the DC system has a higher equipment cost, but it can be easily justified by cost reduction from the loads mainly due to the implementation of VSDs.

The implementation of PE technology does not have to be either AC or whole DC. Instead, it can be in different levels. For example, only implementing DC electrical system in Class I&II can solve the high complexity and high loss issues in traditional configuration where Class II is AC and Class I is DC. Hence, the following sections investigate the possible options of implementing PE technology, from only using VSD technology to half-AC-half-DC or hybrid system.

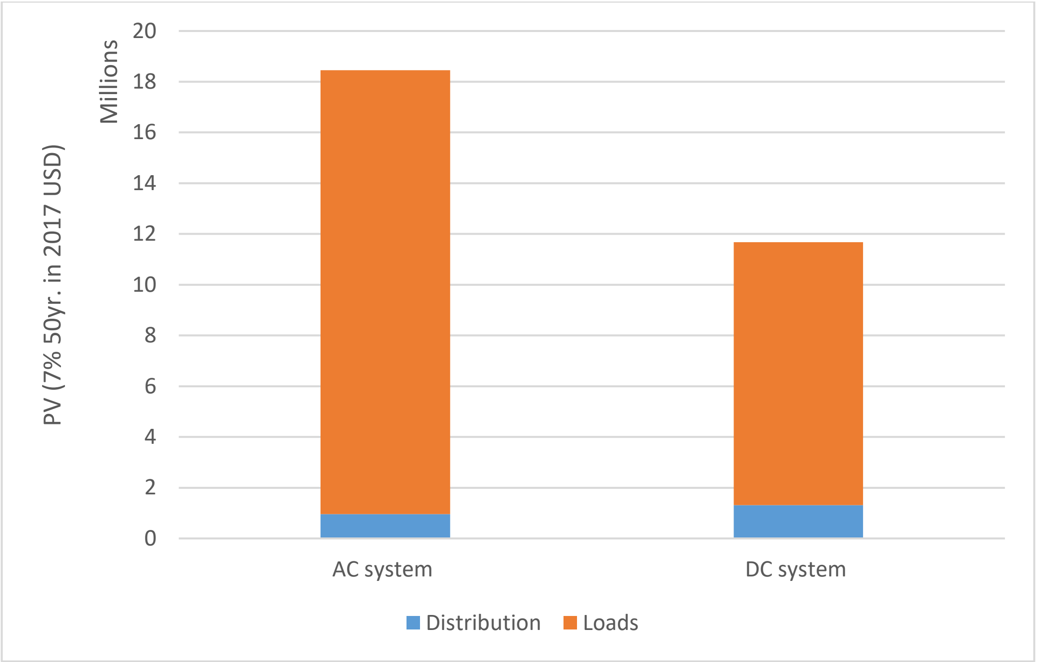


Figure 4-10 PV Comparison of AC and DC system (2017 USD)

(This graph describes the PV comparison between the two systems which are separated into the distribution system and loads.)

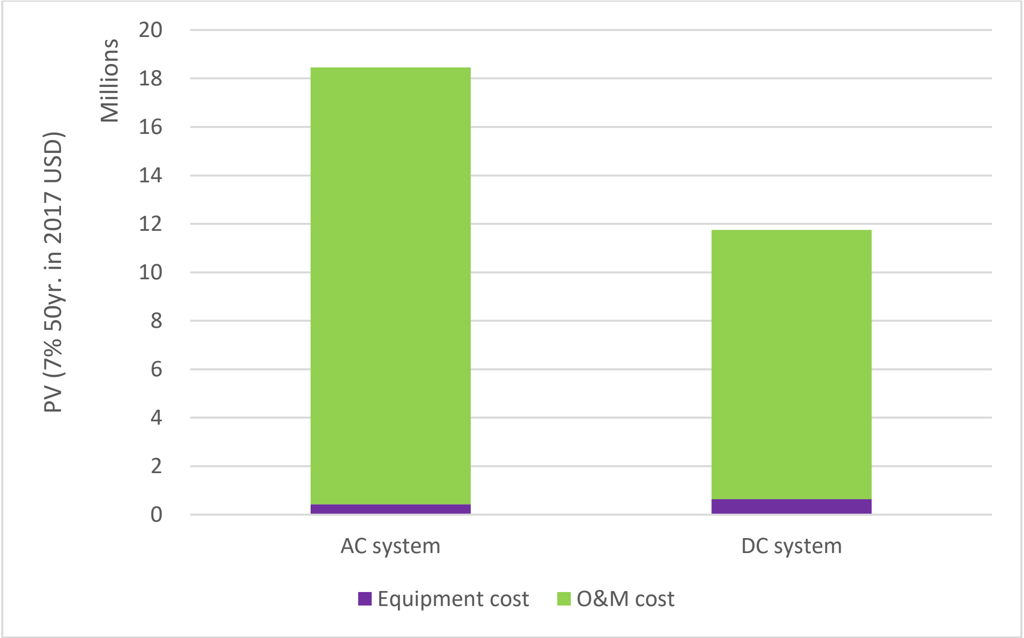


Figure 4-11 PV Comparison of AC and DC system (2017 USD)

(This graph describes the PV comparison between the two systems which is separated into equipment cost and O&M cost.)

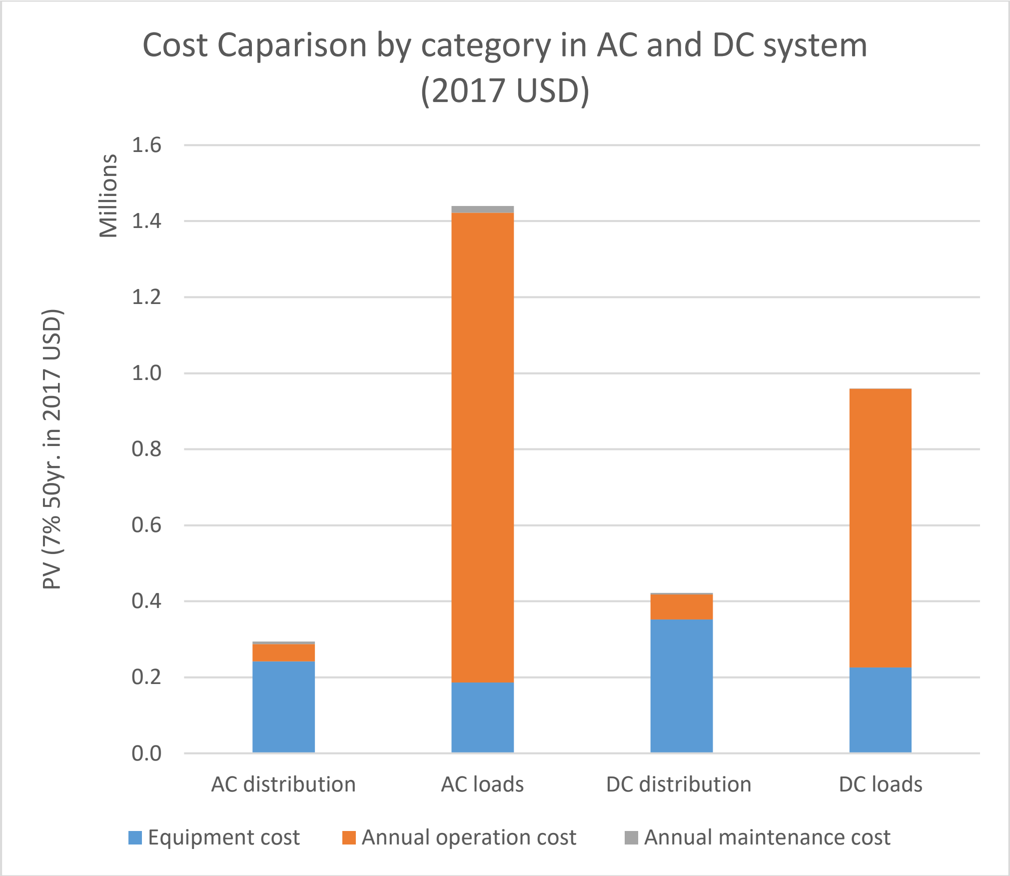


Figure 4-12 Cost comparison by category in AC and DC system (2017 USD)

(This graph describes the equipment cost of the distribution part and the load part of the AC and the DC systems in comparison to the annual O&M cost. More details can be found in Table 8-12, Table 8-13, Table 8-14 and Table 8-15 in Appendix II.)

4.7.2 AC system with VSDs

Most cost reduction in the result section comes from the operation cost and vast majority of it is from the VSDs. However, the VSDs can also be implemented in AC system, in which case they are with a rectifier and an inverter.

From Table 4-9, the overall cost of an AC system with VSD is 6% less costly than the DC system in terms of PV (7% 50 yrs.) and has a significant advantage in equipment cost. Even if a 2% loss and 30% of equipment cost increase is considered in VSDs in AC system for the added rectifier, the DC system is still 3.5% more expensive in PV.

If judging according to cost alone, the DC distribution system does introduce extra cost compared to AC distribution system with VSDs, especially for the equipment cost (DC system costs 45% more). However, it is about 5% increase in PV (7% 50yrs.). Therefore, unless PE devices become low cost and high efficient, implementing DC distribution system is a trade of advanced control and stability features with 5% cost increase overall 50 years. Another factor is that VSDs for AC system have been commercially available, which means NPP designs today can implement this technology for much higher efficacy without much R&D efforts, which seems to be very cost effective.

Table 4-9 Cost comparison of Systems DC, AC and AC with VSD

	System		
	DC	AC	AC w/ VSD
Equipment cost (2017 USD)	640,000	428,000	445,000
Annual electricity cost (2017 USD)	799,000	1,280,000	762,000
Annual Maintenance cost (2017 USD)	6,200	24,700	9,400
PV (7% 50 yrs.) in USD (2017)	11,800,000	18,500,000	11,100,000

4.7.3 Hybrid system

Considering the power level of DC-DC converter technology and the possible advantages when it is used to simplify and optimize Class I and Class II layout as well as the relatively high cost of the high-power rectifier systems at UST/SST, a solution of balancing between cost and improvement could be modifying only some of the existing classes into DC (termed hybrid system). In this hybrid system model, Class IV and Class III are AC and combined Class I & II is DC. The reason why Class IV and III are both AC is that some of the loads are connected to Class IV and Class III depending on the availability of the Class IV power. If Class IV is AC and Class III is DC, then some of the loads may need a different electricity converter in order to work properly. For example, conversion technologies for EMP drives are fundamentally different in an AC system (which is a rectifier) and in a DC system (which is a DC-DC converter), which means the two classes must have the same form of electricity (either AC or DC) to avoid the cost of complexity of the implementation of two completely different converters in Class IV and Class III. The combined Class I&II is considered a better idea since it is simpler in system layout with less converters and higher overall efficiency, which results in lower equipment and O&M cost.

Figure 4-13 shows the equipment cost comparison of the DC, AC, AC with VSDs and hybrid systems, and the hybrid system has the lowest equipment cost ($411,000) followed by the AC system ($428,000) which is about 4% higher, and the DC system equipment is more costly than the others at $640,000 which is about 50% higher than the AC system. The reason, as mentioned above, is the high cost of the high-power rectifiers and DC-DC converters.

In terms of PV, Figure 4-14 shows that over the system life time, the cost in PV (7% 50yrs) is also 5% or $800,000 lower than DC system, which means the hybrid system costs 41% less than the AC system. The conclusion is the hybrid system has lowest cost compared to both AC and DC systems in both equipment cost and PV over 50 years.

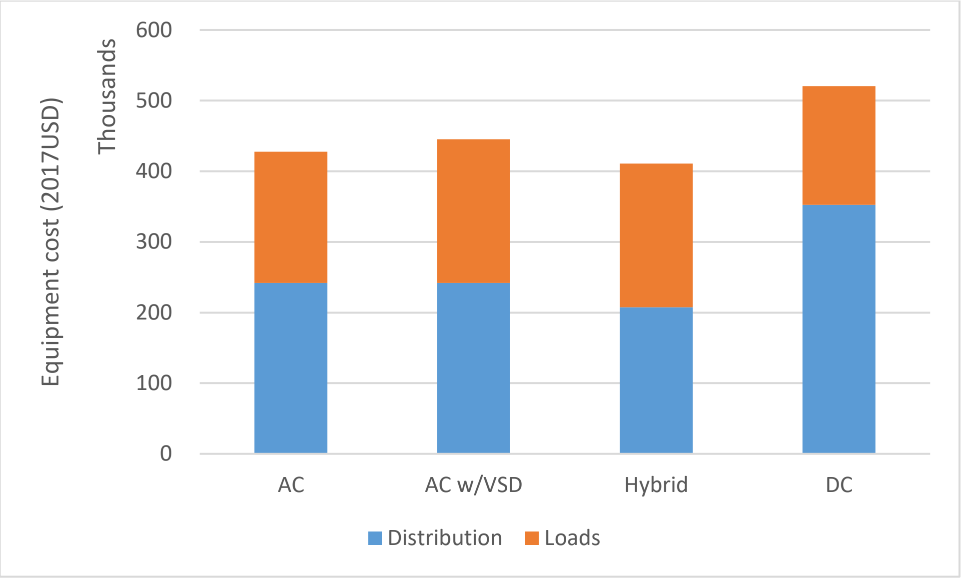


Figure 4-13 Equipment cost comparison between different configuration[23]

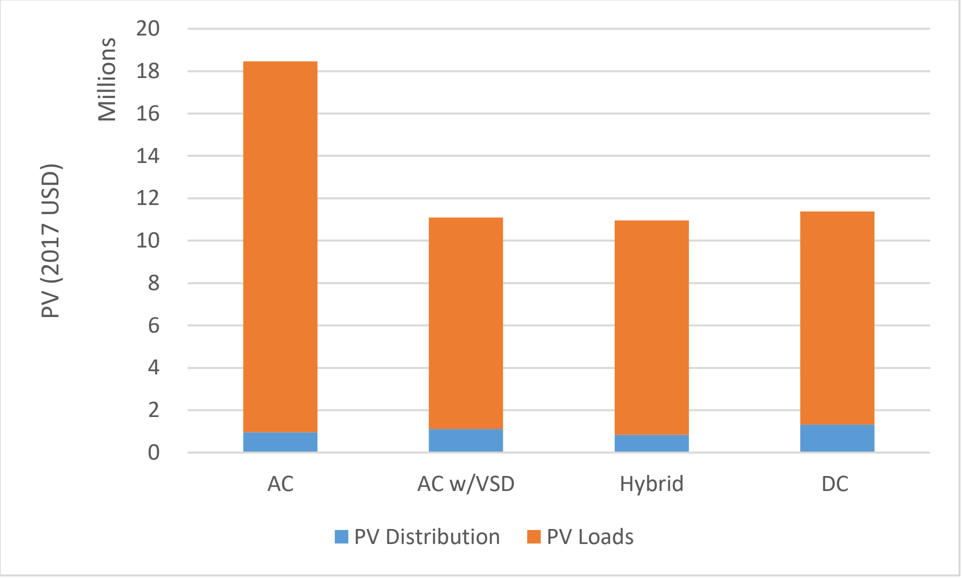


Figure 4-14 PV comparison between different configurations

[23] The EMP used in the DC system is the induction EMP in order to achieve optimal configurations for each system (see Section 4.8.2). Same as in Figure 4-21

4.8 Sensitivity analysis

In this study where new concepts such as DC distribution system and high-power DC-DC converter are discussed, the unavoidable uncertainties introduced by factors such as non-commercially existing components (e.g. VSDs for DC electrical system), by a specific selection(e.g. DC conduction EMP), and by components that are difficult to quantify (e.g. cable) are discussed in this sensitivity analysis which are separated into several categories—1) uncertainties in equipment cost where cost data is not reported in literature, 2) choosing different technologies which may result in a different higher or lower overall efficiency, and 3) uncertainties associated with economic parameters.

