CRANFIELD UNIVERSITY

JUNXIANG CHEN

Study of 270VDC System Application

SCHOOL OF ENGINEERING
Aircraft Design Programme

MSc

Academic Year: 2009 - 2010

Supervisor: Dr.Craig Lawson
Jan 2010

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ABSTRACT

As increasing power requirement in more or all electric aircraft, electric power system is required to be more efficient and lower in weight. Among the current power generation technologies, 115V variable frequency (VF) system and 270VDC system are regarded as the two optimal options for future use in MEA or AEA. Therefore, it is very important to compare their relative merits in order to determine the optimal choice on the primary power type.

As the reviewed literature mainly represents the comparison between 270VDC system and 115V constant frequency system, it is very necessary to conduct the comparison between 270VDC system and 115V/VF system. The aim of this study is to grasp the nature of these systems and evaluate these two systems in terms of some engineering aspects.

Literature regarding the power generation technology is first investigated. Based on initial comparison, the 270VDC brushless generating system and 115V VF generating system are selected for this study. Before conducting system architecture design and wiring system design, the load requirement analysis and optimization are conducted. Finally, a comparison between these two systems will be made in terms of weight, power off take, minimum voltampere (VA) capacity requirement, voltage drop, reliability, life cycle cost and risk.

The results show that the 270VDC system is superior to the115V/VF system in terms of weight and efficiency. With regards to system reliability, the 270VDC system can be designed as either an active parallel system or a standby system while the 115V/VF system can only be designed as a standby redundant system. As far as risk is concerned, the 270VDC is more dangerous than the 115V/VF system in terms of arcing risk and corona discharge. All in all, the 270VDC system can be considered as the optimal choice for future use in AEA or MEA.

Keywords:

Variable Frequency, Electric, Architecture, Wiring, MEA

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NOMENCLATURE

Abbreviations

MEA	More Electric Aircraft
AEA	All Electric Aircraft
IDG	Integrated Drive Generator
CSD	Constant Speed Drive
VSCF	Variable Speed Constant Frequency
TRU	Transformer Rectifier Unit
VF	Variable Frequency
VA	Volt-ampere
EMF	Electromotive Force
RBD	Reliability Block Diagram
RAT	Ram Air Turbine
P.O.R	Point of Regulation
APU	Auxiliary Power Unit
PPDU	Primary Power Distribution Unit
HVDC	High Voltage Direct Current
DC	Direct Current
AC	Alternating Current
RMS	Root Mean Square
CAD	Computer Aided Design
ELMC	Electric Load Management Center
ACP	Air Conditioning Pack
GCB	Generator Circuit Breaker
EPC	External Power Contactor

APB	APU Generator Contactor
BTB	Bus Tie Breaker
AWG	American Wire Gauge
RBD	Reliability Block Diagram
RAE	Royal Aircraft Establishment
RMS	Root Mean Square
MTBF	Mean Time Between Failure
SRG	Switched Reluctance Generator
Ni-Cd	Nikel Cadmium
ECS	Environmental Control System
NASA	National Aeronautics and Space Administration

Symbols

R_i	Reliability of the i^{th} components
P_{DC}	DC Power (KW)
P_{AC}	AC power(KVA)
U	Voltage
W	Weight of each conductor (kg)
ρ	Specific weight of the wire (kg/m)
L	Length of the wire (m)
I	Carrying current of the wire(A)
R_{DC}	DC resistance of the wire(Ω)

R_{AC}	AC resistance of the wire(Ω)
α	Radius of the conductor(centimetre)
f	Frequency in cycles per second (cycles per second)
μ	Relative magnetic permeability
ρ	Resistivity (abohm-centimeter))
P_{Loss}	Power loss in each wire of the main feeder(KW)
R	Resistance of the wire(Ω)
V_d	Output voltage of the rectification unit (V)
I_d	Output current of the rectification unit (A)
V_a	RMS value of the stator line voltage (V)
I_a	RMS value of line current (A)
m	Number of stator phases
N	Number of pulses within one interval
V_D	Voltage drop across the semiconductor (V)
i_{av_D}	Average current across the semiconductor(A)

1 INTRODCTION

1.1 Introduction

This thesis mainly introduces the author's individual research project that is about the primary power type selection for future more or all electric aircraft. Through literature review and initial comparison, the 115V variable frequency system and 270VDC system are chosen as two candidates. This study is mainly about the relative merits comparison between these two candidates. Meanwhile the work done by the author in the group design project will be briefly described. The group design project is about the environmental control system and electric power system preliminary design for a 130-seat civil aircraft. Due to the limited pages, only the ECS design is given in this thesis.

1.2 Project Background

With the development of aviation technology, the more electric aircraft (MEA) and all electric aircraft (AEA) concept emerges. In conventional aircraft, the secondary power includes electrical power, pneumatic power and hydraulic power. The hydraulic power is normal used to power the actuators. The pneumatic power is mainly used for environmental control system, ice protection system and so on. In order to increase system efficiency, the power supply for airframe systems is heading for electric power. Generally speaking the more electric aircraft means adding more electrical motors to the aircraft. It is reported that 35% of total energy is saved due to elimination of pneumatic power extraction from the engine on B787 [17].

As the development of aviation technology, electric power system becomes one of the most important airframe systems. Electric power system affects not only the passenger comfort but also the flight safety. On the other hand, the electric load requirements increase enormously. The following graph illustrates the trend of the generating capacity.

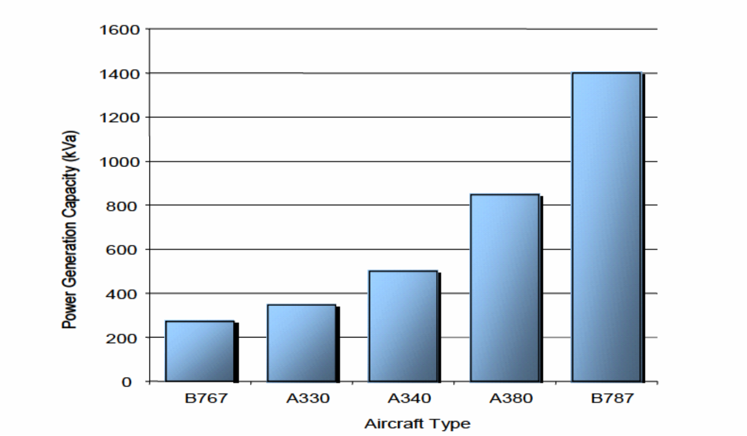


Figure 1-1 Aircraft Electric Power Generating Capacity by Aircraft Type[1]

Furthermore, different types of electric power are required in the MEA or AEA as the electric power in lieu of mechanical, hydraulic and pneumatic power. So, electric power system will be a hybrid AC and DC system which employs different voltage level in the future MEA and AEA [10].

The increasing demand on electric power drives the electric power system to be more reliable and efficient. In order to meet such requirements and optimize aircraft performance, fuel efficiency, cost and so on, the selection of primary power for MEA and AEA is concerned. The choice of an electric power system must be based on total impact of airframe.

1.3 Project Description

1.3.1 Project Scope

In terms of current power generation technologies, the 28VDC system is not suitable for the modern aircraft because the capacity of this kind of system is limited at 12KW per channel [18]. The conventional 115V/400Hz system is widely used in modern aircraft. In order to improve system reliability and efficiency, the variable frequency system and high voltage direct current system is regarded as the solutions for the MEA or MEA. In this project, the author just intent to further study the electric power system which is based on 270VDC brushless generating system and make a comparison with the 115V variable frequency system because these two types of power are more efficient and reliable compared to other types of system. Because Flying Crane is an all electric aircraft, so it is chosen for this case study.

1.3.2 Project Objective

1. Review the power generation technology.
2. Electric power system preliminary design for all electric aircraft which is based on the 270VDC generating system.
3. Electric power system preliminary design for all electric aircraft which is based on the 115V variable frequency power.
4. Evaluate these two systems in terms of engineering aspects. Finally, give a conclusion on the choice of primary power source.

1.3.3 Methodology

Case study is a very useful way to demonstrate the method used in this study. Since Flying Crane is an all electric aircraft and the detailed information can be obtained, it is chosen for this case study. The study process is shown in Figure 1-2. The first step is to optimize the load requirement since the practical consideration of choosing the primary power type is the based on power type which is required by the majority of electrical loads, In order to make the comparison between these two candidates, the primary power distribution architecture and wiring system will be designed. Finally, the conclusion can be given through the comparison of their relative merits.