4.8.1 Individual equipment cost

In this study, the estimated cost of some components involves more uncertainty than others (e.g. estimation of some PE devices is less reliable than that of the transformers, which is based on industrial historical data). This sensitivity analysis investigates how individual equipment cost influences the result based on the scenarios where the subject cost is 1000% and 10% of the estimated value. The equipment in this study which is relatively uncertain in cost includes PE devices and control valves. This is due to the fact that the estimation of PE devices is based on cost of sub-component building the devices which does not consider profit margin or R&D cost, while the estimation of control valves is based on cost relative to VSDs reported in literature, which subject to uncertainty of cost variation of VSDs and specific design of the system.

Figure 4-15 shows that the component that influences the DC system equipment cost the most is the DC-DC converters', either in negative or positive side, while the component that influences the AC system the most is the cost of rectifier. Additionally, there is no cross over between the AC system and the DC system equipment cost from 20% to 200% as shown in Figure 4-16, which means if result does not change if there is only one variable or the cost changes at the same percentage. This can also be spotted in Figure 4-17, which means the DC system costs more within this range. Even at the full range (10% to 1000%) as shown in Figure 4-17, there are only 4 (out of 30) scenario which changes the result--the cost of the DC system could be lower than the AC system.

When those 10% or the 1000% scenario of all components are added into one system uncertainty, the result is shown in Figure 4-18. By the size of the cost, it shows that the DC system is of higher cost implications. By the 20% scenario, it seems that the result of the DC system has higher equipment cost could be altered in this scenario, even though this is not likely.

4.8.2 Total system equipment cost

In the last section, the influence of the equipment cost uncertainty of individual component to the total equipment cost is analyzed. This section discusses the impact of the system equipment cost in the system as a whole and how it influences the PV over 50 years.

As described in Section 3.4, different types of components have a different level of uncertainty based on the availability of information. For example, the equipment cost of the transformers is much more reliable than that of the DC-DC converter, which results in less uncertainty of the AC system. Also, higher cost of some components such as DC-DC converters has more impact the estimated result. To understand how the cost and uncertainty of these components impact the overall system equipment cost, total equipment cost of the AC and the DC systems when a multiplier (%) applies to all components with higher uncertainty (see the legend of Figure 4-15). The impacts of the uncertainty of these components are described in Figure 4-19 and Figure 4-20.

In comparison to Figure 4-18 which shows the range of equipment cost as the result of uncertainty, Figure 4-19 shows the sum of system equipment cost under the scenario of different range of multiple (at a specific percentage). This illustrates the trends the two systems cost from 10% to 1000%.

- The AC system: $Y_{AC} = 219{,}580X + 207{,}992$ *(4.1)*
- The DC system: $Y_{DC} = 513{,}479X + 126{,}179$ *(4.2)*

(Y is the system equipment cost and X is the factor.)

The result of the base model (X=100%) is that the DC system equipment cost is higher than the AC system’s. Given by the two equations above, the equipment cost of the AC system and the DC system equalizes at 28% (X=28%). If the cost of the AC system is kept unchanged, the equipment cost of the DC system equalizes to that of the AC system at 58.6%. on the other hand, if the DC system equipment cost remains, the AC system equipment cost needs to increase by 97% of the base model in order to match the DC system equipment cost.

In Figure 4-20 shows the impact of equipment cost to the PV result when the equipment cost of both the AC and the DC system is at a specific percentage. The result of the base model described in Section 4.7.1 shows that the implementation of the DC system is able to reduce O&M cost by $7,130,000 (PV, 7% 50yrs). Figure 4-20 shows that:

1) At 2500%[24], the equipment cost increase by implementing the DC system alters the result in terms of PV (7% 50yrs.), which means the conclusion of the base model is invalid when the actual cost of those components listed in Section 4.8.1 is 25 times of the estimated.
2) At 1500%, the PV result will be altered if the equipment cost of the AC system is kept unchanged, which means the conclusion of the base model is invalid when the actual cost of those DC components listed in Section 4.8.1 is 15 times of the estimated.
3) The conclusion of the base model is always valid if the only the AC system equipment cost is changed.

There are also other scenarios where the equipment cost of the two systems is multiplied by the same factors regardless the individual uncertainty associated with a component, such as the increased requirement of redundancy. For example, the design of this model is having two identical halves with inter-connection (see Section 4.2 and Section 4.3) for redundancy. When the number of the redundant parts increases from 2 to 4, then the overall equipment cost will double. In this case, the multiplier (x-axis in Figure 4-21) is 200%. In Figure 4-21, the sum of the system equipment cost is multiplied by a factor[25], and the result shows that:

[24] The result (in %) will change according to the reduction of discount rate, which will be investigated in later section. This applies to other results in this section.
[25] In comparison, Figure 4-20 uses Equation 4.1 and Equation 4.2 to calculate the impacts.

1) At 3300%, the equipment cost increase by implementing the DC system alters the result in terms of PV (7% 50yrs.), which means the conclusion of the base model is invalid when the total cost of both system is 33 times of the estimated.
2) When the DC system cost is of 1200% (or 12 times), the PV result will be altered if the equipment cost of the AC system is kept unchanged;
3) The conclusion of the base model is always valid if the only the AC system equipment cost is changed.

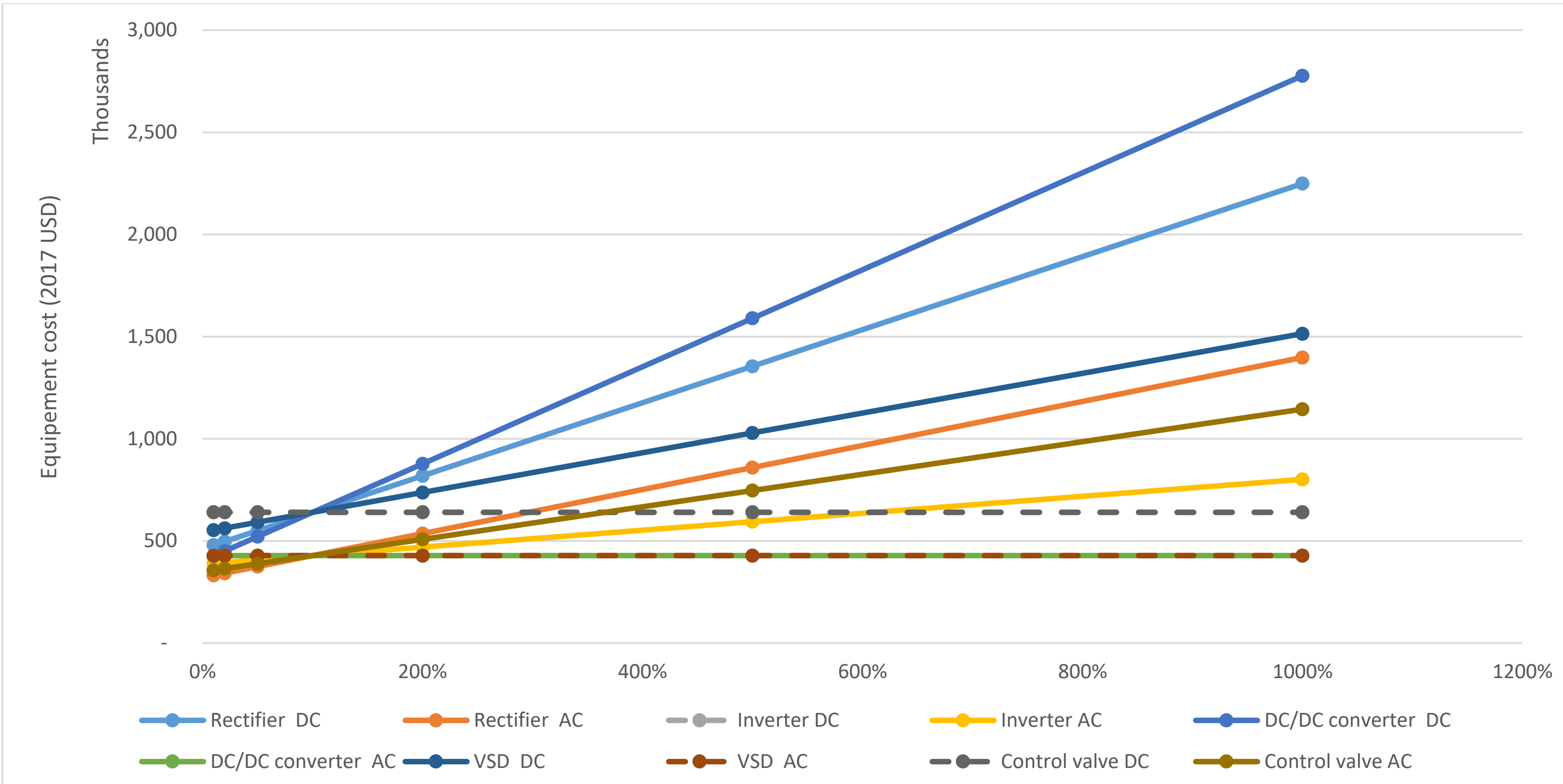


Figure 4-15 Influence of individual component equipment cost to total system equipment cost

(It shows the relationship of the total system equipment cost under the influence of individual component cost uncertainty)

(The equipment cost of VSDs and DC-DC converters do not influence the cost of the AC system since there is no VSD or DC-DC converter in the AC system. The equipment cost of control valves and inverters has no influence in the DC system for the same reason.)

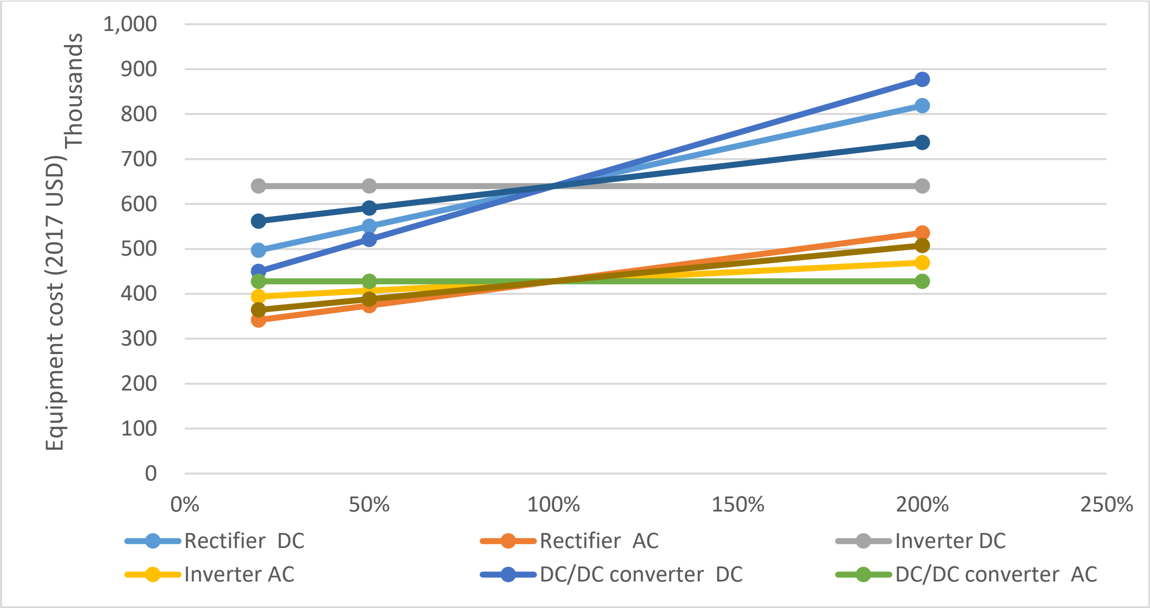


Figure 4-16 Influence of individual component equipment cost to total system equipment cost (20% to200%)

(It shows the relationship of the total system equipment cost under the influence of individual component cost uncertainty, and this graph focuses on the range of 20% to 200% and excludes components that do not influence the system cost at all.)

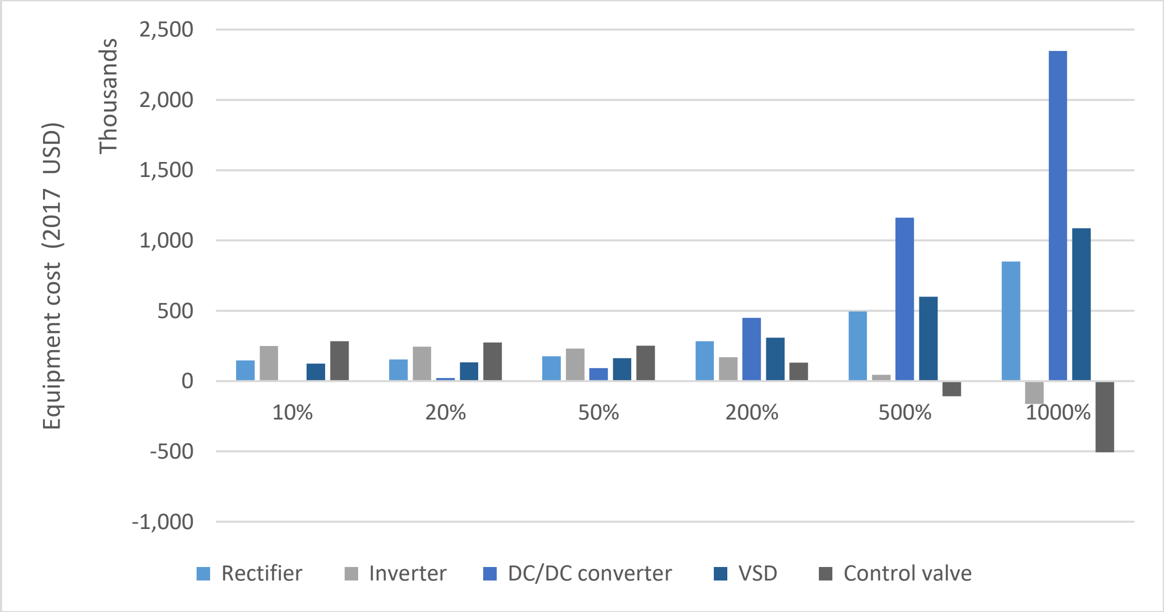
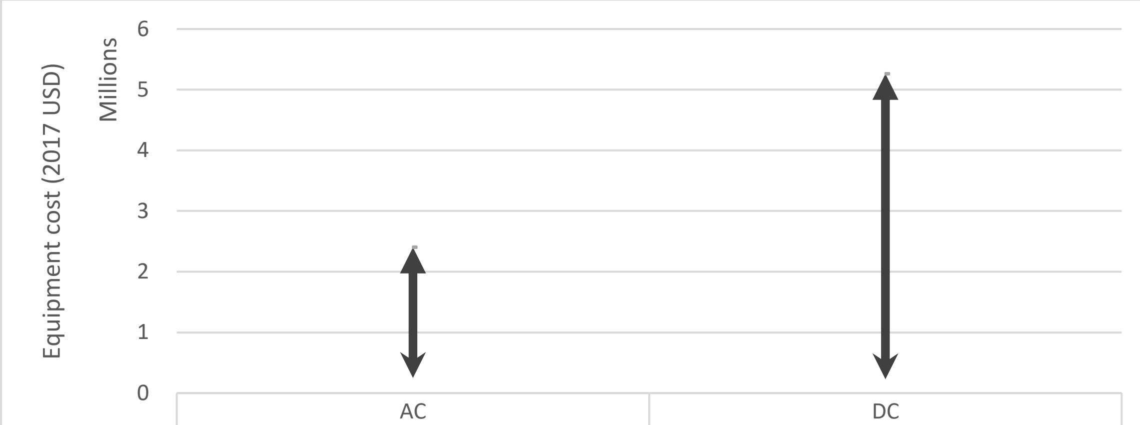


Figure 4-17 Cost difference between the two system

(This graph describes total DC system equipment cost minus total AC system equipment cost in scenario where individual component equipment cost is subjected to the stated multiple factor.)



	AC	DC
20%	251,119	228,875
100%	427,828	639,658
1000%	2,403,694	5,260,973

Figure 4-18 Total equipment cost uncertainty

[This figure describes the highest possible cost and lowest possible cost for the two systems based on specific scenarios. For the DC system, the highest cost ($5,300,000) is based on the scenario that the cost of all components (e.g. DC-DC converter, rectifier, VSDs) is 1000% of the estimated value), while $2,400,000 is the 1000% result of the AC system. This makes the difference to be $2,900,000.]

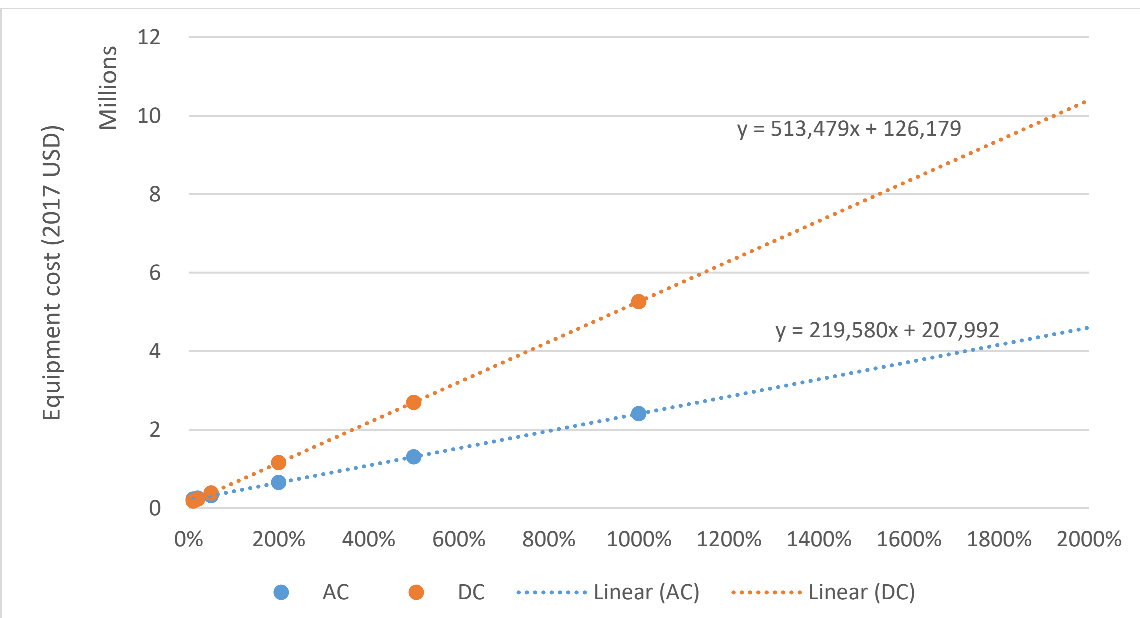


Figure 4-19 System equipment cost under the different scenario

(This graph describes the system equipment cost under the variable of individual equipment cost.)

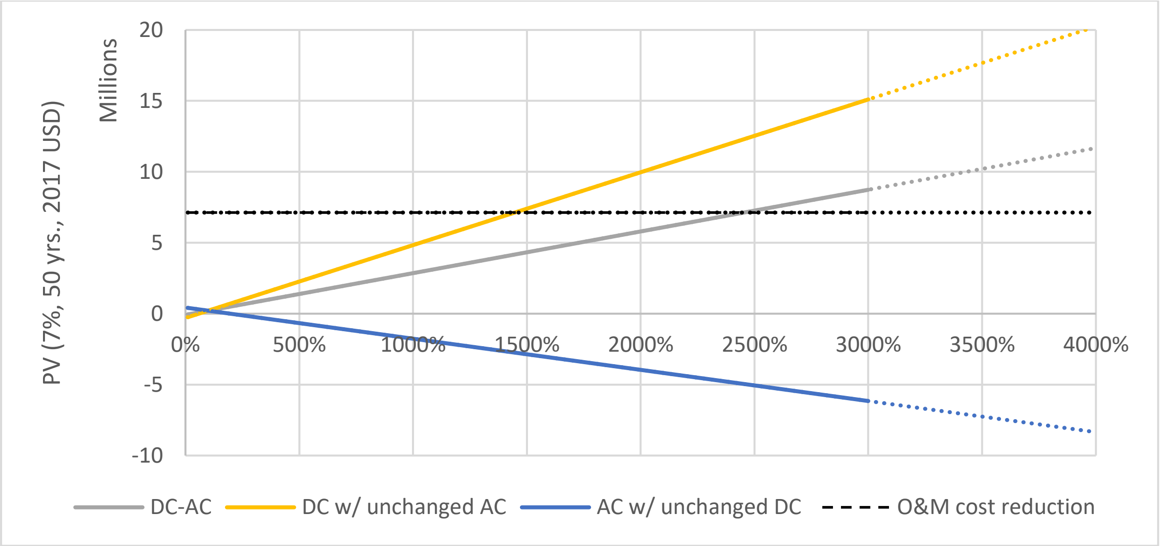


Figure 4-20 Effect of individual component equipment uncertainty to overall cost in PV[26]

(This graph describes the influence of equipment cost uncertainty under different scenarios. Noticed: The negative value means it is the cost of the AC system is higher than that of the DC system.)

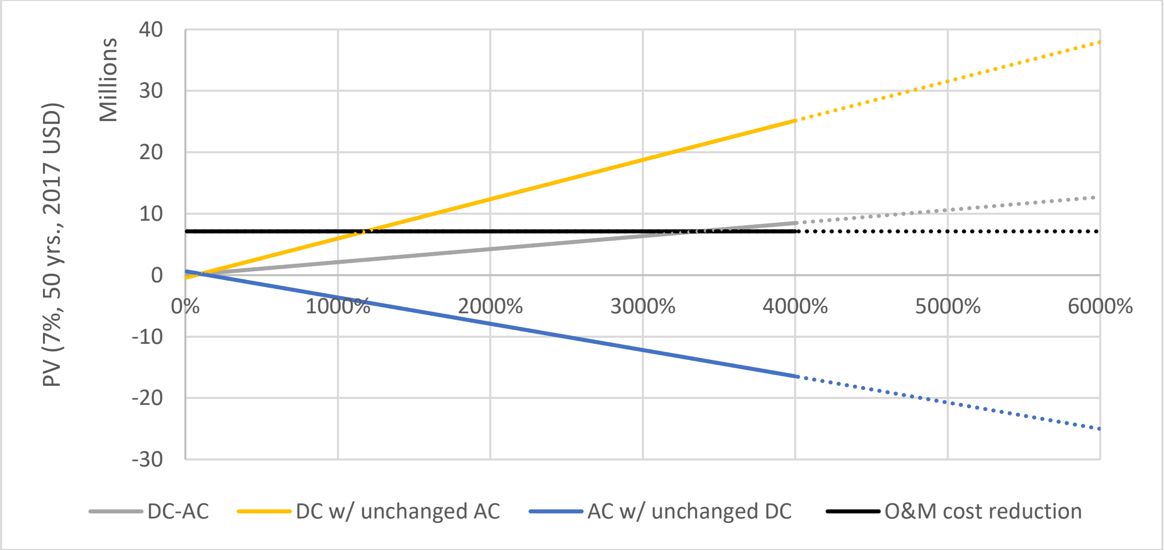


Figure 4-21 Effect of total equipment uncertainty to overall cost in PV

(This graph describes the influence of the uncertainty when the total system equipment cost is multiplied by a factor.)

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[26] DC-AC, the PV difference between the DC and the AC system when equipment cost is at a x%, DC w/unchanged AC, the PV difference between the DC and the AC system when only the DC system equipment cost is at a x%.

4.8.3 Influence of discount rates and LCOE on O&M cost

There are many factors influencing the operating cost, the most important of which one in this model is the LCOE since the energy losses is the biggest variable. Mentioned previously in Section 3.4.1, LCOE and discount rate are relative as the calculation of the former involves the later. Therefore, the discount rate and LCOE are varied simultaneously in the first part of this analysis, and in the second part, only the LCOE is varied.

It is shown in Figure 4-22, the PV of both the AC and DC systems declines as the discount rate increases which results in the decrease of the O&M cost reduction, however, the percentage of this cost reduction (from AC to DC) only changes within 1%. By extending the range of LCOE while keeping the discount rate at 7%, O&M cost in PV at different LCOE is plotted in Figure 4-23, which shows that the O&M cost is always greater than the base model equipment cost and the DC system is always a better option. However, if the uncertainty of equipment cost is considered, the result is dependent and can described by Equation 4.3. For example, if the LCOE is \$50/MWh, then the a more than 1200% equipment cost of the estimated value will change the result in PV.

$$z=63000x-294000y+337000 \tag{4.3}$$

Where z is the cost reduction by implementing the DC system (2017 USD),

x is the LCOE (\$/MWh),

y is the multiplying factor in equipment uncertainty (%).

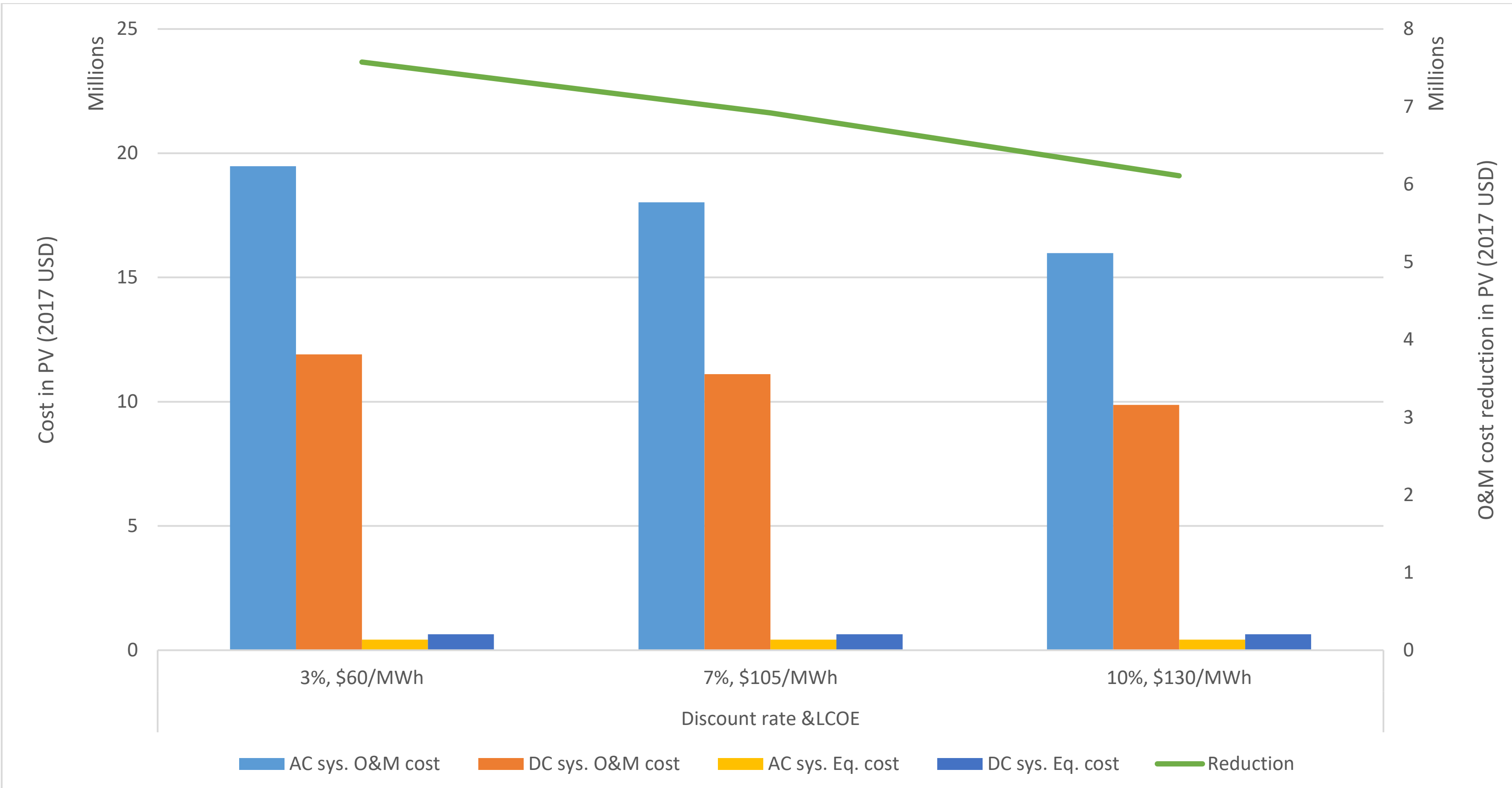

Figure 4-22 O&M cost and Equipment cost in PV under different discount rates and LCOE and the O&M cost reduction

(This graph describes the O&M cost in PV under stated discount rates and LCOE, the O&M cost reduction from the AC sys. to the DC sys., and the equipment cost for comparison.)

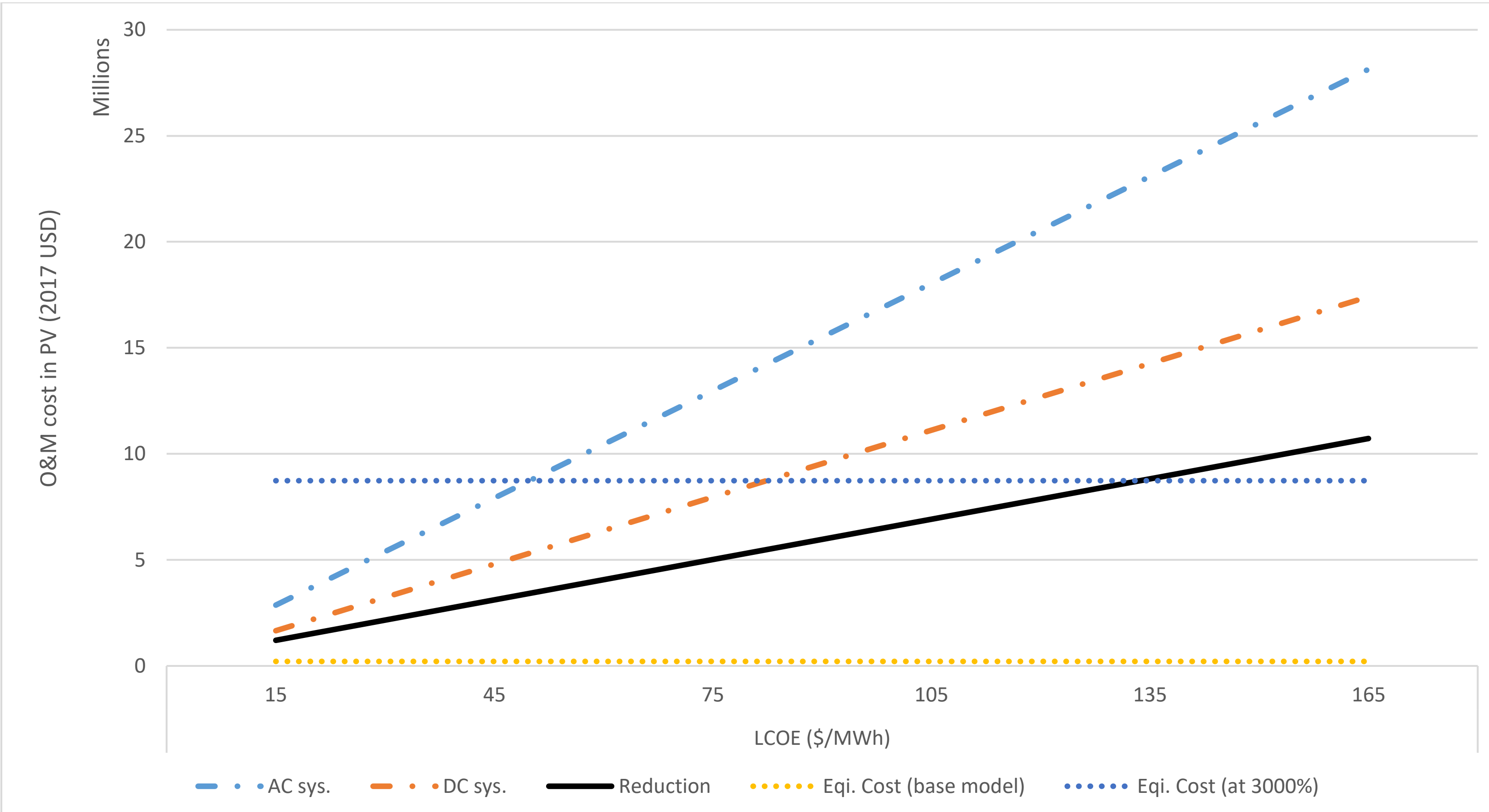

Figure 4-23 O&M cost of the AC and DC systems at different LCOE (with comparison to equipment cost)

(This graph highlights the O&M cost reduction in PV (7%, 50 yrs.) in comparison to the equipment cost reduction from the result of equipment cost sensitivity analysis.)