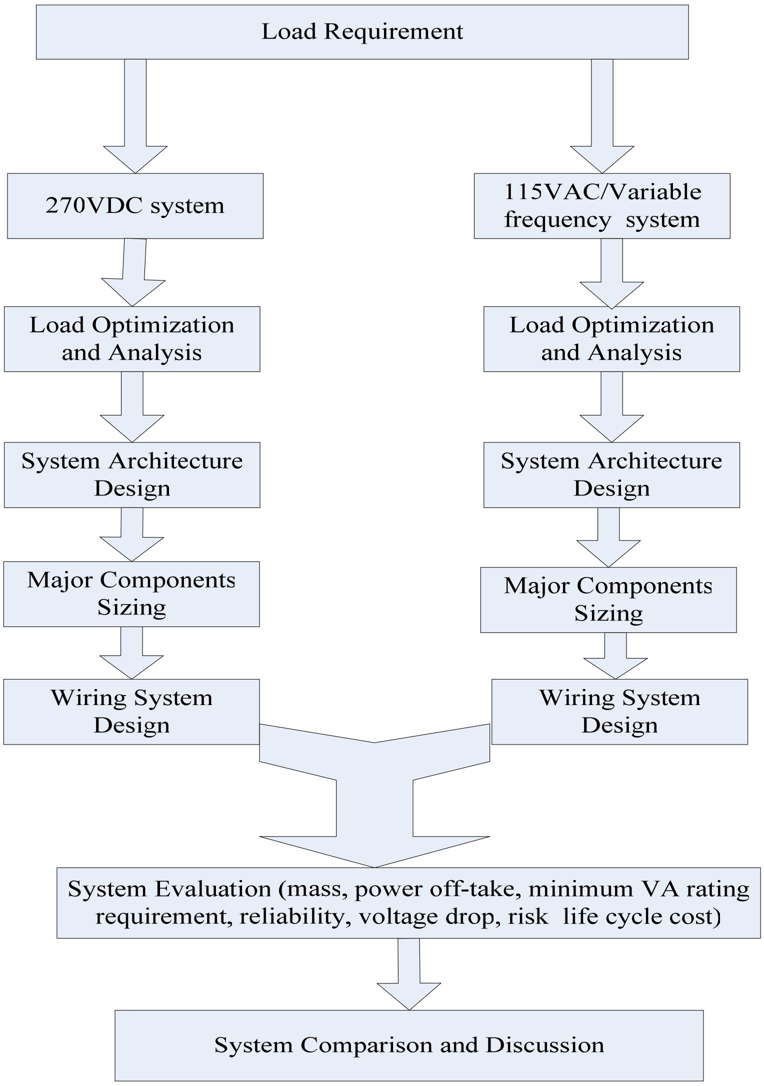


Figure 1-2 Study Process

In this thesis, chapter 1 describes the profile of the whole project. The literature review will be represented in chapter2. As the group design project-Flying Crane is selected for this study, the related information of Flying Crane will be given in Chapter3. In terms of electric power system, the first step is to analyze the load requirement which will be discussed in Chapter 4. Chapter 5 and chapter 6 describes the system architecture design and wiring system design respectively. System evaluation and comparison will be represented in chapter 7. Chapter 8 mainly discusses the generated results. The conclusion of this study will be given in chapter 9.

2 Literature Review

2.1 Introduction

This chapter mainly describes the current generating technologies except the low voltage (28VDC) generating system. The discussion regarding these generating systems will be given. Finally, the 270VDC system and VF system is chosen to study further.

2.2 Power Generation Technologies

Electric power system is one of the most important systems for an aircraft as aircraft has become more dependent on electricity. The following graph (Figure 2-1) shows all the power types which are currently used on modern aircraft.

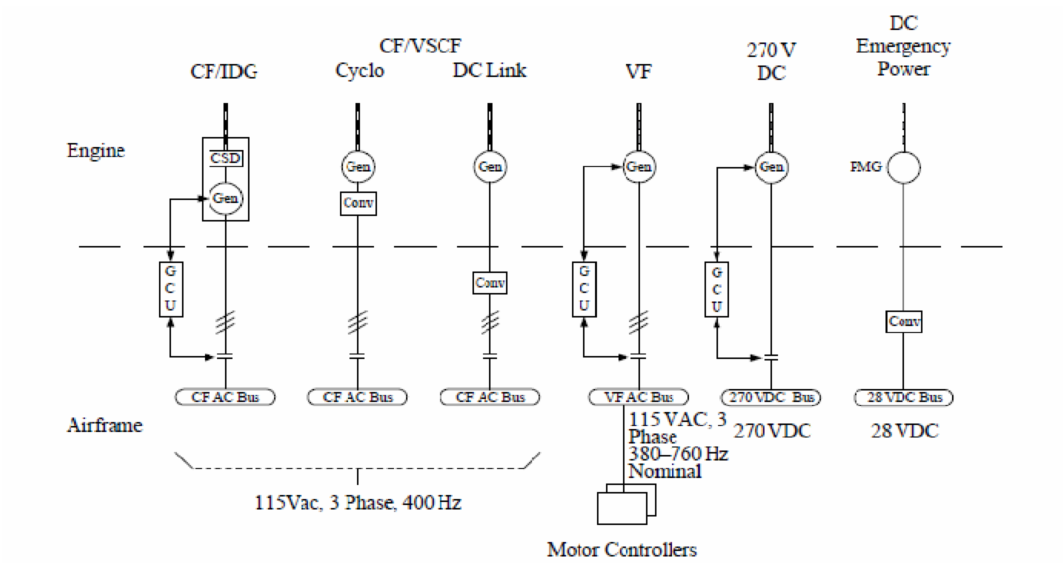


Figure 2-1 Power Generation Types [18]

Generally, all of these power generation types can be divided into three categories, namely constant frequency system (400Hz), wild frequency system and high voltage (270VDC) direct current system. The following paragraph will simply review those types of system respectively.

2.2.1 Constant Frequency System

The shaft speed of turbo fan engine varies with flight phases. The speed is at 100% of maximum speed during take off and 60% during descending [5]. As to an alternator, the power frequency is proportion to the shaft speed.   As far as the constant frequency system is concerned, there are two options to obtain constant frequency power. One is to maintain the shaft speed constantly. Therefore, an intermediate stage is required between the accessory gear box and the alternator. This type of system is so called integrated drive generating (IDG) system. The other is to convert the variable frequency power into constant frequency power by electronic conversion equipment. This kind of generating system is called variable speed constant frequency system (VSCF).

◆ **CF/IDG**

This type of power generation system is shown in Figure 2-2 which comprises of a synchronous generator and a constant speed drive. The CSD is a hydromechanical device which is used to maintain the shaft speed constantly.

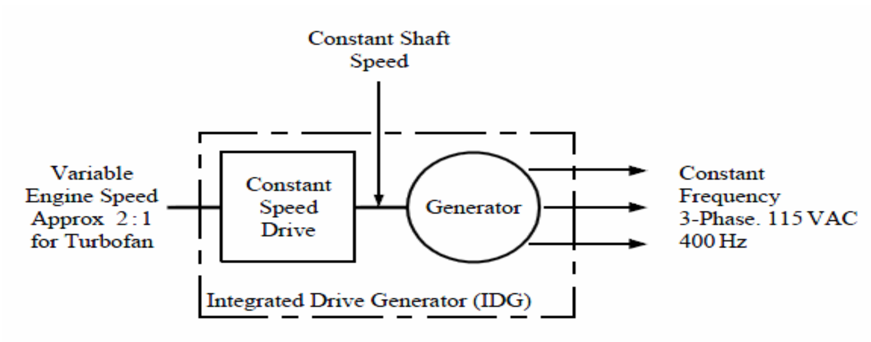


Figure 2-2 CSD/IDG [18]

This type of power generation system is widely used in civil aircraft. But the main disadvantage of this kind of system is that frequent maintenance is required due to its complex architecture.

◆ **VSCF**

The variable speed constant frequency (VSCF) system is regarded as the replacement of the constant speed drive generating system. The VSCF system consists of a brushless synchronous generator and a solid state converter. The generator is driven by the engine. The function of the converter is to convert the variable frequency power into 400Hz constant frequency power. The following diagram simply illustrates this kind of system.