4.8.4 Influence of the PE devices reliability on system cost PV

As mentioned in Section 3.4.3.5, there are two main factor affecting the reliability of PE devices, which are the failure rate and the lifetime. In Figure 4-24, it shows that as the lifetime of those PE devices come shorter, the cost of replacement in the DC system is higher resulting in a decrease of overall cost reduction (PV) due to the fact that the number and unit cost of the PE devices in the DC system is higher. However, it also shows that the decrease is relatively small (less than $1,000,000) from 50 years' lifetime to 5 years' lifetime in terms of PV. This is because the annual energy reduction (equivalent $500,000/y) is relatively large compared to the equipment cost increase ($212,000/y). Even if the replacement happens annually which is very unlike, it does not alter the result financially.

The other factor is redundancy affected by failure rate. If the PE devices cannot meet the regulation for reliability, redundancy could be one of the solutions. Redundancy could be internal (redundant critical components) which is a less costly option or external (multiple devices). [121] For example, in a DC-DC converter, having two control model (one for backup) is internal redundancy, while having two DC-DC converter is external redundancy which costs more than the former. The following analysis is based on the later strategy. In Figure 4-25, the influence of reliability in terms of redundancy is analyzed, which is based on a lifetime of 10 years. It shows that if all PE devices have lifetime of 10 years and each one has 3 sets of redundant units which are all replaced after the lifetime, the total system reduction in PV (7% 50yr.) will decrease from $6,400,000 to $4,500,000. In order to alter the PV result, the number of sets of required redundant units must be higher than 10 and the replacement happens to all units every 10 years.

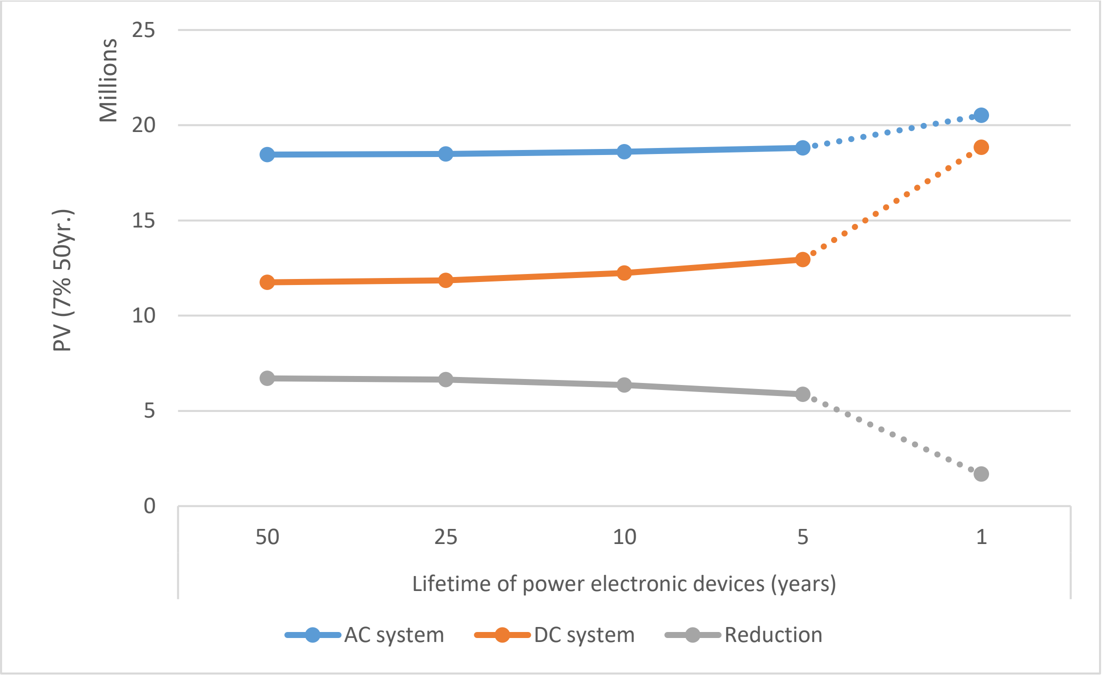

Figure 4-24 Influence of PE device lifetime to system cost in PV

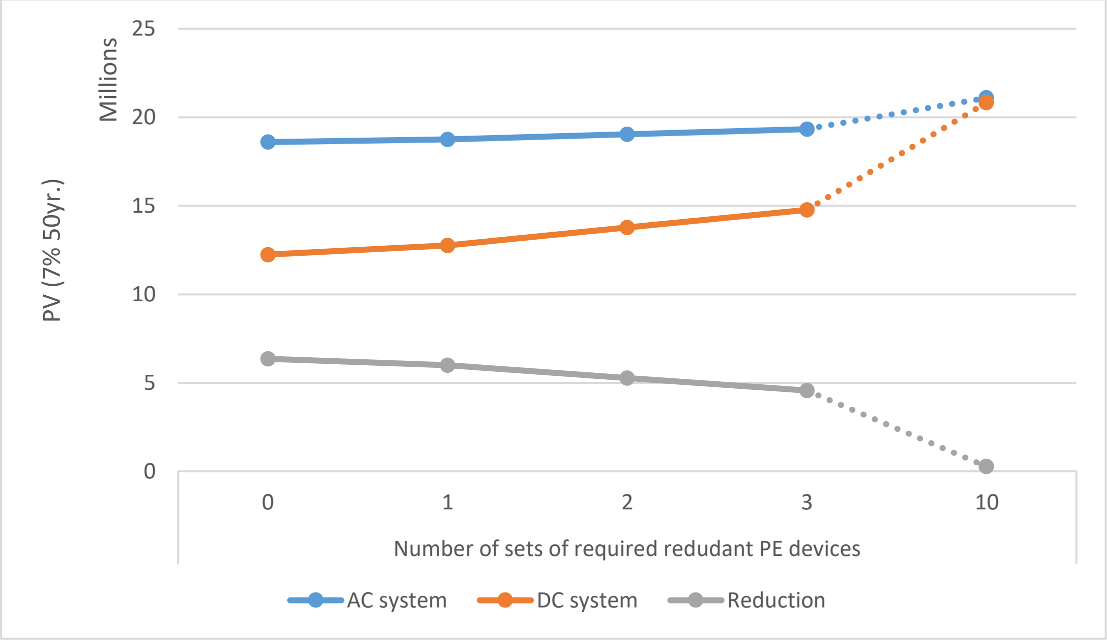

Figure 4-25 Influence of required redundancy to system PV

(This graph describes the influence of required redundant units for every PE device, which is based on a replacement period of 10 years.)

4.8.5 Influence of multiple pumps in parallel on the operating cost

In order to make the work load manageable, the method of generic analysis is used in the main analysis where all loads are assumed to be in the number of one in each load. However, in reality, this may not be the case due to reliability and regulatory concerns. In most pumping applications, the number of operating pumps (backup pump is not included) is usually more than one, and they are in the same power [10]. For example, in a two-pump system, either pump is of 50% of the total pumping requirement, while, in the 3-pump system, each one takes 33% of the total requirement. Since the majority of the cost reduction is a result of implementing VSDs to control the flowrate, it is necessary to discuss the impact to the operation cost (power consumption) of a non-generic model.

In parallel operation, the two/three pumps are set at the same power in VSD applications because this is more efficient mode compared to that one is at full load while the other is at a smaller load condition (confirmed by calculation). For example, both pumps are 80% in flow instead of one at 100% and one at 60%, when total of 80% is required. However, it is the opposite for control valve applications. It is more efficient to run one pump at full load and the other one at a reduced power. Therefore, to optimize the pumping efficiency in VSD applications, the motor could be slightly larger (e.g. 110%) than the required in size, and both/all pumps are running at a reduced load at the same power. For control valve applications, the most efficient operating point is when one pump is at full load, and the other(s) is shutoff.

Table 4-10 shows the power in percentage of the full power under different number of pumps in parallel. It is evident that multiple pumps configuration seems to improve the pumping efficiency, especially under low load. However, the power of VSD is mostly smaller than that of control valve application regardless how many pumps are in operation, and the reduction is significant---around 40% at 80% flowrate condition, 65%-70% at about 60% flowrate, about 80% at 50% flowrate. Therefore, the method of generic analysis does not significantly affect the accuracy of the estimated cost of VSD application compared to the control valve applications.

Table 4-10 Power comparison with different number of pumps in parallel

Number of pumps	Flowrate (%)	Power with VSD (%)[27]	Power with control valve (%)	Power reduction (%)
1	100%	103%	100%	-3%
1	80%	53%	93%	43%
1	60%	23%	82%	72%
1	50%	14%	76%	82%
2	100%	103%	100%	-3%
2	80%	53%	90%	41%
2	60%	23%	80%	71%
2	50%	14%	50%	73%
3	100%	103%	100%	-3%
3	80%	53%	98%	45%
3	60%	23%	64%	64%
3	50%	14%	59%	77%

4.8.6 Induction electromagnetic pump

As mentioned in the background information section, the induction EMP drive may work more efficiently in the DC electrical system and the drive is cheaper and already commercially available PWM inverter instead of the expensive DC-DC converter for DC conduction pump. [131] The drive for induction EMP in AC system becomes similar technology used in AC VSD, which is a combination of a rectifier and an inverter with a DC link in between assuming transformer is not needed (see Section 2.2). The motor pump in the AC system in this analysis is with VSDs which means the result does not include the large impact from having the efficient VSDs, so that the focus can be placed on the EMP drives. The result is shown in Table 4-11.

The reduction in PV over 50 years is 2.4% for DC system, and the loss of drive is reduced by 53% which is considerable. The AC system, on the other hand, suffers from using a PWM inverter, the loss of which is relatively large compared to rectifier. That directly leads to 68% increase in overall system loss, and 1.1% increase in PV of the AC system. Therefore, an induction EMP seems to be a better choice for DC electrical

[27] Losses of VSDs are considered, hence, power could be as high as 103%.

system which can reduce the drive loss by about 50% and improve the overall system economy by 2.4%.

In conclusion, from the perspective of the cost associated with the drives, the induction EMP works better with the DC system, and DC conduction works better in the AC system. Due to the low-voltage high-current requirement of the DC conduction EMP, the engineering of its DC-DC converter drive in a DC system seems to be challenging and the cost and loss of such devices is higher than the drive used to drive an induction EMP. (see Section 2.3) From the power factor point of view, induction EMPs could have low power factor due to the inverter (see Section 2.2.4 and Section 2.2.6), but the DC system has no power factor issue. DC EMPs drive in an AC system can also have power factor issue due to the fact that Silicon Control Rectifier may consume a lot of reactive power which post challenge to the electrical system (see Section 2.2.6). To address this problem, a PWM rectifier may be a better choice as it can provide control over reactive power as well (see Section 2.2.4).

Table 4-11 Cost reduction of replacing conduction EMPs with induction EMPs

	PV of whole system (2017 USD, 7%, 50yrs)		Drive losses (kW)	
Type of EMP	AC electrical system	DC electrical system	AC electrical system	DC electrical system
Conduction EMP	11,200,000	11,810,000	12.7	34.1
Induction EMP	11,310,000	11,520,000	21.4	15.90
Reduction (%)	-1.1%	2.4%	-68.0%	53.4%

4.8.7 Influence of low-loss DC-DC converters on the distribution system cost

In Section 4.7.1, it is shown that the cost of the DC distribution is much higher in terms of both equipment cost and O&M cost than the ones of the AC system, partially due to the losses associated with high-power DC-DC converters. There are many advanced technologies in literature claiming potentially highly-efficient DC-DC converters. Therefore, in this section, the influence of these high efficiency DC-DC converters to the distribution system cost is investigated.

There are many advanced technologies regarding to PE devices (e.g. soft-switching, Silicon carbide-based transistor, etc.) which can make a DC-DC converter reaching efficiency to 99.5%. Many converter across a wide range of power are proposed in literature [32-34, 38, 132], most of which seem to have peak efficiency at about 50% load which is the case under the power plant normal operation (see Section 3.4.3). To emphasize the influence of the DC-DC converter efficiency to the electrical system, the AC system in this analysis is with VSDs. Table 4-12 illustrates that even if all DC-DC converters in the DC system have 1% losses (compared to 4% in the base case) which significantly raises the system efficiency, but the DC distribution system has 13% more losses compared to the AC one. Therefore, it seems that the DC distribution system will have higher energy cost even the advanced PE technologies are used.

The key to improving the efficiency of the DC distribution system and making it competitive to the AC system is to improve the efficiency of high-power devices. For example, one of the possible solution is implementing rectifier using technologies such as PWM rectifier, soft-switching and Silicon Carbide transistor. It has many promising features such as eliminating the need of reactive power compensation as PWM rectifier itself is a Power-factor Correction, reducing harmonic issue to both AC and DC sides. [133] However, it is not included in this analysis for the amount of information available is limited and the PWM rectifier may require an effective high-power DC breaker.

Table 4-12 Sensitivity analysis on high-efficiency DC-DC converters

	PV (7% 50yrs) in USD (2017)		Increase (%)
	DC	AC	
Distribution sys. Alone	1,092,000	965,000	13.2%
Whole system	11,188,000	11,100,000	-0.7%

4.8.8 Influence of cable cost on system equipment cost

One of the biggest advantages of a DC system is the reduction of cabling cost as a result of the higher utilization of cable capacity and reduced number of cables along with the associated structure. [2, 22, 59] The AC system requires minimum 3 cables to transmit the power, one for each phase (4 cables, if the neutral is required), while the DC system requires minimum 2 cables. Each cable must have its own isolation and may need its own supporting structure which are a significant portion of the total cost. [134]

However, the environment of a NPP makes it difficult to estimate the actual length, types and cost of cable used in a plant. Therefore, to estimate cable cost reduction, several assumptions must be made.

1. Cable from generator to reactor building or to control room is two kilometers.
2. Cable usage for distribution system including cabling between converters and buses is two kilometers.
3. Cable usage between each load and its bus is 25 meters, and there are 30 major loads (similar to number of loads listed in Table 8-1). Hence, the total length is 0.75 kilometer.
4. All power cables are of the same cable type with the same price per meter.
5. The DC system I&C cable is assumed to be unchanged from the AC system. Thus, it is excluded.
6. The cost of cable with supporting structure for an AC distribution system is about $65 per meter. [134]

Based on the assumption, the length of cable used is about 4.75 km, and the material cost of cables with supporting structure is $309,000 for AC system. Implementing DC system could reduce the cable cost by about 30%. [22] Hence, the cable cost in DC system is about $216,000 with the reduction of $93,000.

Figure 4-26 shows the relationship between system cost increases of implementing DC system, cable length and unit cable cost. According to this relationship, the unit cable cost needs to be higher than $150/m in order to justify the cost of implementing the DC system with the cable length of 4.75 km. However, it should be mentioned that,

1. Cables in a NPP may have special designs to encounter the radiation, high temperature or meet a certain standard which could raise the unit cable cost to $150/m.
2. Certain cable design may also influence the impact of considering cable cost either positively or natively. For example, if the cable is shielded or protected in individual phase, then the cost reduction of using DC is significant since the DC system only needs two phase rather three in the AC system. On the other hand, if it is a 2-core or 3-core cable with protection and shield on the outside, then the impact is reduced.

What is not covered in this analysis is the labour cost of installation which differs between AC and DC systems (about 30% reduction for DC cables). [22] However, the difference also depends on actual system designs, and it is even harder to estimate for a NPP application due to its complexity and specialty. Referencing chemical plant where installation cost could be 75% (or higher) of the material costs [73], the estimated cross point (currently, 4.75 km in length and $150/m unit cost) will be lowered. Again, it highly depends on actual designs.

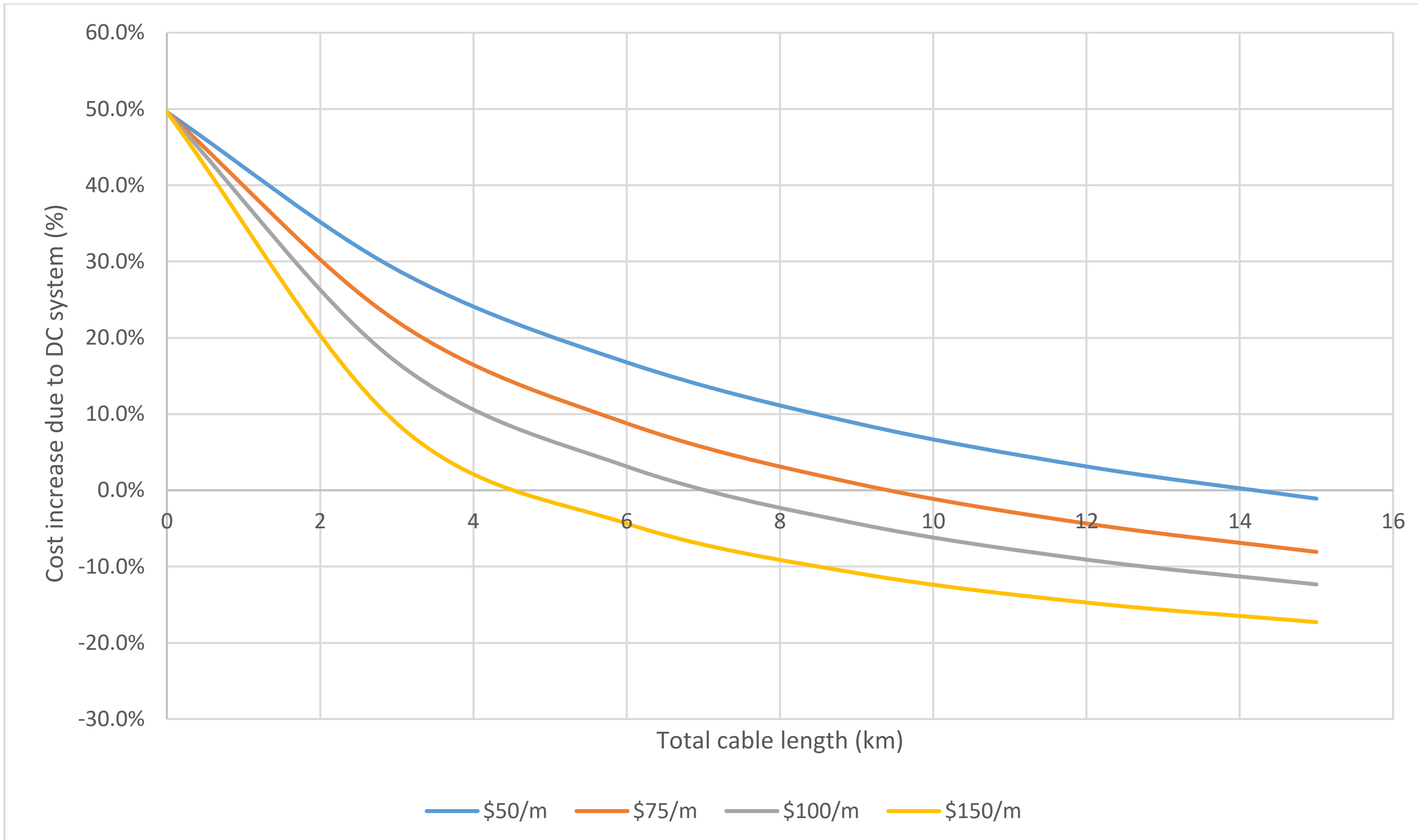

Figure 4-26 Cost increases of implementing DC system regarding to cable cost

4.9 Financial analysis result summary

In the financial analysis, the generic analysis is used to find out the cost difference between the two systems. The result is expressed in present value, and several uncertain variables are also investigated.

At current state, the DC system costs significant more than the AC system about 50% (or $212,000) in equipment cost due to the higher cost of high-power PE devices such as a DC-DC converter and a rectifier, which are essential to the DC system. However, the increase of the equipment cost can be easily justified by O&M cost as the O&M cost is the majority of the cost (overall 94%). After 50 years' operation, the PV (7%, 50 yrs.) shows that the DC system can reduce the cost by about 37% (or about 7 million USD) due to the much more efficient control method of motor driven pumps. Since the cost of powering the motor loads is dominant, the whole system is separated into two parts, which are the distribution system and the loads for a more comprehensive result. In the base model, the implementation of the DC distribution cost 43% or $422,000 more over 50 years. An investigation intending to determine the influence of low loss of the DC-DC converters is conducted, and the result shows that these potential technologies cannot make the DC distribution system as efficient as the AC system.

In terms of the equipment cost, there are several sensitivity analyses conducted to determine the influence of individual component equipment cost that has higher uncertainty, as well as the equipment cost of the whole system. It shows that the equipment cost uncertainty is not likely to change the result of this analysis which means the DC system equipment cost is more likely to be higher than that of the AC system. However, due to the fact that the equipment cost is relatively small compared to the O&M cost. That the DC system is able to reduce overall cost in PV still valid. In fact, according to the sensitivity analysis in Section 4.8.2, the equipment cost needs to be as high as 33 times (for the whole system) and 25 times (for only the PE devices) in order to alter the result.

In terms of the O&M cost, the influence of discount rate, LCOE and reliability of PE devices is also investigated. The result shows that the LCOE and discount rate does impact the actual cost reduction in PV, but the percentage of reduction stays at 38%. An investigation of an extended range of LCOE shows that LCOE will not alter the result of the base model, which means the PV of the AC system is always higher. The cost of redundancy and replacement period are also investigated, which shows unless there are more than 10 sets of full power redundant PE devices (replaced every 10 years) or replace the entire system more than once a year, the result still valid.

Other highly uncertain variables are also investigated. The influence of multiple pumps in parallel operation is also investigated and the result shows the calculation of the base model still is valid for multiple pumps setup. Additionally, the technology choice of EMP only have minimum influence to the estimation result (3%). Similarly, the more advanced low-loss DC-DC converters also does not influence the result (<1%). Power cable is another factor considered in sensitivity analysis which concludes that if the cable costs more than $150/m or is more than 4.75km in length, then the cable cost could justify the cost of the DC system. However, it depends on the types of cable used in a power plant.

4.10 Discussions

4.10.1 Financial result discussion

The objective of this work is investigate the feasibility and financial impact of implementing PE technology to a nuclear power plant. The implementation has been determined to be feasible as all necessary components are technologically feasible and the overall DC system meets all design requirements as the AC system does (see Section 4.1 to 4.4) and also shows some potential improvements to the plant (see Section 4.3.4 and more details in later sections).

The reason of the system design directly implements the PE technology to an entirely DC system is that, 1) this approach can provide an insight of which part of the technology is not feasible and where the weaknesses are, and 2) investigation of partial implementation can be conducted afterwards which is how this work is done. Additionally, from performance perspective, the more the PE devices are implemented, the more flexible the system can be. However, from the view of financial impact, the result is not "the more, the better."

In the financial analysis, the result seems to suggest that the implementation, overall, significantly reduces the system cost by about 38% in PV (see Section 4.7.1). However, not all of the implementation of PE devices influences the financial result positively. There are some devices (e.g. DC-DC converter) that increases the loss compared to the AC system, and, hence, impacts the economy negatively. Therefore, Section 4.7.2 and Section 4.7.3 investigate the relationship between performance and cost by looking at different levels of implementation. There are three levels, which are:

1. Only implementing the PE technology to the loads for better control to the loads;
2. Implementing the PE technology to the loads and the lower power classes of the distribution system where there may be more buses in different forms (voltage and frequency);
3. Implementing to both the loads and the whole distribution system, the result of which is the DC electrical system.

As shown in Figure 4-13 and Figure 4-14, the most cost effective implementation is the VSDs, which reduces the overall cost (in PV) by 40% ($7,400,000). The implementation of DC Class I&II (hybrid system) give additional 1% cost reduction. The optimal implementation level for reducing equipment cost is the hybrid system which costs about 4% ($16,800) less than the AC system and 35% ($229,000) less than the DC system. In terms of the PV, the configuration with the lowest cost is the also the Hybrid system which has a 41% ($7,500,000) advantage over the AC system, and one of 6.8% ($799,000) over the DC system. This is due to the fact that the hybrid system does not have the expensive high-power rectifiers and DC-DC converters as the DC system, but takes the advantages of the VSDs and simpler Class I&II layout.

As discussed in Section 4.8.1, it is possible for the PE technology to advance to point where the DC system is competitive as the AC system with VSDs or the hybrid system[28]. Until then, the reason to choice the DC system is its controllability and flexibility in Class IV and Class III, but the additional cost is 5.5% ($654,000) compared to the AC system and 6.8% ($794,000) compared to the Hybrid system. Additionally, this extra cost can potentially be addressed by the cost of the cable (see Section 4.8.7).

Considering the uncertainty associated with the components' equipment cost and with the system operation cost, the analysis results indicate that the conclusion of this work will not likely be altered by any of those variable alone unless they are set to be in an extreme case. However, if all variables swing to the side preferring the AC system, then the result will be altered by less extreme numbers.

Additionally, from the power perspective is that the DC electrical system can potentially increase 1% to 2% of the electrical power that goes onto the grid. For a unit (e.g. around 800MWe output), 1% to 2% means 8-16MWe per unit or 60-120MWe for the whole plant, and this amount of electricity is steady and can be sold to the grid directly. For such plant which could have annual generation around 50TWh of electricity (assumingly

[28] When the cost of a whole DC system becomes lower than the hybrid system? The answer is that there are two possible scenarios: 1) the converter transformers at UST/SST are no longer needed for the rectifier system, which is possible with active rectifiers and proper selection of Class IV voltage; 2) the combined associated cost of a DC-DC converter is lower than a converter transformer, so that it can replace the transformer to alter the DC voltage for Class IV.

sold in Ontario where electricity price is relatively low at about 0.07CAD/kWh [141], the 1-2% power output increase could potentially bring annual 35 million CAD revenue to the plant.

The financial result seems to suggest that the DC electrical system is more likely to have a positive impact to the plant economics, additional to the technological potentials (discussed in Section 4.3.3 and Section 4.10.2). A big concern of implementing such technology is the challenges of designing a DC to meet the nuclear relative regulations, which is discussed in later section.

Additional to the analyses based on the model built for this study, the concern of how close is this model to an actual plant is discussed. What needs to be point out first is the conceptual nature of this work and the limitation of available information regarding to list of loads or an actual design of a plant. In this work, the load information available is only of the large and typical loads. Since this work is about conceptually investigating the ability of such a DC system to supply power to the types of loads in a NPP and its sufficiency in power level. In terms of the financial analysis, this work aims to achieve the accuracy of the class "order of magnitude", while improves the precision by designing both the AC and the DC system based on the same requirements, by the same design philosophy and strategy. The result does show that implementing PE technologies is likely to have positive financial result, but the actual benefits highly depends on the reactor designs (e.g. types, size, etc.) and the regulation environments (e.g. redundancy, reliability requirements, etc.). What is more, the implementation does not have to be either non or power electronic distribution system, it can be done in multiple stages (e.g. installation of VSDs, improving Class I and Class II efficiency by converting them to DC, etc.). There are other strategies that can balance the risk and benefits such as operating the DC system while having the AC system as backup. This strategy helps pass regulation and improve defence-in-depth, which could be the best solution when modifying an existing plant.

4.10.2 DC electrical system potential benefits and issues

In this section, there are some discussions regarding to the technological advantages and disadvantages of the DC electrical system that are not quantified in this study.

Performance

One of the motivations of this thesis is the performance provided by PE devices which can potentially improve the safety and economy of a NPP. The HVDC transmission systems have been used for long-distance power transmission or power grid zoning which has demonstrated its capability of improving the power grid stability due to its superior controllability and economy [2, 26, 28]. In fact, system parameters such as voltage and power in a DC system can be constantly monitored and precisely maintained as PE equipment has sophisticated I&C system and is capable of altering output in milliseconds. For example, in the case of motor short-circuit, the VSD can react as the first- line defence cutting off power to the motor, which keeps the whole power plant from shutting down. Even the fault is at a bus, it still can be isolated by converters or breakers and an alternative path can be established quickly. The additional performance and information give plant designer more flexibility and room for improvement.

When the power plant is staring up from either maintenance or emergency shut down, it needs control on breaker so that not all loads are engaged at once which will over-load the electrical system because of the high start-up current on motors and transformers. Traditionally, a timer or delay mechanism provides that function. However, it does not solve high start-up current on individual component which needs some tuning with the over-current protection system. In the DC system, current and voltage can be controlled by drives and converters so that no extra gear or tuning is needed for starting up which saves cost and improves stability.

Overcurrent protection

One of the biggest drawback of DC system in general is its constant voltage making the design of DC breaker much difficult. Although it may not be a big concern in this specific model which is based on a reactor size in the category of SMR (see previous sections), breaker rated capacity could potentially become the limit of the DC application when attempt to scale up the DC electrical system is made. One of the reason why most HVDC projects are point-to-point configuration (instead of multi-terminal configuration) is because the breaker capacity. (see Section 2.4.3) Therefore, some efforts are put into developing high-power solid-state breaker using PE devices, and, surely, these breakers can be used in a NPP. Impact of using these breakers would more likely be raising the cost due to the fact that their cost is much higher. [67, 68]

Low frequency system oscillation

Oscillation occurs when a system responds to change of parameter and improper design could significantly affect the system stability. [135] In the case of electrical system in a nuclear power plant, it can leads to temporary or permanent loss of power. Therefore, it need to be damped to a reasonable range. The flexibility and controllability of a DC electrical system also means it involves control systems over a lot of parameters which may be lead to oscillations. For example, there is a disturbance caused by a malfunctioning motor at Class IV which has been disconnected from the system by the VSDs. In response to the initial drop in voltage at the bus, the converter connected to supply power to the next bus will try to raise the conversion ratio to compensate that, while the other converter from higher voltage bus also try to raise the conversion ratio to compensate the drop in voltage. These two increases in voltage may eventual lead to over voltage in lower voltage busses, continuously voltage instability, inconsistent conversion ratio, etc. Therefore, it is necessary to have a well damped system, and hardware limitation as the responding time of PE devices is fast. In fact, one of the function of a HVDC system is provide damping to the power system which is effective. [128] However, it does need researches to ensure the tuning of the control system characteristics is right and can withstand all possible disturbances.

Power factor

In AC systems, power factor is always needed to be controlled within a reasonable range. Large equipment such as main boiler feed pump may need local compensation which adds complexity, while over-correction may also post threat to system stability in some cases (e.g. low power operation). In contrast, there is no power factor issue in the DC system. Although the rectifier system at the SST and UST need compensating devices, the centralized layout may be easier for maintenance and control. If PWM rectifier is used, then the amount of compensation capacity can be significantly reduced.

Weight and size

Generally, the weight of PE devices is much less compared to traditional AC equipment and the reason is the materials used. (see Section 2.2.5.4) Transistors in PE devices are made of Silicon which is much lighter than copper and iron in a transformer. There are heavy items in those devices such as inductor and cooling system, but, compared to AC requirement, the overall weight is still smaller. This weight reduction also reduces the mounting requirement in the building which gives plant designer more flexibility of equipment placement and reduce building cost.

In terms of size, there is no evidence suggesting that DC system require less space, and the rectifier system may also require additional space for rectifiers and compensation devices. This means differently to plants in design stage and plants in construction or in operation. Modifying an existing plant design to implement a DC electrical system, whether it has been built or not, could be challenge for adding the rectifier system which has many high voltage parts requiring proper isolation and space clearance.