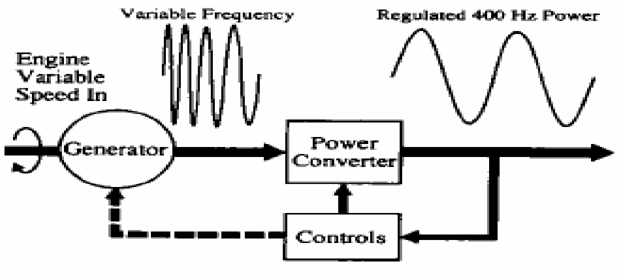


Figure 2-3 Simplified VSCF Principle Diagram[13]

Compared to CSD power generating system, this type of system has longer mean time between failures (MTBF) and has quicker mission turn around times[9].

In terms of electronical converter, there are two types of system that are currently used on modern aircraft, namely DC-link and cycleconverter.

Cycleconverter: As can be seen from Figure 2-4, the main parts of this kind of generating system are synchronous alternator and converter. The fixed frequency output power is directly converted from the wild frequency power generated by the alternator. The main disadvantage of this kind system is that the output frequency of the alternator must be a minimum three times the system output frequency(400Hz) in order to minimize the size of output filter. Furthermore, the alternator is required to have at least six phases to interface with converter stage[7].

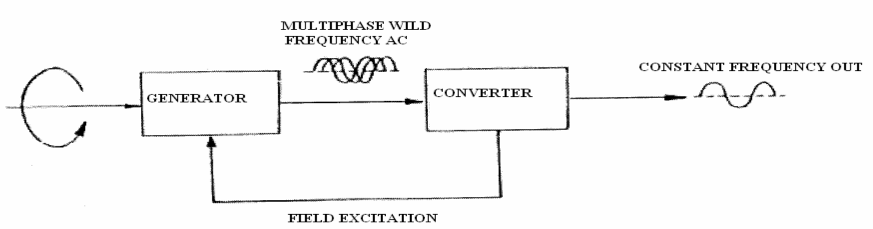


Figure 2-4 Schematic Diagram of Cycleconverter VSCF System [8]

DC-link: The schematic diagram of this kind of system can be seen in Figure 2-5. This kind of system consists of an alternator, a rectifier unit and an inverter. The output of the alternator is firstly rectified to provide an intermediate DC power link. Then, the DC power is converted to the 400Hz AC power by a conventional state converter. The advantage of this system is that it is relatively simple compared to cycleconverter because there are no special requirements for the alternator. The main drawback of this kind of system is that the generating capacity is limited at 60KVA due to solid state technology[8].

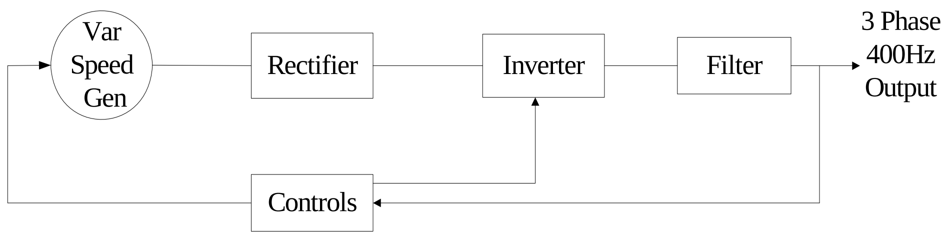


Figure 2-5 Schematic Diagram of DC-link VSCF system [8]

2.2.2 Variable Frequency System

This kind of system is regarded as the cheapest and simplest power type due to its simple architecture. This type of system is shown in Figure 2-6. This type of power has been adopted in the most modern aircraft (B787 and A380). The frequency varies with the shaft speed from 380Hz to 720 Hz. This kind of system is also called wild frequency system. It is also the lightest generating system due to elimination of the constant speed drive or power conversion stage which is used in VSCF system. In MEA and AEA, electric motors are widely used to drive pumps, fans and so on. However, this type of power can not be provided to this type of loads directly. Therefore, power conditioning equipment are required for those frequency sensitive loads.

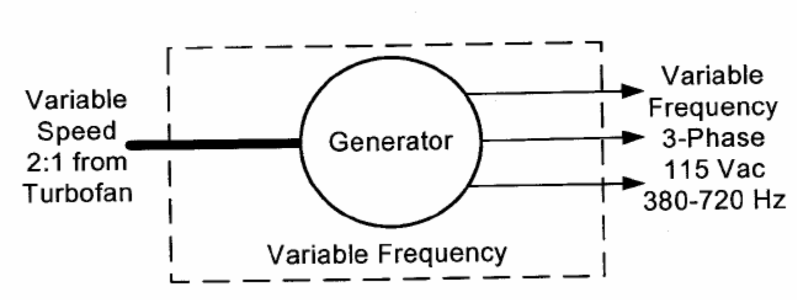


Figure 2-6 Variable Frequency Generating System [5]

2.2.3 270VDC System

As electric power demand increases enormously in modern aircraft, the low maintenance highly reliable electric power system is required by advanced military and commercial aircraft. Because electric power continuity and quality now affects every aspect of modern aircraft from passengers convenience and comfort to flight safety and mission completion, the importance of electric power system in aircraft is one of ever increased. Due to the relative simplicity, flexibility, and the unique ability of direct current systems to provide uninterrupted power to the electrical loads, the high voltage DC (270V) system concept is now regarded as the new solution for future aircraft [20]. Up to now, this kind system has been used successfully in the US military aircraft， Such as F22 and F35. Besides the advantages mentioned above, the kind of system also has the following advantages:

1. High Efficiency The power loss of this kind of generating system only occurs in the generator and rectifier unit. No other type of power loss occurs, Such as CSD and power converter which are used in VSCF generating system.
2. Light weight "High speed light weight machine designs can be used without incurring penalties such as cycloconverter power factor[20]" . Besides, the conductor mass will be saved compared to other type of power.
3. High reliability Compared to the CSD/VSCF generating system, this type of system is more reliable due to its relative simple architecture.
4. Power continuity This is the unique feature of DC power system which is easy to run in parallel. Therefore, it is easy to provide uninterrupted power to the loads.

5. safety-shock hazard to personnel

In terms of electric shock hazard, the effects on human are determined by the passage of current through tissue. Human sensitivity to the electricity is based on the value of let-go current. The term let-go-current is defined as the current level above which muscle contraction can not be consciously controlled. According to the result (Figure 2-7) of the research which is about the relationship of electric frequency and let-go current [20], it suggests that the most dangerous frequency range is from 5 to 1000Hz. Apart from this frequency band, the value of let-go current becomes higher than that of this band. From this let-go-current point of view, DC power is much safer than AC power.

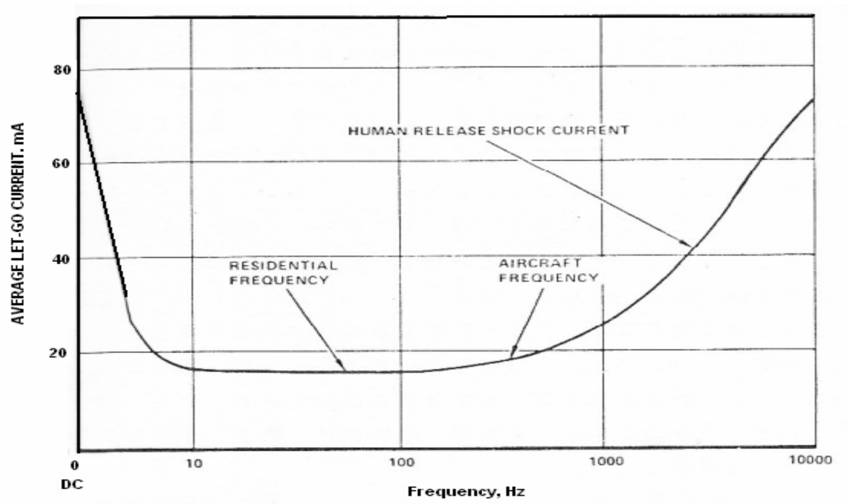


Figure 2-7 Personnel Hazard Versus Power Source Frequency [20]

In terms of DC power, the ripple voltage comprises some ac components which will increase electric shock sensation. So, the ripple voltage of a DC system should be controlled as low as possible in order to increase safety.