Availability and life time

As mentioned in performance discussion, the DC system is much more flexible and faster when responding faults which could potentially makes the system more capable of withstanding severe faults and retain power generation. When maintenance is needed on electricity converters, PE devices can take advantages of their lighter weight, no asynchronous issue and on-line power control so that it is possible to design modular converters with a hot-swap function which potentially reduces difficulty of doing the maintenance without shutting down the reactor. These improvements in fault response and maintainability can improve plant availability. A VSD can benefit motor in reducing maintenance requirement and extending it lifetime because variable speed method takes considerable stress off both bearings and impellers and decreases motor temperature, which reduces maintenance and extends the lifetime of motors, hence, improve the availability and safety of a plant.

Backup power

Since less power is consumed by loads when Class IV is not available, the capacity of backup generators and the stored fuel can also be downsized which, in turn, reduces cost of maintenance and space. In terms of the battery bank capacity, due to the fact that the DC system has much higher efficiency in Class I and Class II (up to 30%, see Section 4.6 for load power rating and electricity converters in Class I and Class II), the required number of battery banks can be lowered or the backup time can be increased. However, this highly depends on operating conditions of a plant. The more efficient DC-DC converter in Class I & II can reduce 30% of loss compared to the solution in the AC system.

Standardization

There is no standard for such DC electrical systems (see Section 2.5.4). This could potentially lead to an international standard which reduces overall system cost and design work load. However, the lack of standard could be a big issue to implementing the DC electrical system to nuclear industry because the components for the system are mostly proprietary which means higher cost and difficulties to find spare parts. Also, without standard, it is hard to complete design verifications which means it could be hard to get approval from regulator. The details will be discussed in regulatory impact section.

4.10.3 Applicability to other type plants

The SFR is chosen to be the reference model, but PE technology and the DC electrical system concept presented in this thesis can also be implemented into other types of reactor with some adjustments of loads (e.g. EMP drives) and specific choice of electricity converters (e.g. PWM rectifier or SCR) depending on the design requirements. Table 4-13 shows the main design requirement differences compared to the reference SFR model when designing electrical system. Differences in requirements include EMP power requirement whether increases or decreases; water pumping requirement whether increases or decreases; and motor driven molten salt pumps (molten salt cannot be pumped by EMP).

For EMP power requirement, as discussed in sensitivity analysis sections, the financial impact of the difference of EMP drive cost or efficiency is relatively small. Therefore, the difference in EMP requirement does not influence the compatibility of the DC system to other plants.

Similarly, difference in water pumping requirement does not affect the compatibility of the DC electrical system, but the increase of proportion of water pumping power tends to widen the gap of overall impact of implementing the DC system due to the fact that water pumping application is more likely to benefit from VSD.

For plants with combined Brayton cycle where water pumping requirement is reduced due to the fact that the compressor is driven by the turbine and a motor is required to start the turbine. In normal generating operation, the gas turbine generates about 60% of the power and the condenser cooling is done by circulating water (in close cycle configuration). [136] Although the water pumping requirement is reduced compared to steam cycle only plant, there is no evidence that the DC electrical system is not compatible with the design.

In terms of pumping molten salt, the challenge is of the high temperature environment that the impeller is in, not the motor or the drive. The value of implementing VSDs into this pump is that the inlet and outlet temperature can be control precisely which may increase generating efficiency. Also, it can reduce the chance of leakage associated with the control valve as the valve is working under less stress. (see Section 2.2.7)

Table 4-13 Design requirement difference of types of reactors

Type of Plants	Main Difference from reference model
Boiling Water Reactor (BWR)	• No EMP required • Higher water pumping requirement
Pressurised Water Reactor (PWR)	
Pressurised Heavy Water Reactor (PHWR)	
Supercritical Water Reactor (SCWR)	
Molten Salt Reactor (MSR) with steam cycle	• No EMP required • Higher coolant pumping requirement
Molten Salt Reactor (MSR) with Brayton cycle	• No EMP required • Higher coolant pumping requirement • Reduced water pumping requirement
Gas Cooled Reactor (GCR) with steam cycle	• No EMP required • Reduced water pumping requirement
Gas Cooled Reactor (GCR) with Brayton cycle	• No EMP required • Reduced water pumping requirement
Lead Fast Reactor (LFR) with steam cycle	• Reduced EMP required (no IHTS)
Lead Fast Reactor (LFR) with Brayton cycle	• Reduced EMP required (no IHTS) • Reduced water pumping requirement
Sodium Fast Reactor (SFR) with Brayton cycle	• Motor driving compressors required • Reduced water pumping requirement

4.10.4 Regulatory impacts

The financial result shows a potential in a significant improvement in generation efficiency which may bring a considerable profit to a plant, especially the VSDs. However, there is no evidence to suggest the existence of a DC electrical system in a NPP, or using VSDs to improve efficiency. This section discusses the reason why nuclear industry does not adopt the DC electrical system or the proven VSD technologies.

4.10.4.1 Two aspects of cause

Nuclear industry is strictly regulated industry. Many commercially available products cannot be directly used in a NPP, and many need to be custom-built or/and go through many tests in order to prove its ability to meet the regulations. This can also greatly impact the implementation of the PE technology, especially for safety related components. This discussion is carried out from two aspects: PE technologies (e.g. maturity); and components of a NPP whether it is safety relative or not;

From the PE technologies point of view, most of them used in the DC electrical system design are proven technologies expect for the DC-DC converter. Rectifiers, inverters, VSDs have been used in various industries for decades. In fact, nuclear industry has also used rectifier and inverter in plant designs (see Section 2.1.3). Therefore, the DC-DC converter technology is the key to the implementation of the DC electrical system. Specifically, the development of high-power high-efficiency converters, and the commercialization of such converters. There are a few research orientated DC-DC converters found in literatures which are to either improve the efficiency or improve power (see Section 2.5). For lower power level, there are commercial products available at a lower power scale (e.g. estimated 3.5 kW each converter for Tesla POWERPACK[137]), and this could be a source for studying the failure model and reliability of DC-DC converter because there are many of them in a single project (e.g. estimated 192 of DC-DC converters in the Benzinga energy storage project[138]). However, it seems that more effort need to put into the commercialization of those in high power level, and this is one the key to the DC electrical system.

From the nuclear power plant component point of view, implementation of the DC electrical system is futuristic due to the fact that design verification of some components is difficult. The DC electrical system is not yet well studied while there is a lack of code and standards (see Section 2.5.4), which make it difficult for the design verification. For proven technologies but without much nuclear operating experience such as VSDs, it is easier to implement a well design one, especially for non-safety relative component. The following section describe an example the regulatory impact to PE technologies and possible solution to such challenge.

4.10.4.2 Potential solution from safety design perspective

The PE technologies are relatively new to the nuclear industry which involve many new components, hence, the safety design of a specific component focuses more on the risk-based approach regulatory environment rather than the prescriptive approach where there are set rules for the designers to follow. Also, safety design is about balancing risk. Every technology involves risk and risk cannot be completely eliminated, but it can be reduced to an acceptable level. One of the important method to analyze risk is by the concept of stylized accidents (design basis accidents) and there are two approaches to identify those potential accidents: top-down approach and bottom-up approach. [10] The top-down approach is by identifying the undesirable consequences and looking for components failure that may cause them, while the bottom-up approach is by, first, identifying the potential each component failures and then the results of these malfunctions.

The example of this discussion is the VSDs due to the fact that it is the most cost effective implementation of PE devices and the most accessible technology (Section 4.10.1). The approach to safety design of a VSD is the bottom-up approach as it is a component being analyzed, and the target is the VSD of the steam generator water feed pump.

A VSD is capable of output various voltage at various frequency to control the motor output torque and output power (see Section 2.2.7). The input of the drives could be a request of accelerating the motor or a set point of water level (e.g. water level in a steam generator), and the internal logic will be compared the set point to the actual point of operation and set a new operation point for the PWM inverter controller. The controller will adjust the torque output and motor speed by changing the modulating signal (Details in Section 2.2.6 and 2.2.7).

One of the potential failures of a VSD as a motor control device is making the motor running out of the requested range. This may include 1) VSD failure (no output at all), 2) VSD not responding to request, and 3) motor operating constantly off but by a small margin to the requesting point, and these events usually result in a reactor trip or turbine trip due to water level in the steam generator .[21] Another potential failure that may cause equipment damage is 4) the VSD applies a DC voltage to the motor which may result in stator winding overheat. The worst scenario is 5) the VSD accelerates the motor to a very high level which may over pressurize the system, damage the impeller and potential breaks of pipes. If the reactor uses water as coolant, this failure could result in a loss of coolant event.

Those possible failures listed above mostly relate to its control system and software, expect for Number 4 which could be due to the simultaneously failures of two transistors, which is a very unlikely event. Another unlikely event is Number 5---the VSD overdrives the motor by a large margin without any command input. However, in nuclear industry, the safety standard is relative high, and the over-drive is a serious concern, even it is an unlikely event. For example, in The Westinghouse AP1000 nuclear power plant design, the concern of an unlikely over-speed scenario of the VSD for coolant pump makes it “not qualified as Class 1E” results in that it is only used during start-up and shut-down, and is bypassed by a breaker under normal operation [139], which greatly reduces the benefits of using a VSD. The point is that the control system and software seems to be the main issue of the VSD technology for nuclear power plants.

VSDs control requires relatively more computation and software involvement to compute need set point and generate control signal (modulating signal), but it does not mean it cannot meet the safety standards. The AP1000 is used as an example to demonstrate possible solution and R&D directions. There are several key improvements from different aspects can be done to such system.

- Defence-in-depth: Adding an additional I&C system to turn on the bypass breaker once the speed or torque passes a certain limit. This I&C system monitors the V/f value at the VSD output terminal, or rotational speed obtained by an optical rotational speed sensor.

- Separation: This additional I&C system is physically separated from the VSD and controlling the bypass relay.
- Reliability: The control logic done by hardware. Low level control system is preferred by regulators because it is easier to demonstrate its reliability. [10]
- Redundancy: Inside the VSD, two parallel control modules can be used to verify each other and division of these two output signals can be used to trip the VSD.

4.10.4.3 Potential solution from regulation perspective

New design using new technologies is difficult to get approval from regulators, even the technologies are proven ones and the component is well designed and tested. This is mostly due to the lack of nuclear operating experience. Therefore, the solution to gain more experience is by adopting step-by-step. Previous section discusses how to improve the reliability of the VSDs which is used in this section to discuss how to adopt the technologies to nuclear industry.

VSD technology has been used for decades in manufactures where precision control over speed is required and in automobile industry to accurately control transition motor for power and re-generation in hybrid or electric vehicles (see Section 2.2.7). The problem is more about getting trust in the industry. Extra safety design is one of the solution described in previous section, another solution without these designs which introduce extra cost is by first implementing them to non-safety relative loads and then to safety relative loads. For example, implementing a VSD to one of station service water pumps to gain operating experience while the others are not controlled by VSDs. The loss of service water flow is a Class 1 design basis accident which is expect to occur occasionally. [10] When the pump fails, the second will start up and the failed one can be investigated.

If it is proven to be reliable and ready to for safety relative components such as coolant pumps, then the same approach can be adopted. Safety relative component requires backup, and the VSD will not be implemented into the backup one. The bypass breaker as described previously can also be implemented, if it is necessary.

4.10.4.4 The DC electrical system

Previous sections discuss about how to meet the regulations from the technology and regulation perspectives where the VSD is used as example. Indeed, the same strategies of improving safety design and implementation step-by-step can be applied to the DC electrical system.

From safety design perspective, improvements can be done to solve the potential issues described in Section 4.10.2 and to raise the reliability of the individual component, etc. so that it can meet the regulatory requirement. From the regulation perspective, the DC electrical system can be first experimented by implementing it in a smaller scale such as research SMR or building one beside the AC system which will contribute to operating record. Then it can be brought to commercial design by either modifying existing plant design or starting with a smaller scale.

4.10.4.5 Other regulatory requirements

There are other regulatory requirements stated in the standards regarding to issues such as seismicity [18], indicator locations [8], which are not addressed in this work. The reason is this work is a highly level conceptual investigation with a focal point of the capability of power delivery using PE electrical system. These regulatory requirements may be considered in future work where a DC system is designed at a more detailed level for a specific jurisdiction.

4.10.5 Scaling discussion

In this section, the impacts of implementing the DC system in different sizes of nuclear power plant designs are discussed.

4.10.5.1 Two main scaling method and four main variables

There are two main ways to scale up a system and maintain the similar operating condition which are Strategy 1) by multiplying the number of the components, and Strategy 2) multiplying the size of the components. However, there are many variables influencing which approach to take, such as the design of a plant (e.g. AP1000, Integral fast reactor or Toshiba 4S), the components themselves (e.g. technology available, low power components in Class I and Class II tend to remain in the same power even the plant is scaled up), and the regulatory requirements (safety relative or not).

It cannot simply scale the system up by just purchasing 10 of every components or by just buy 10 times bigger components. The decision is influenced by the factors above, hence, different approaches apply to different components. To one specific component, there are four main variable considered in this discussion that determine the decisions:

1. Size is how big it will be up-scaled, which is measure by times. The baseline for this study is a 100MWe power plant, if the new design is 1000MWe, then the size factor is 10. This is consistent with previous analysis. (Section 3.1.2)
2. Scaling factor is a method used to estimate the cost of a component having a different capacity from the known data. (see Section 2.6.2)
3. Additional cost describe the cost introduced by regulation and customization of a component. In the main analysis, the cost from regulation is not included since it is highly uncertain, it may by caused by additional tests, documentation and reviewing fee because of regulation requirements. Customization means the component is specifically designed for the order (e.g. special failure safe feature). This could be because of the requirements of safety, reliability, radiation protection, etc. that commercial products cannot meet. The additional cost is highly influenced by category of a components because there are more and higher standard for safety relative component (Class 1E) than a non-safety-relative component.
4. Number of components in a group means applications that use the same design but different number to meet the requirements. For example, there are three applications in one group (usually because the power is not very different and the function is widely required such as water pump), then these three applications (e.g. 10kW, 20kw, 30kW) can utilize 1 of 10kW pump, 2 of 10kW pumps and 3 of 10kW pump, which means there are total 6 components in this group.

Two equations are used to describe the cost under different strategies. Equation 4.4 describes the cost of purchasing more, and cost is the number of same purchased components with one additional fee. Equation 4.5 describes the cost of larger size components but each one has its own extra cost.

$$Cost_{more} = Cost_{Base} * (YX + \alpha) \tag{4.4}$$

$$Cost_{bigger} = Cost_{Base} * (X^n + Y\alpha) \tag{4.5}$$

Where Y is the number of components in a group,

X is the power ratio between the new requirement and the old one,

α is the additional cost, which is described in proportion of the base case cost,

n is the scaling factor.

4.10.5.2 The influence of the variables

The curves in Figure 4-27 shows the case when $Cost_{more} = Cost_{bigger}$ based on the scaling factor of 0.7, which is common for electrical components [73]. When a point is located above an individual curve, it means the strategy of purchasing bigger components is costlier. For example, the plan is to scale up the design by 10 times and the number of components in the same group that can share the design is 3, then by looking at the orange line in the chart, it is determined that if the additional cost (α) is more than 13 times of the component in base model, then purchasing bigger components for each application is more expensive, and, hence, it is better to adopt parallel operation.

From this placement of those curves in Figure 4-27, there are several conclusions about the four parameters.

1. As the size(X) raises, it will become increasingly favorable to adopt the Strategy 2 which is to utilize bigger components.
2. As the additional cost (α) rises, it will become increasingly favorable to adopt the Strategy 1 which is to utilize multiple components.
3. As the number of component in a group (Y) rises, it will become increasingly favorable to adopt the Strategy 1 which is to utilize multiple components.
4. As the scaling factor (n) rises, it will become increasingly favorable to adopt the Strategy 1 which is to utilize multiple components. The scaling factor increases

means the cost reduction from bigger component is smaller. (This is not illustrated in the chart.)

4.10.5.3 Application

As mentioned at the beginning of this discussion, scaling an actual plant design could be complicated, but those principles about the four variable can help decision making. The following examples may help illustrate the applications.

1. If the systems are applied to a smaller plant (e.g. SMR, <300MWe) which means the X value is relatively lower, then Strategy 1 is better. The physical meaning could be that the additional cost (α) could be significant compared to the relatively lower cost of the components or plants themselves. However, if the application is large (e.g. X>10), then Strategy 2 is usually better. Also, sometimes it is impractical to utilize multiple pumps in parallel due to space constraint or the complexity of connection may increase the α value (e.g. piping).
2. If the systems are applied to a new design which means the amount of additional cost (α) is high, then Strategy 1 is better because it could reduce the R&D cost and licensing effort. Projects or designs expected to be built more, on the other hand, would prefer Strategy 2 because the components' additional cost (α) of the second one and third one is much lower.
3. For systems that could potentially be grouped and share the same design, it is better to adopt Strategy 1. When more identical components are being implemented, the cost will be lowered due to the share in additional cost (α) and potential discount from vendors. However, it is more likely to be how to design a component that can be shared or a plant that utilize the same components, which will be discussed later.

4.10.5.4 Other considerations

This main discussion is based on a simplified model where there are only a few parameters or decisions. In this section, more parameters are discussed.

If a component is to be scaled largely (e.g. 15 times), the potential issues with the two strategies are that 1) implementing 15 identical components may be impractical. For example, the cost, space and balance requirement of the 15 pumps with the associated piping could be too high. 2) Purchasing one very large components could also be impractical due to the technology available, and such equipment can be much more expensive than 15 of the smaller one. Therefore, the best method of scaling to somewhere in between (e.g. purchase 3 of 5 times bigger components). When optimizing the balance between component size and component quantity, there are more considerations beside the four basic ones which includes: technological availability, R&D effort which may influence the delivery time and overall cost, experience with such design, regulations, jurisdictions where the plant is built, future implementation of such plant, etc.

The main advantage of the DC system to scaling is that it is possible to increase the Y value which means implementing more identical component to the various applications. In Section 4.8.3, it could be beneficial to system efficiency by implementing a bigger pump and running it at reduced speed, which means a pump rated at a larger power could still be used for a smaller application with increased efficiency. This may also raise the total application number of a single design resulting in a reduction of regulation and R&D effort, and the total additional cost (sum of α). Additionally, the DC-DC converters can also be potentially used for a wider range of applications which increase the Y value.

The main concern for such system regarding scaling is the availability of the maximum power available especially the DC-DC converter technology. There is no evidence indicating there is a limit about the maximum power of this technology, but the time to develop a DC-DC converter with competitive reliability, efficiency and equipment cost is unclear. The challenges are the maximum power of individual transistors, the circuit designs and the converter designs. The transistor technology is developing rapidly due to the demand of high performance transistors for higher power VSD-HVDC systems and VSDs. In terms of circuit design, there are different designs for different purposes. Similarly, there are researchers developing different converters attempting to raise the maximum power or implementing new technologies (e.g. soft-switching) to raise the maximum efficiency. (See Section 2.2 and 2.4) However, the scale, maturity and availability of commercial products are not close to AC transformers.

Figure 4-27 Scaling curve

4.10.6 Final discussion

The initial motivation of this study is to investigate the improvement that the PE technologies can make to a nuclear power plant which is inspired by the previous study of HVDC transmission systems [128] and by a discussion about variable speed drives for nuclear power plants with Dr. Dan Meneley (see Section 1.1). Both HVDC systems and VSDs are proven technologies that have been well studied and commercialized for decades. A HVDC system can increases the transmission efficiency and the stability of a power system (the grid), while the VSDs are able to significantly raise pumping efficiency and operating condition of the motor and the electrical system which powers the motors (See Section 2). Therefore, implementing these PE technologies seems to be a good way to improve the stability and generating efficiency of a nuclear power plant.

One of the main challenges of this implementation is the complexity of the electrical systems in a nuclear power plant (see Section 2.1) including the variety of loads (e.g. pumps in different sizes, electronic devices, EMPs, etc.) and buses (e.g. different voltages, configuration, power sources, etc.), and safety relative requirements (e.g. redundancy, backup power, etc.). That means the system must be able to support multiple voltage level and multiple power sources. These system characteristics prevent the direct implementation of HVDC systems, which are usually of single voltage and point-to-point configuration.

In order to achieve the DC electrical system, several elements must be implemented, and they are high-power rectifier which converters AC power from the generator to DC power, high-power DC-DC converters which provides different voltages to different loads, and the power supply units which provides proper power desired by different loads. The power supply units could be an inverter (e.g. when supplying an AC pump) or DC-DC converter (e.g. when supplying some I&C systems)—details could be found in Section 3.3. The rectifiers and inverters are commonly found in industrial application at a wide range of power rating, the HVDC systems are one of examples, whilst there is no commercial high-power DC-DC converter example found (see Section 2.5). Although the number of researches on DC electrical system is limited, it is still technologically feasible.

By referencing the Canadian 4-Class electrical system and implementing those converters, a DC electrical system for a SFR nuclear power plant is designed and further studied for its potential impacts (see Section 3.2 and Section 4.3). The system includes rectifiers to provide DC power, DC-DC converters to alter the DC voltages, inverters with variable speed function (also referred as VSD) to supply power to water pumping equipment, and electromagnetic pump drives.

The DC distribution system seems to have potential benefits in improving the system stability due to the responsiveness, the non-synchronized operation and no power factor issue, in reducing weight, and in improving efficiency. However, there are potential issues regarding to overcurrent protection which could limit the maximum feasible DC power. For this DC distribution system, this is not a big issue as the power is relatively low, and breakers at this rated power is commercially available. Additionally, potential system oscillation due to control system tuning is another concern, but a careful design and testing can solve this kind of problems. (see Section 4.10.2)

Financially, the implementation of PE devices seems to have positive impact. In equipment cost, the DC distribution system is more likely to cost more due to the relatively higher cost of PE devices (e.g. rectifier and DC-DC converters. Nevertheless, the extra cost of the equipment is relatively insignificant compared to the O&M. Indeed, the DC system can reduce the total cost overall 50 years by 38%. The uncertainty of LCOE, discount rate and reliability does not alter the result individually, but it is possible but less likely that these parameters combined will alter the result, which means the AC system being a financially attractive option. In Section 4.7.2 and Section 4.7.3, several configuration of PE devices implementation is discussed, which shows that the rest of the system beside the VSD makes less than 5% difference. Therefore, it is very important for plant designer to take the advantage of the VSDs as it is already a mature technology, and then advance to the Power Electronic distribution system (the DC system).

Since VSDs can be implemented into existing system and it contributes the largest saving, the implementation of VSDs can be the first step of implementing PE technologies. Then, the first step to this implementation is to make the drive meet the relative regulations. As discussed in Section 4.10.4, the VSDs are only used to start up and shut down the coolant pumps due to a concern of the VSD control systems. This attempt indicates that the high safety standards in nuclear industry and the will to adopt new technology. Therefore, the R&D effort could be placed at ensuring the drive will operate within the designed range and developing fail safe features (see Section 4.10.4). Similarly, all PE devices will face the challenge to their reliability and safety features as software is essential to PE devices, and the approach to improve VSDs can also be used for other devices.

When those necessary technologies are ready for the nuclear power plant applications and a scaling is needed, the DC electrical system seems to follow the same principle as the AC system which is highly dependent on the economic parameters of an individual components (e.g. scaling factor, extra cost introduced by nuclear relative regulations or standards, number of one type of components, etc.) However, PE devices may be able to increase the number of suitable applications of one design due to the flexible power control (see Section 4.10.5).

Overall, implementing PE technologies in a nuclear power plant seems to have many potentials in improving generation efficiency and internal power system stability, but there are also some critical challenges regarding to component control system design, regulation and converter design that need to be solved. However, all those challenges do not need to be resolved at once. Instead, it would be more effective to implement step-by-step. The following list a recommendation for future R&D works in time order.

1. Design a more reliable control system for VSDs either software or hardware to ensure that it can meet the regulations (e.g. control the flow rate properly under required condition). Also, implementing this technology to non-safety relative equipment first. This can be used to gain the operating experience of PE devices, then this technology can be used in safety relative equipment. The same approach can be used for other PE devices.
2. Implement DC-DC converters and extend the usage to more classes (e.g. the concept of the hybrid system) to improve the efficiency and reliability, and VSD for DC systems to drive the motors in those classes which can reduce the overall

cost on the motor. Similar to VSDs, the partial system may need to be built next to the AC system and only applied to non-safety relative components first.

3. Implement the DC distribution system to the whole plant, to improve the efficiency and reliability of the power plant when there is enough experience about the risk and failure models.

5 Conclusion

5.1 Achievements

This thesis studies the feasibility of implementing power electronic technology into the electrical system of a NPP which enable DC distribution which has considerable potential that may benefit a NPP in terms of safety and economy. The achievements of this thesis include:

- Selected a SFR design (PRISM) as the referenced reactor design layout.
- Determined key system parameters (e.g. classification, types of loads, and their power) through various reactor designs (e.g. ASTRID from France and CANDU 6 from Canada,).
- Identified ten electrical system design requirements by referencing existing designs (e.g. Canadian 4-class electrical system) and standards (e.g. IEEE's)
- Conceptually designed a reference AC system for the selected reactor and a new DC system via systematic methodology.
- Determined that both of the AC and the DC electrical systems meet all design requirements.
- Examined and selecting technologies of each key component (e.g. rectifier, DC-DC converter, pump drives) in the DC system.
- Determined the DC electrical system as feasible by reviewing the feasibility and availability of the components in literature and commercial products.
- Estimated the AC and the DC systems equipment cost and annual O&M cost by various techniques.
- Determined the PV of the AC and the DC systems over 50 years.
- Determined the implementation of the whole DC system reduces the overall cost in PV by about 38%.
- Determined the implementation the hybrid system which has VSDs and DC Class I&II reduces the cost by 41% compared to the AC system.
- Determined the implementation of the VSDs is the most cost effective configuration which reduces cost by 40%.

- Conducted sensitivity analysis on components with relative high uncertainty of equipment cost, which shows that individual component cost could change the result that equipment cost of the DC system is higher than one of the AC system. However, the scenarios are limited.
- Conducted sensitivity analysis on equipment cost in total, which shows that the uncertainty does not change the overall result in PV unless the uncertainty is more than 25 times (for only uncertain equipment) or 33 times (for the whole system), due to the fact that O&M cost is very significant compared to the equipment cost.
- Conducted sensitivity analysis on LCOE and Discount rate, which shows that these two variables does not alter the result, but they can increase or decrease the reduction of having a DC system.
- Conducted sensitivity analysis on how reliability influences the cost in terms of periodic replacement and redundancy, which shows that these two variables do not alter the result until an extreme case (e.g. replacing the whole system more than once a year), but can alter the result in the scenarios where they both acts against the DC system (e.g. high redundancy and short replacement period).
- Conducted sensitivity analysis for scenario where cable cost is considered, and the result shows that if the cable is about 5 km long with average price about $150/km, then the equipment cost of the DC system can be justified by cable cost saving. However, it highly depends on the actual plant designs.
- Conducted sensitivity analysis for implementing induction EMP instead of DC conduction, which shows that the induction pump with inverter slightly reduces the cost by 2.4% in the DC system.
- Conducted sensitivity analysis for high efficient PE devices for the distribution system, which shows even when PE devices becomes very efficient (1% losses), the PV of the DC system over 50 yrs. is still about 14% higher due to the extra losses for converting AC to DC and the high efficiency of traditional AC equipment.
- Discussed overall financial impact of different level of implementation which suggests that the implementation of the VSD (reducing cost by 40%) and hybrid

system (reducing cost by 41%) is beneficial, but not the whole DC system (increasing cost by 5% in PV).

- Discussed the potentials of implementing the DC system to other NPPs and there is no evidence against the implementation to other NPPs.
- Discussed the regulatory impact which may prevent the implementation of PE devices or limit its potential. Also, possible solutions are provided for nuclear industry to adopt these technologies from safety design perspective which is potential improvement to these devices and from regulatory experience perspective which is step-by-step implementation.
- Discussed the potentials of scaling the systems which suggests that the cost of scaling depends on individual component and does not differ between AC and DC system, but the PE electronic devices may be helpful in reducing cost when scaling up the system by increase the number of repeated designs.
- Identified possible future R&D directions. (see Section 6)

5.2 Objectives fulfillment

In this study, a DC electrical system for nuclear power plants is successfully designed in conceptual level along with its reference AC system. The DC system is technologically feasible and demonstrate its ability to meet the same requirements as the traditional AC system with considerable potential in improving safety and efficiency of a power plant. In current state, the DC system may cost more in equipment cost, but it can be quickly paid off by the large saving from O&M cost. Currently, a full DC electrical system needs considerable effort in development in order to bring it to nuclear industry and explore its full potential, but implementing some power electronic technologies such as VSD into current plant designs with minimum modification can surely be beneficial.

6 Future work

From electrical engineering perspective, physically studying the whole system is not practical for an individual or a laboratory at this stage. Instead, a simulation is very helpful. Simulating the system under different scenario (e.g. more loads, various parameters, and different configuration, etc.) can help understand its statics and dynamics of the system providing fundamental data for developing sophisticated flow control and over-current protection system. Additionally, more R&D work need to be done on specific components (e.g. VSD control systems, VSDs for DC system) for the nuclear industry and components that is not yet mature (e.g. DC-DC converters). A study on how the DC system influences the I&C system is also necessary.

From nuclear engineering perspective, one of the direction is a more detailed design with more comprehensive data (e.g. more pumping equipment, operating conditions for pumps) for the purpose of a specific design. Another path is to study how a PE device influence a particular sub-system (e.g. a VSD to a circulating water pump or DC-DC converter to the bus voltage control) from a nuclear related viewpoint such as regulation and risk analysis.

From plant economics perspective, one of the directions is to have more comprehensive plant data to build a more accurate model for the estimation of the cost of modifying an existing plant to DC and the efficiency gain.

7 Reference

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8 Appendices

Appendix I Tables

Table 8-1 Major loads information in CANDU 6 [10, 19, 21]

Class	Loads	Power(kW)	Functions
IV	Main boiler feed pump	3700	Feeding water into the boiler
IV	Main heat transport circulating pump	6700	Circulating D_2O coolant in PHTS
IV	Condenser cooling water pump	2600	Circuiting water from outside into the condenser
IV	Generator excitation	N/A[29]	Providing excitation current to the generator
IV	HVAC	N/A	HVAC for plant buildings
IV	Condenser extraction	1900	Extracting water out from the condenser
IV	Water cooling for Generator's stator winding pumps	75	Providing cooling water to Generator's stator
IV	Normal lighting system	300	
III	Moderator circulation pumps	750	Circulating the D_2O moderator
III	Auxiliary boiler feed pump	260	Feeding water into the boiler
III	Auxiliary condensation extraction pump	56	Extracting water out from the condenser
III	Shutdown system cooling pump	220	Providing cooling to reactor when it is in low power
III	Turbine turning gear	N/A	Keeping the turbine turning when there is no steam
III	Fire water pumps	N/A	Providing water to fire distinguish system
III	Instrument air compressor	N/A	Providing power to compressor
III	Service water pumps	410	Pumping service water in the plant
II	Digital control computer	N/A	Reactor regulation logic control
II	Reactor regulation instrumentation	N/A	Measuring Neutron Power, Thermal Power, etc.
II	Electrical operated process valves	N/A	Power the process valves
II	Emergency lighting	N/A	
II	Auxiliary oil pumps for turbine and generator	N/A	Pumping oil to turbine and generator
I	Class II Inverter	150	Provides power to Class II
I	Emergency seal oil pumps	7.5	Pumping seal oil under emergency situation
I	Turbine lube oil emergency pump	55	
I	Emergency stator water cooling pumps	N/A	Providing cooling water to Generator's stator
I	Protective relay	N/A	Detecting and cutting off over current
I	Logic command circuit control	N/A	
I	Circuit breaker control	N/A	

[29] N/A: Information is not available in literature.