6. 270VDC power can be obtained directly from full wave rectification of three phases AC 115V power source[22].

7. Voltage drop In a generating system, there is only one point of regulation (POR). In order to ensure that all the loads work properly, the voltage drop between load input terminal and POR should keep minimal. In terms of 270VDC power distribution system, the voltage drop in a two-wire system will be twice as

much as that of one-wire system [29]. Compared with 115VAC system, the 270VDC one-wire system outperforms the AC system in terms of voltage drop[21].

With respect to 270VDC generating system, there are mainly two types. One is brushless DC generator. The other is switched reluctance generator.

- **Brushless DC generator:**

As for this kind of generating system, the 270VDC power is obtained via full wave rectification of three-phase 115VAC power. The type of system consists of a synchronous alternator and a rectifier unit which can be seen in Figure 2-8. The rectifier unit can be either uncontrolled type or controlled type.

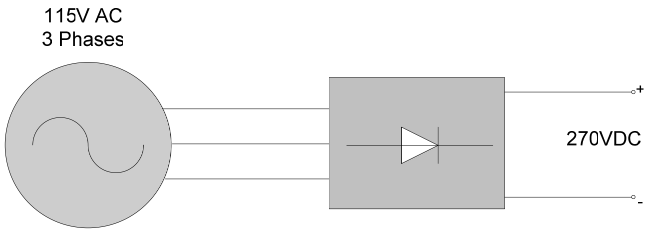


Figure 2-8 270VDC Brushless Generating System

- **Switched Reluctance Generator**

This kind of system mainly comprises of a double salient variable reluctance machine and a converter. Meanwhile, other auxiliary circuit is required, such as the shaft position sensing circuit and control unit and so on. The schematic diagram of switched reluctance generating system is shown in Figure 2-9.

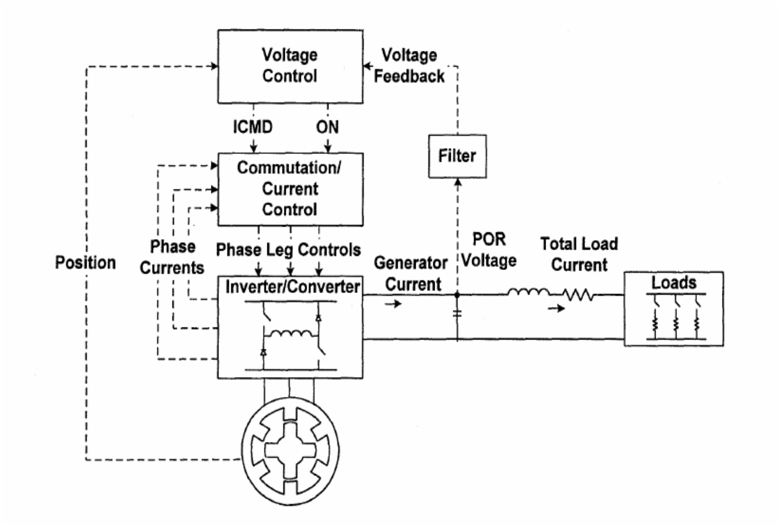


Figure 2-9 Schematic Diagram of SRG System [11]

The switched reluctance generator (SRG) can be used in very high speed or high temperature conditions because there is no windings or permanent magnetic on the rotor. Furthermore, it is easy to operate in generating mode or reversible mode without any additional equipment.[15]

2.3 Discussion and Summary

Up to now， all the power generating types that are currently used have been reviewed. Different power generating systems have there own features. Their relative merits have been roughly summarized in

Table 2-1. In terms of future MEA and AEA, it is not efficient to use constant frequency (400Hz) power as the primary source due to the comparative low efficiency and limited generating capacity. As regards the variable frequency system, even it is the most reliable and efficient generating system, it might not be the best solution for MEA and AEA yet, because different types of power source affect the whole electric power system in terms of mass, efficiency and so on.

Table 2-1 Generating Systems Initial Comparison

	Constant Frequency System			Variable Frequency System	High Voltage (270V) DC System	
	IDG	**DC-Link**	**Cyclo-converter**		**Brushless DC generator**	**Switched Reluctance Generator**
Weight	Moderate	Highest	High	Lowest	Low	High
Efficiency	Lowest	Moderate	Moderate	Highest	Moderate	Moderate
Reliability	Medium	Good	Good	Best	Good	Good

In terms of high voltage DC(270V) system, conductor mass and power dissipation can be reduced compared to 115V system. The 270v impact study which has been done by Lockheed-California company shows that some valuable benefits were obtained by utilizing 270VDC power for avionics system. Power supply efficiency increased 14% and aircraft electrical power mass reduced 75.1 pounds[16] compared to 115V/400Hz system. An assessment on a twin-channel military aircraft shows that system mass was saved 26kg when 270v system in lieu of conventional 115v/400Hz system[3]. All these results prove that the electrical power system which is based on 270V generating system outperforms the conventional 115V/400Hz system.

Based on the discussion above, the author can not analyse all these state of the arts power type in detail within such short period. The author just intent to further study the 270VDC brushless generating system and make a comparison with the 115V variable frequency system because these two types of power are more efficient and reliable compared to other types of systems. Moreover, the comparison study has already been done before is between 270VDC system and 115VAC/400Hz system. So the author will study the application of 270VDC system and 115V variable frequency system in detail. Then, the benefits as well as the risks of these two systems will be evaluated.

3 Case Study Introduction

3.1 Introduction

In order to study the pros and cons of these two types of system, a case study will be conducted. In this project, Flying Crane, AVIC group design project, is chosen for this case study. In this Chapter, the case study aircraft, Flying Crane, will be introduced firstly, followed by the depiction of the electric power system of Flying Crane.

3.2 Flying Crane

Flying Crane is a medium to short haul aircraft with 130 seats which is mainly aimed at Chinese domestic air transport market. Also, it is considered to be a competitor of those current aircraft B737 series and A320 series. Therefore, Flying Crane has its unique features and advantages over others. The extra wide body and lower fuel cost are considered as the main features of Flying Crane. The figures and main parameters of this aircraft are listed below (Figure 3-2).

In terms of the structure, the fin, wing and horizontal tail is made of composite material. The rest of parts are made of metal material. It can be seen in the following graph Figure 3-1.

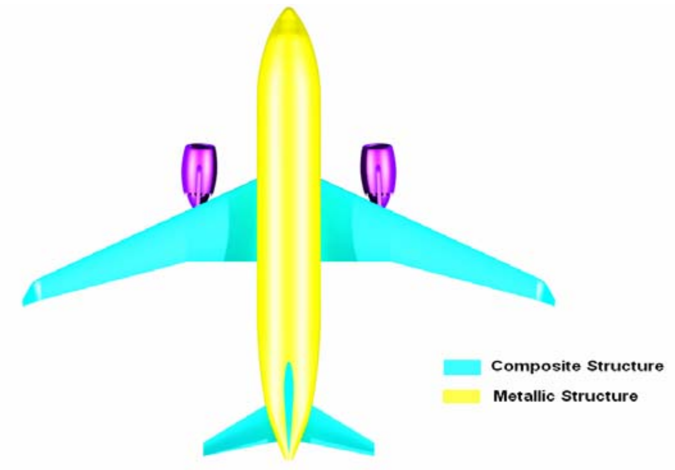


Figure 3-1 Structure Material

As regards the airframe systems, it is an all electric aircraft. The hydraulic power and pneumatic power are substituted by electric power. It is also the highlight of this aircraft. As a result, Flying Crane will be more cost-effective and more competitive in civil transport market.

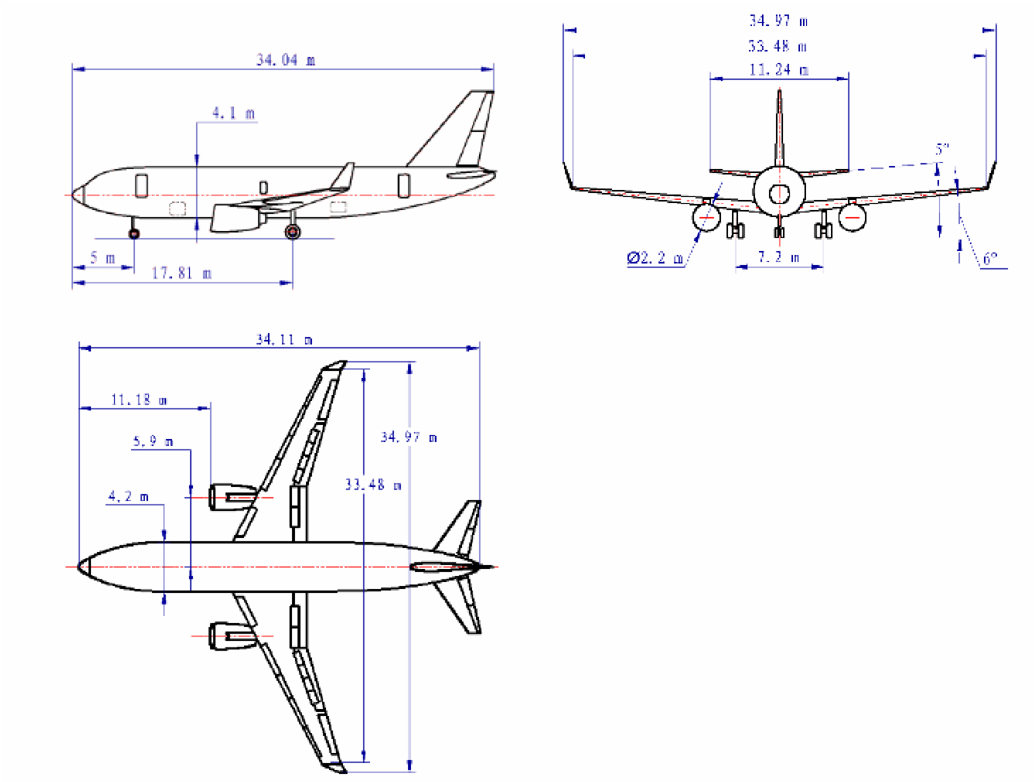


Figure 3-2 Flying Crane Three View Drawing[3]

3.3 Electric Power System

Flying Crane has a power generation capacity of 500KVA supplied by two 250kVA variable frequency starter/generators. The conversion to 270VDC, 28VDC and 115VAC/400Hz operating voltages to drive the various airframe systems were enhanced through the use of state of the art power converters. Each type of power is supplied by two power conversion equipment. The auxiliary power unit (APU) generator is the same type as the main generator. In terms of emergency power system, it consists of two Ni-Cd batteries and a ram air turbine (RAT) generator which will be extended automatically in the event of all the generators failure.

In terms of the power distribution system, it is a remote power distribution system which consists of two primary power distribution units (PPDU) and six electric load management centers(ELMC). The architecture can be seen in Figure 3-3. Their relative position is represented in Figure 3-4.

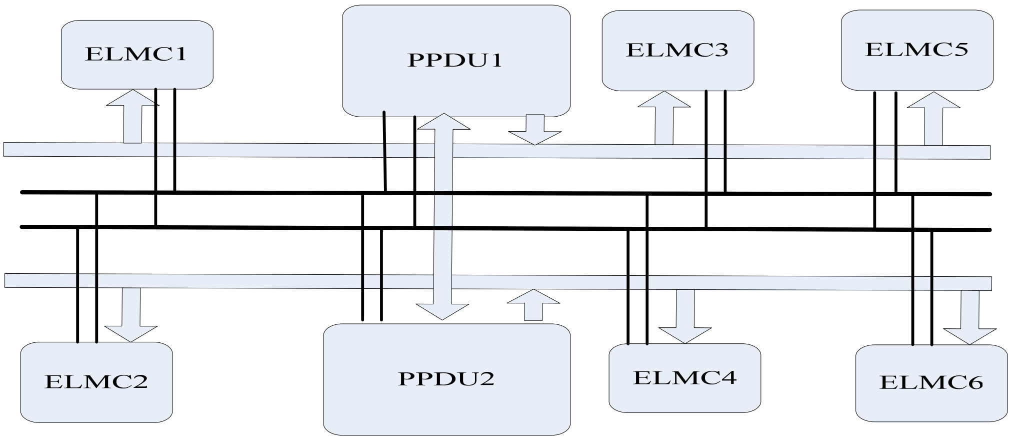


Figure 3-3 Power Distribution Architecture

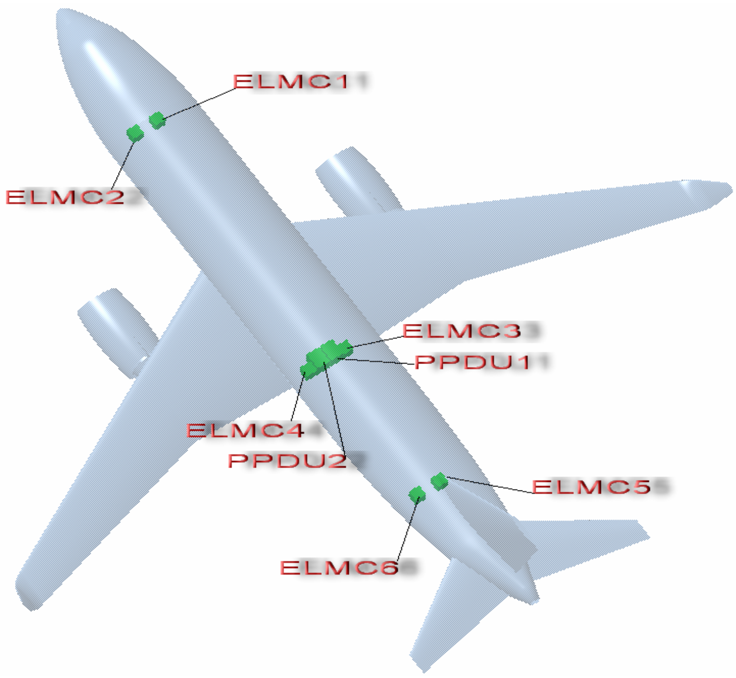


Figure 3-4 Layout of the Power Distribution System

4 Load Analysis

4.1 Introduction

The aim of electric power system is to provide electric power to all the loads. So, the electric load requirement is regarded as the fundament of electric power system design. According to the airworthiness regulation CCAR25.1351(a) “The required generating capacity, and number and kinds of power sources must be determined by an electrical load analysis[4]”, the first thing needs to be done is to analyze the electrical load. Since the two types of generating system are selected as the primary power source, the optimal way to design the electric power system is that the power type required by the majority of loads should be the same type as the primary power source. Therefore, the load optimization needs to be conducted.

4.2 Method and Procedure

The method of load analysis is based on the AC21-38(0) aircraft electrical load analysis and power source capacity [12]. Load analysis should include continuous analysis, 5-minute analysis and 5-second analysis. Because the detailed load information can not be obtained, the 5-second analysis can not be included in this project.

The step is to collect all the information of load requirement. Then all these loads will be divided into three categories according to their functions. The power requirement of these three types load will be computed. The detailed process can be seen Appendix B.

4.3 Load Optimization

In terms of electric power system, the predominant concern is the power distribution from the power source to the busbars as well as the power supply of primary loads.

Therefore, the electric majority of power requirement should be the same as the power source in order to get the optimal system efficiency. Due to time reasons, the author can not discuss each load in detail. Here, the power requirement of environmental control system(ECS) will be discussed in detail because the power requirement of ECS occupies nearly half of the total power requirement.

The environmental control system of Flying Crane is powered by electric power according to group design report[20].The total power requirement is 265.17KW which is consumed by the electric-driven compressor and other miscellaneous equipment. In terms of the air compressor, the shaft speed varies with the flight conditions, such as altitude, ambient air temperature and so on. In order to save energy, the shaft speed of air compressor need to be controlled. Therefore, a motor controller is required.