Table 8-2 Component summary in AC system

Components	Quantity	Electricity converter in AC system	Capacity
Electricity converters to Class IV from main generator	2	Traditional transformer	4500kAV
Electricity converters for Backup generator	2	N/A	
Electricity converters in Class IV	2	Traditional transformer	1000kAV
Electricity converters in Class III (to Class I)	2	Converter transformer+ Silicon control rectifier	300kAV
Electricity converters between Class I and Class II	2	Inverter+ converter transformer	150kAV
Electricity converters inn Class I	2	Inverter+ converter+ rectifier	20kW
Cabling	Unknown	3 sets for 3 phases	
PHTS Electromagnetic pump solution	1	Converter transformer+ Silicon control rectifier	1500kW
IHTS Electromagnetic pump solution	1	Converter transformer+ Silicon control rectifier	1390kW
Flow control solution	**[30]	N/A[31]	**

[30] Number and power depends on specific loads which is given in later analysis.
[31] Flow control functionality is achieved by control valves in the AC system.

Table 8-3 Component summary in DC system

Components	Quantity	Electricity converter in DC system	Capacity
Electricity converters to Class IV from main generator	2	Converter transformer+ Silicon control rectifier	4500kW
Electricity converters for Backup generator	2	Converter transformer+ Silicon control rectifier	600kW
Electricity converters in Class IV	2	DC-DC converter	1000kW
Electricity converters in Class III (to Class I)	2	N/A	
Electricity converters between Class I and Class II	2	DC-DC converter	150kW
Electricity converters inn Class I	2	DC-DC converter	20kW
Cabling	Unknown	2 sets	
PHTS Electromagnetic pump solution	1	DC-DC converter	1500kW
IHTS Electromagnetic pump solution	1	DC-DC converter	1500kW
Flow control solution	**[32]	Variable speed drive	**

[32] Number and power depends on specific loads which is given in later analysis.

Table 8-4 Summary and comparison of estimated system equipment cost

Position	AC system	Capacity	Estimated cost (2017 USD)	DC system	Capacity	Estimated cost (2017 USD)
UST/SST	Traditional transformer	4.5MAV	106,000	Rectifier system	4.5MW	244,000
Backup Gen	N/A			Rectifier system	600kW	61,000
Class IV	Traditional transformer	1MAV	29,000	DC-DC converter	1MW	72,000
Class III	Rectifier system	300kAV	45,000	N/A		
Class I	Inverter system	150kAV	38,000	DC-DC converter	150kW	27,000
Class I	Traditional DC-DC converters	20kW	23,000	DC-DC converter	20kW	10,000
PHTS EMP	Rectifier system	1500kW	53,000	DC-DC converter	1500kW	64,000
IHTS EMP	Rectifier system	1390kW	53,000	DC-DC converter	1390kW	64,000
Flow controller	Control valve		80,000	VSDs		97,000
Total Estimated Cost (2017 USD)			428,000	Total Estimated Cost (2017 USD)		640,000

Table 8-5 Annual energy usage of electricity converters in AC system

Location	Converters	Number of equipment	Capacity	Load factor	no-load losses(kW)	load losses(kW)	load hours per year	annual energy usage (kWh)
SST/UST	Transformer	2	6000	40%	7.46	9.54	8592	146,000
Class IV	Transformer	2	1400	39%	1.94	2.26	8592	36,000
Class III	Transformer	2	300	50%	0.62	1.12	8592	15,000
Class III	Rectifier	2	300	50%	0	0.60	8592	5,000
Class I	Inverter	2	150	50%	0.00	0.87	8592	7,500
Class I	transformer	2	150	50%	0.35	0.58	8592	8,000
Class I	Inverter	2	20	50%	0.00	0.12	8592	1,000
Class I	Transformer	2	20	50%	0.12	0.18	8592	2,500
Class I	Rectifier	2	20	50%	0.00	0.04	8592	300
PHTS	Converter transformer	1	1500	48.60%	2.0598	3.75	8592	50,000
	Rectifier	1	1500	48.60%	0	2.83	8592	24,000
IHTS	Converter transformer	1	1390	48.60%	1.9278	3.50	8592	47,000
	Rectifier	1	1390	48.60%	0	2.63	8592	23,000

Table 8-6 Annual energy usage of electricity converters in DC system

Location	Converters	Number of equipment	Capacity (kW/kVA)	Load factor	no-load losses(kW)	load losses(kW)	load hours per year	annual energy usage (kWh)
UST/SST	Transformer	2	6000	40%	7.46	9.54	8592	146,000
UST/SST	Rectifier system	2	6000	40%	0	7.81	8592	67,000
Class IV	Chopper	2	1400	39%	0	8.49	8592	73,000
Class III	Chopper	2	150	50%	0	6.00	8592	13,000
Class I	Chopper	2	20	50%	0	0.80	8592	1,700
PHTS	Transformer type DC-DC converter	1	1500	48.60%	0	17.71	8592	152,000
PHTS	Transformer type DC-DC converter	1	1390	48.60%	0	16.42	8592	141,000
	VSDs		1487	48.60%	0	21.98	8592	189,000

Table 8-7 Electricity usage of motor driven pumps in AC system

Class	Loads	Rated power (kW)	Actual electrical input (kW)	Annual Electricity usage (kWh)
IV	Main boiler feed pump	520	473	4,100,000
IV	Condenser cooling water pump	366	333	2,900,000
IV	Condenser extraction	267	243	2,100,000
III	Auxiliary boiler feed pump	37	34	290,000
III	Auxiliary condensation extraction pump	8	7	63,000
III	Shutdown system cooling pump	31	28	240,000
III	Service water pumps	58	53	450,000
II	Representative pump in Class II	130	91	780,000
I	Representative pump in Class I	130	91	780,000
	Total	1547	1353	11,700,000

Table 8-8 Electricity usage of motor driven pumps in DC system

Class	Loads	Rated power (kW)	Actual electrical input (kW)	Annual Electricity usage (kWh)
IV	Main boiler feed pump	520	272	2,300,000
IV	Condenser cooling water pump	366	191	1,600,000
IV	Condenser extraction	267	140	1,200,000
III	Auxiliary boiler feed pump	37	19	170,000
III	Auxiliary condensation extraction pump	8	4	36,000
III	Shutdown system cooling pump	31	16	140,000
III	Service water pumps	58	30	260,000
II	Representative pump in Class II	130	52	450,000
I	Representative pump in Class I	130	52	450,000
	Total	1547	776	6,610,000

Table 8-9 Estimated maintenance costs

Location	Equipment	Annual maintenance cost in AC system (2017 USD)	Annual maintenance cost in DC system (2017 USD)
SST	Transformer	400	800
UST	Transformer	400	800
IV	Transformer A	400	400
IV	Transformer A	400	400
III to I	Rectifier system A	800	400
III to I	Rectifier system B	800	400
I to II	Inverter system A	800	400
I to II	Inverter system B	800	400
I	DC/AC/DC converter A	1,200	400
I	DC/AC/DC converter B	1,200	400
IV & III	PHTS EMP Drive	800	100
IV & III	PHTS EMP Drive	800	100
IV	Main boiler feed pump	4,700	100
IV	Condenser cooling water pump	3,300	100
IV	Condenser extraction	2,500	100
III	Auxiliary boiler feed pump	550	100
III	Auxiliary condensation extraction pump	220	100
III	Shutdown system cooling pump	500	100
III	Service water pumps	800	100
II	Representative pump in Class II	1,700	800
I	Representative pump in Class I	1,700	800
	Total	24,800	7300

Table 8-10 AC system model cash flow for the first 3 years

Location	Equipment	Purchase price (2017 USD)	Annual Operating cost (2017 USD)	Annual Maintenance cost (2017 USD)	0	1	2	3
SST	Transformer	53,154	14,679	399	53,154	15,078	15,078.38	15,078.38
UST	Transformer	53,154	14,679	399	53,154	15,078	15,078.38	15,078.38
Class IV	Transformer A	14,368	3,782	399	14,368	4,181	4,180.68	4,180.68
Class IV	Transformer A	14,368	3,782	399	14,368	4,181	4,180.68	4,180.68
Class III	Rectifier system A	22,604	2,110	798	22,604	2,908	2,908.29	2,908.29
Class III	Rectifier system B	22,604	2,110	798	22,604	2,908	2,908.29	2,908.29
Class I	Inverter system A	19,160	1,625	798	19,160	2,423	2,422.52	2,422.52
Class I	Inverter system B	19,160	1,625	798	19,160	2,423	2,422.52	2,422.52
Class I	DC/AC/DC converter A	11,671	412	1,197	11,671	1,609	1,608.57	1,608.57
Class I	DC/AC/DC converter B	11,671	412	1,197	11,671	1,609	1,608.57	1,608.57
Class IV & III	PHTS EMP Drive	53,138	7,799	798	53,138	8,597	8,596.57	8,596.57
Class IV & III	PHTS EMP Drive	53,138	7,799	798	53,138	8,597	8,596.57	8,596.57
Class IV	Main boiler feed pump	23,594	426,911	4,719	23,594	431,630	431,630.32	431,630.32
Class IV	Condenser cooling water pump	16,739	300,480	3,348	16,739	303,828	303,827.90	303,827.90
Class IV	Condenser extraction	12,333	219,203	2,467	12,333	221,669	221,669.21	221,669.21
Class III	Auxiliary boiler feed pump	2,794	30,376	559	2,794	30,935	30,935.15	30,935.15
Class III	Auxiliary condensation extraction pump	1,073	6,568	215	1,073	6,782	6,782.41	6,782.41
Class III	Shutdown system cooling pump	2,438	25,450	488	2,438	25,938	25,938.03	25,938.03
Class III	Service water pumps	4,040	47,617	808	4,040	48,425	48,425.07	48,425.07
Class II	Representative pump in Class II	8,313	82,098	1,663	8,313	83,761	83,760.99	83,760.99
Class I	Representative pump in Class I	8,313	82,098	1,663	8,313	83,761	83,760.99	83,760.99
	Total	427,828	1,281,615	24,705	427,828	1,306,320	1,306,320	1,306,320

Table 8-11 DC system model cash flow for the first 3 years

Location	Equipment	Purchase price ($)	Annual operating cost($)	Annual maintenance cost ($)	Year 0	Year 1	Year 2	Year 3
SST	Rectifier system	121,754	22,445	798	121,754	23,243	23,243.49	23,243.49
UST	Rectifier system	121,754	22,445	798	121,754	23,243	23,243.49	23,243.49
Class IV	DC-DC converter A	36,003	8,860	399	36,003	9,259	9,258.94	9,258.94
Class IV	DC-DC converter B	36,003	8,860	399	36,003	9,259	9,258.94	9,258.94
Class III	DC-DC converter A	13,654	1,353	399	13,654	1,752	1,752.24	1,752.24
Class III	DC-DC converter B	13,654	1,353	399	13,654	1,752	1,752.24	1,752.24
Class I	DC-DC converter A	4,876	180	399	4,876	579	579.43	579.43
Class I	DC-DC converter B	4,876	180	399	4,876	579	579.43	579.43
Backup Gen	Rectifier system A	30,745	0	399	30,745	399	399.00	399.00
Backup Gen	Rectifier system B	30,745	0	399	30,745	399	399.00	399.00
Class IV & III	PHTS EMP Drive	64,201	15,981	399	64,201	16,380	16,380.49	16,380.49
Class IV & III	IHTS EMP Drive	64,201	15,981	399	64,201	16,380	16,380.49	16,380.49
Class IV	Main boiler feed pump	31,459	245,215	67	31,459	245,281	245,281.19	245,281.19
Class IV	Condenser cooling water pump	22,319	172,593	67	22,319	172,660	172,659.91	172,659.91
Class IV	Condenser extraction	16,444	125,908	67	16,444	125,975	125,974.81	125,974.81
Class III	Auxiliary boiler feed pump	2,794	17,448	67	2,794	17,514	17,514.47	17,514.47
Class III	Auxiliary condensation extraction pump	1,073	3,773	67	1,073	3,839	3,839.03	3,839.03
Class III	Shutdown system cooling pump	2,438	14,619	67	2,438	14,685	14,685.07	14,685.07
Class III	Service water pumps	4,040	27,351	67	4,040	27,417	27,417.37	27,417.37
Class II	Representative pump in Class II	8,313	47,157	67	8,313	47,223	47,223.17	47,223.17
Class I	Representative pump in Class I	8,313	47,157	67	8,313	47,223	47,223.17	47,223.17
	Total	639,658	798,861	6,185	639,658	805,045	805,045	805,045

** LCOE is $0.105/kWh

Table 8-12 Cost of Distribution part in AC system

Location	Equipment	Purchase price (2017 USD)	Annual Operating cost (2017 USD)	Annual Maintenance cost (2017 USD)
SST	Transformer	102,298	15,338	399
UST	Transformer	102,298	15,338	399
Class IV	Transformer A	24,855	3,791	399
Class IV	Transformer A	24,855	3,791	399
Class III	Rectifier system A	23,597	2,110	798
Class III	Rectifier system B	23,597	2,110	798
Class I	Inverter system A	19,715	1,625	798
Class I	Inverter system B	19,715	1,625	798
Class I	DC/AC/DC converter A	14,414	412	1,197
Class I	DC/AC/DC converter B	14,414	412	1,197
Total		369,758	46,552	46,551
PV (7%, 50 years)		1,111,317		

Table 8-13 Cost of distribution part in DC system

Location	Equipment	Purchase price (2017 USD)	Annual Operating cost (2017 USD)	Annual Maintenance cost (2017 USD)
SST	Rectifier system	174,305	22,386	798
UST	Rectifier system	174,305	22,386	798
Class IV	DC-DC converter A	40,308	7,658	399
Class IV	DC-DC converter B	40,308	7,658	399
Class III	DC-DC converter A	9,715	1,353	399
Class III	DC-DC converter B	9,715	1,353	399
Class I	DC-DC converter A	9,715	180	399
Class I	DC-DC converter B	9,715	180	399
Total		534,896	63,154	3,990
PV (7%, 50 yrs) in USD (2017)		1,461,534		

Table 8-14 Cost of loads part in AC system

Location	Equipment	Purchase price ($, 2017)	Annual Operating cost ($, 2017)	Annual Maintenance cost ($, 2017)
Class IV & Class III	PHTS EMP Drive	35,874	7,799	798
Class IV & Class III	PHTS EMP Drive	35,874	7,799	798
Class IV	Main boiler feed pump	23,594	426,911	4,719
Class IV	Condenser cooling water pump	16,739	300,480	3,348
Class IV	Condenser extraction	12,333	219,203	2,467
Class III	Auxiliary boiler feed pump	2,794	30,376	559
Class III	Auxiliary condensation extraction pump	1,073	6,568	215
Class III	Shutdown system cooling pump	2,438	25,450	488
Class III	Service water pumps	4,040	47,617	808
Class II	Representative pump in Class II	8,313	82,098	1,663
Class I	Representative pump in Class I	8,313	82,098	1,663
Total (2017 USD)		151,384	1,236,400	17,523
PV (7%, 50 years) in USD (2017)		17,456,460		

Table 8-15 Cost of loads part in DC system

Location	Equipment	Purchase price ($, 2017)	Annual Operating cost ($, 2017)	Annual Maintenance cost ($, 2017)
Class IV & Class III	PHTS EMP Drive	54,755	15,981	399
Class IV & Class III	IHTS EMP Drive	54,755	15,981	399
Class IV	Main boiler feed pump	31,459	245,215	67
Class IV	Condenser cooling water pump	22,319	172,593	67
Class IV	Condenser extraction	16,444	125,908	67
Class III	Auxiliary boiler feed pump	2,794	17,448	67
Class III	Auxiliary condensation extraction pump	1,073	3,773	67
Class III	Shutdown system cooling pump	2,438	14,619	67
Class III	Service water pumps	4,040	27,351	67
Class II	Representative pump in Class II	8,313	47,157	67
Class I	Representative pump in Class I	8,313	47,157	67
Total (2017 USD)		206,702	733,183	1,397
PV (7%, 50 years) in USD (2017)		10,346,188		

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