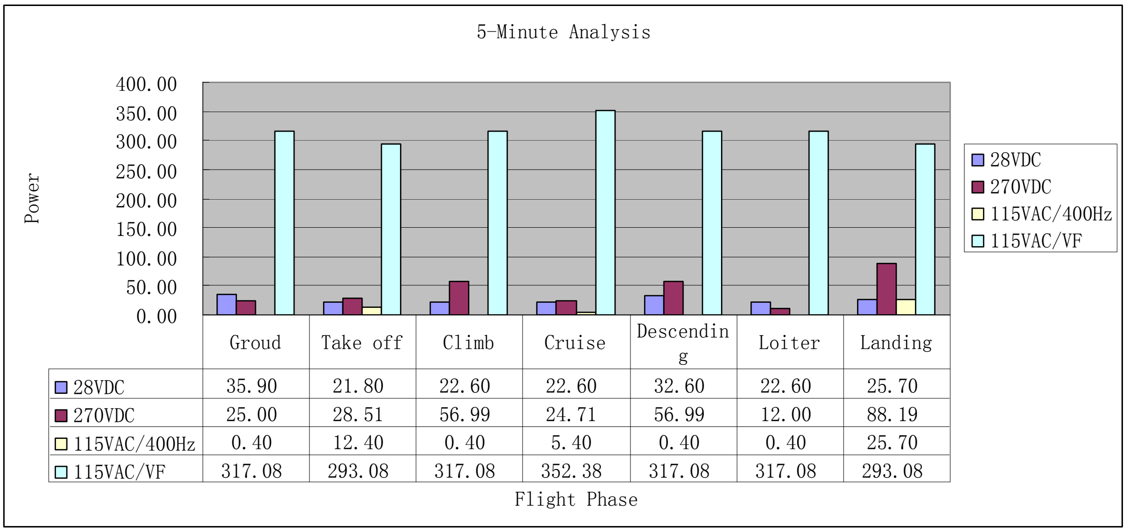
As the motor controller is already required, if the air compressor is still supplied by 115/400Hz which is different from the primary power source discussed in this project, it is a kind of waste energy. Therefore, the power requirement of ECS compressor should be the same the same type as the primary power. So, the power type for ECS compressor will be 115V/VF or 270VDC.

As a result, the further load analysis will be divided into two parts. One is for the system which is based on 115V/VF generating system. The other is for the system which is based on 270VDC generating system.

4.4 Load Analysis for 115V/VF System

4.4.1 5-Minute Analysis

In terms of 5-minute analysis, the total power requirement includes the power required by both continuous loads and Intermittent loads. Figure 4-1 shows the total amount of the power requirement of those four kinds of power source which is arranged by fight phases.



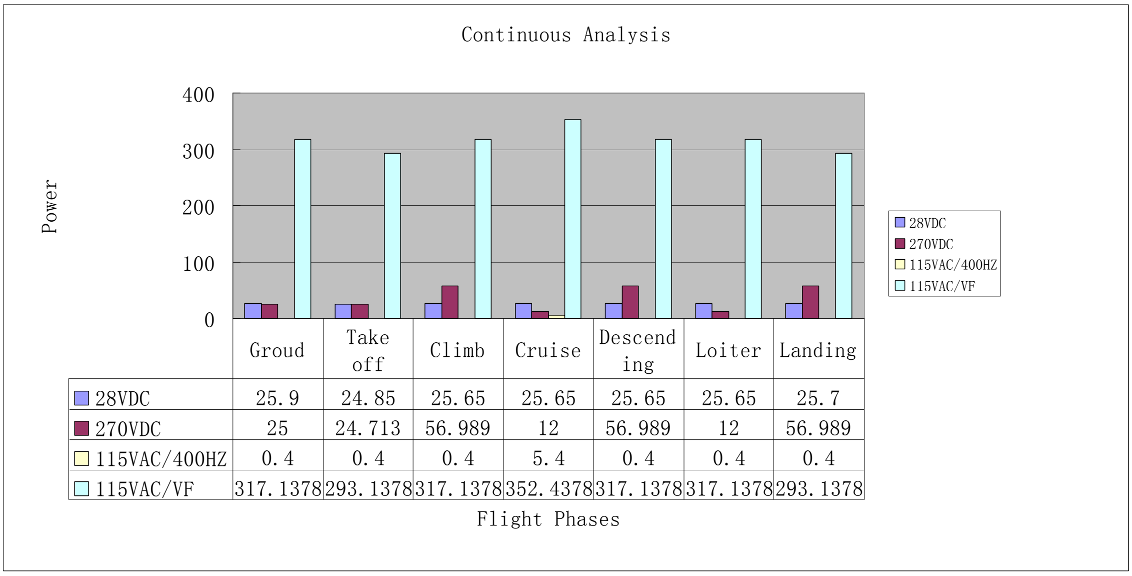
	Groud	Take off	Climb	Cruise	Descending	Loiter	Landing
28VDC	35.90	21.80	22.60	22.60	32.60	22.60	25.70
270VDC	25.00	28.51	56.99	24.71	56.99	12.00	88.19
115VAC/400Hz	0.40	12.40	0.40	5.40	0.40	0.40	25.70
115VAC/VF	317.08	293.08	317.08	352.38	317.08	317.08	293.08

Figure 4-1 5-Minute Analysis

From Figure 4-2, it can be seen that four types of power are required. The Majority of loads require 115V variable frequency power.

4.4.2 Continuous Analysis

As regards the continuous analysis, the power requirement just refers to the power requirement of all the continuous loads. Figure 4-2 shows the power requirement of continuous loads of those four kinds of power source which is arranged by flight phases.



	Groud	Take off	Climb	Cruise	Descending	Loiter	Landing
28VDC	25.9	24.85	25.65	25.65	25.65	25.65	25.7
270VDC	25	24.713	56.989	12	56.989	12	56.989
115VAC/400HZ	0.4	0.4	0.4	5.4	0.4	0.4	0.4
115VAC/VF	317.1378	293.1378	317.1378	352.4378	317.1378	317.1378	293.1378

Figure 4-2 Continuous Power Requirement

The following graphs show the ingredients of each type of power requirement. This information is primarily for sizing the major components of electric power system.

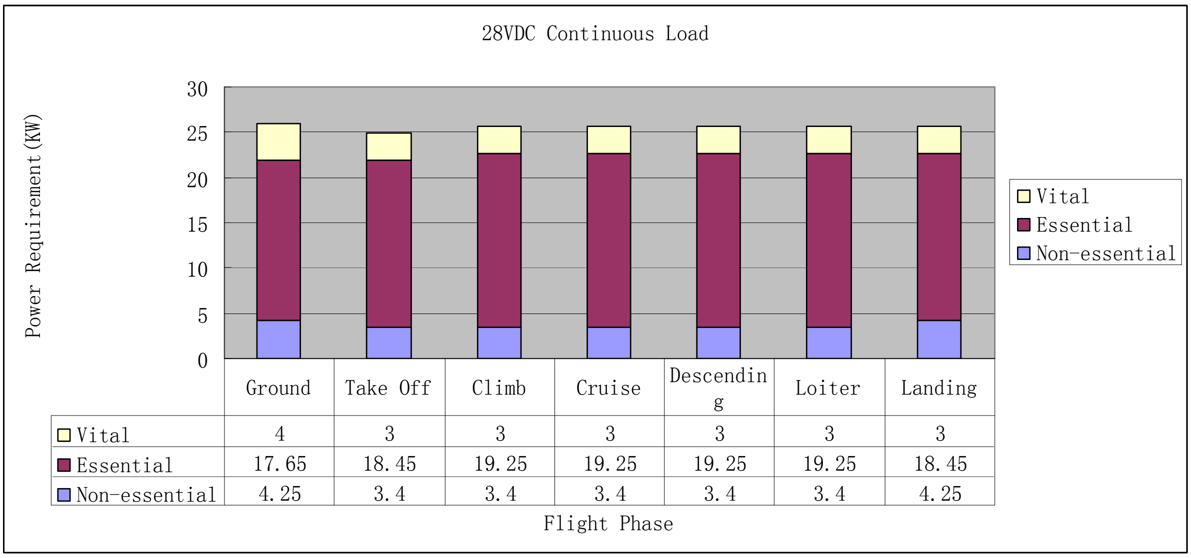


Figure 4-3 28VDC Loads

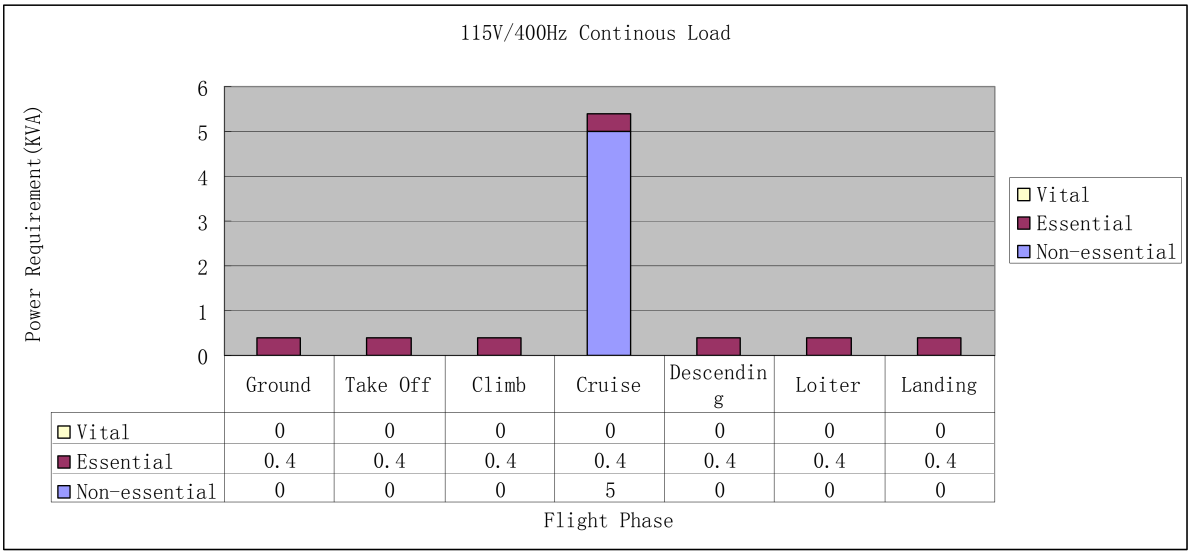


Figure 4-4 115V/400Hz Loads

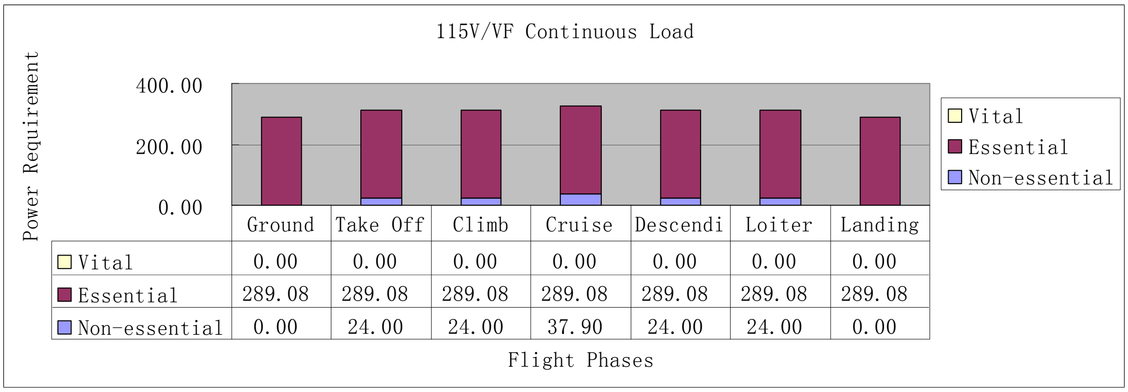


Figure 4-5 115V/VF Loads

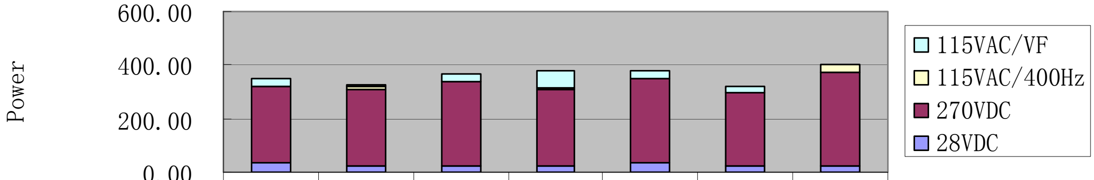
Figure 4-6 270V Loads

4.5 Load Analysis for 270VDC System

The load requirement difference between 115V/VF system and 270VDC system is the power supplied for ECS.

4.5.1 5-minute Analysis

The scope of this kind analysis is the same as the one in 115V/VF system. Figure 4-7 shows the total amount of the power requirement of these four types of power source which is arranged by fight phases.

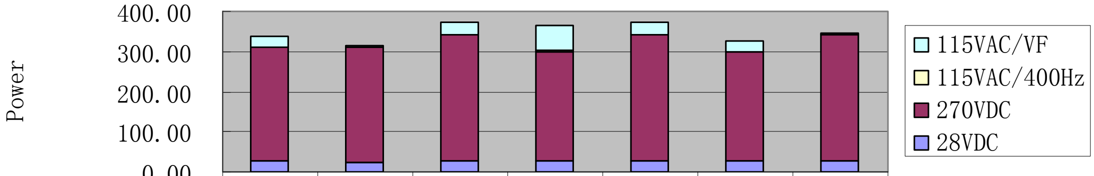


	Groud	take off	climb	cruise	descending	loiter	landing
115VAC/VF	28.00	4.00	28.00	63.30	28.00	28.00	4.00
115VAC/400Hz	0.40	12.40	0.40	5.40	0.40	0.40	25.70
270VDC	285.17	288.68	317.16	284.88	317.16	272.17	348.36
28VDC	35.90	21.80	22.60	22.60	32.60	22.60	25.70

Figure 4-7 5-Minute Analysis

4.5.2 Continuous Analysis

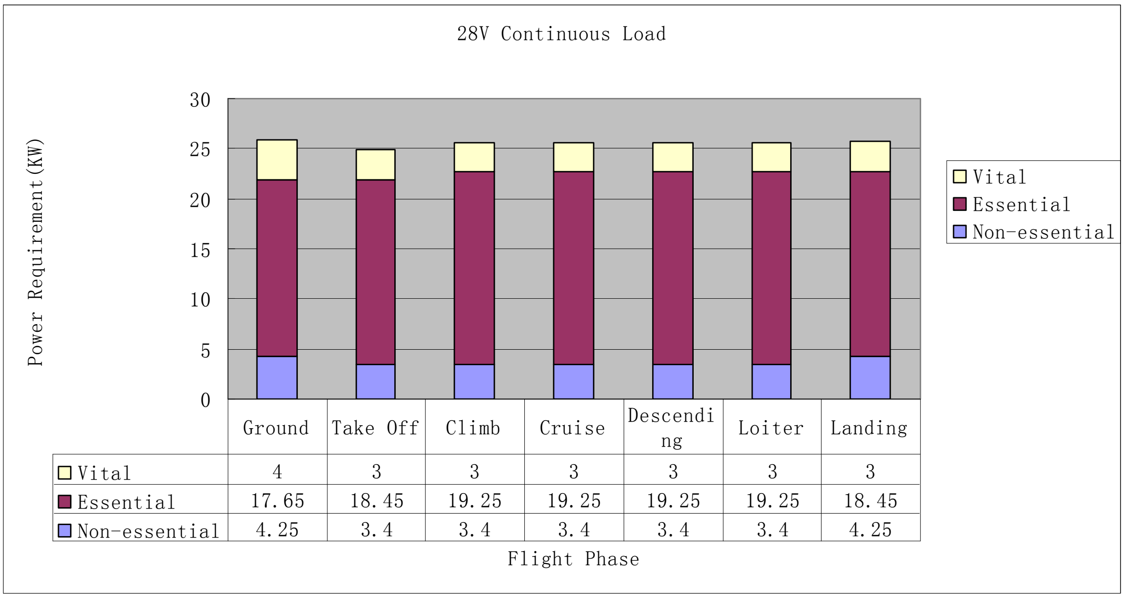
In terms of the continuous analysis, only the continuous loads are taken into account. Figure 4-8 shows the power requirement of continuous loads of these four types of power source which is arranged by flight phases.



	Groud	Take off	Climb	Cruise	Descending	Loiter	Landing
115VAC/VF	28.00	4.00	28.00	63.30	28.00	28.00	4.00
115VAC/400Hz	0.40	0.40	0.40	5.40	0.40	0.40	0.40
270VDC	285.17	284.88	317.16	272.17	317.16	272.17	317.16
28VDC	25.90	24.85	25.65	25.65	25.65	25.65	25.70

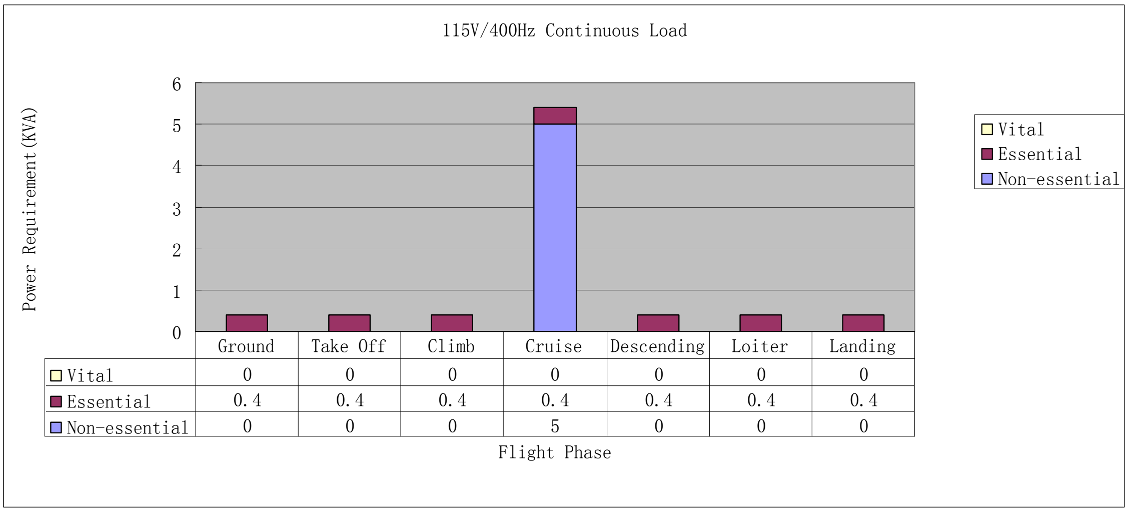
Figure 4-8 Continuous Power Requirement

The following graph shows the ingredients of each type of power requirement.



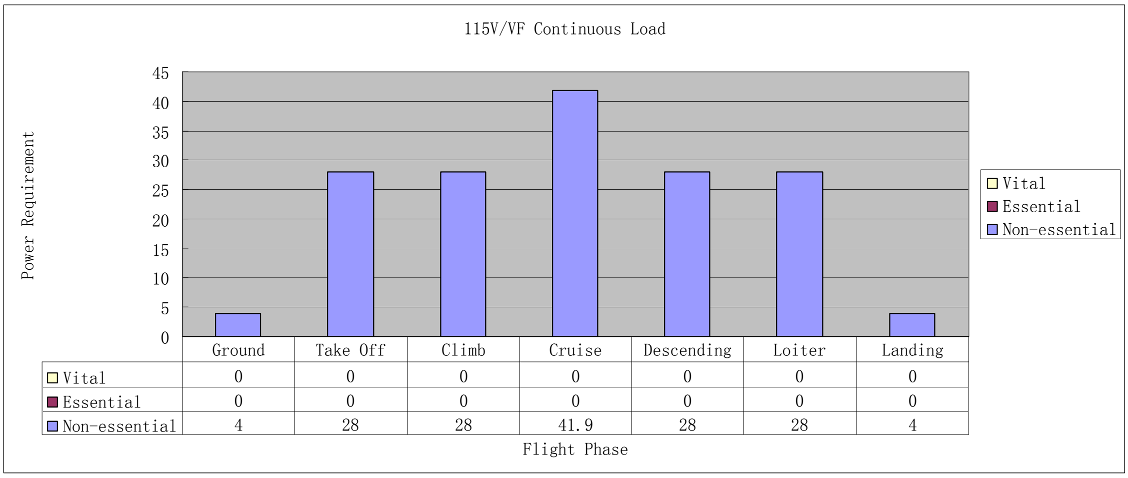
	Ground	Take Off	Climb	Cruise	Descending	Loiter	Landing
Vital	4	3	3	3	3	3	3
Essential	17.65	18.45	19.25	19.25	19.25	19.25	18.45
Non-essential	4.25	3.4	3.4	3.4	3.4	3.4	4.25

Figure 4-9 28VDC Loads



	Ground	Take Off	Climb	Cruise	Descending	Loiter	Landing
Vital	0	0	0	0	0	0	0
Essential	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Non-essential	0	0	0	5	0	0	0

Figure 4-10 115V/400Hz Loads



	Ground	Take Off	Climb	Cruise	Descending	Loiter	Landing
Vital	0	0	0	0	0	0	0
Essential	0	0	0	0	0	0	0
Non-essential	4	28	28	41.9	28	28	4

Figure 4-11 115V/VF Loads

	Ground	Take Off	Climb	Cruise	Descending	Loiter	Landing
Vital	0	0	0	0	0	0	0
Essential	283.17	284.883	284.883	272.17	284.883	272.17	284.883
Non-essential	0	0	32.276	0	32.276	0	32.276

Figure 4-12 270V Loads

4.6 Summary

From the analysis above, it can be found that the power type required by the electric load includes 28VDC, 115V/400Hz, 115V/VF and 270VDC. In order to optimize system efficiency, the power type of ECS varies with the power generated by the main generator. Therefore, the load requirement varies with the primary power source.

5 Electric power System Architecture Design

5.1 Introduction

This Chapter mainly introduces the simplified primary power distribution architecture design which is based on different types of power generation system, namely 115V variable frequency system and 270Vdc system. In addition, the system major components capacity will be determined based on the load requirements analysed in chapter 4. However, the emergency power generating system is excluded in this case study since the emergency is independent of the primary power source.

5.2 Operation Mode

In terms of electric power system, the system operation mode can be divided into two basic types:

- ✧ Parallel operation
- ✧ Nonparallel operation

As regards the system operation mode, each operating mode has its own advantages and drawbacks. Furthermore, the system operation mode also affects the electrical system design in terms of system safety, power supply quality and so on. The following paragraph will describe the pros and cons of these two operation mode respectively:

5.2.1 Parallel Operation

During normal operation, all the generators link together and provide power to all the electrical loads. If a generator has failed, the rest of the generators still run in parallel to provide electricity to all the loads. The feature of paralleling system is that this kind of system can provide uninterrupted power to all the loads in case of engine or generator failure. The advantages of this operation mode are:

a. Improve power supply reliability. A single generator failure would not result in power interruption of any load.

b. Minimize the effects on the electric power system which are caused by the load variation. Because the capacity ratio of any single load to all the generating sources is relatively low.

c. The busbar system design can be simplified. The load balance issue between different generators does not need to be considered.

d. shorter recovery time and lower magnitude of voltage disturbance from faults, motor starting, or loss of generation[11].

The main disadvantages of this type of operation mode are:

a. The control circuit is relatively complicated because good current balance circuit is required. .

b. The whole system will be affected if the short circuit fault occurs[11].

c. Larger switchgear is required because of the greater fault current.

d. The total capacity of generating system is related to the status of load balance between different generators. The generating capacity is inversely proportional to the unbalanced current among the generators which runs in parallel[27].

5.2.2 Nonparallel Operation

In terms of this type of operation mode, each generator powers its own main busbar in normal situation. Moreover, the busbar can also be powered by the other generators in case of its own generator failure.

The main advantages of this type of operation mode are:

a. Load balance circuit is not required.

b. Any load disturbance only affects single generator.

c. Larger switchgear is not required because fault current is comparatively low compared to the parallel operation system.

The main disadvantages are:

a. The generating capacity is relatively low compared to the parallel operation system. As a result, load variation affects the whole system to a larger extent.

b. The control algorithm of the power distribution system is more complicated because the power transfer logic is more complex in the event of fault conditions compared to parallel operation system.

c. It is hard to obtain uninterrupted power from this kind of system. There is 50 to 200 ms power interruption during power switching process [27].

5.3 270VDC System Architecture Design

As described in chapter 2, the electric power system for future aircraft is a hybrid system which employs various voltage levels in the system. It can be found from the result of load analysis that four types of power are required, namely 115V AC / 400Hzpower, 115VAC/VF, 28VDC power and 270VDC power. From the electric characteristic point of view, those loads which require variable frequency AC power also can be powered by constant frequency power. Therefore, the system which is based 270Vdc generating system only provides three types of power for all the loads. In other words, those loads which originally require 115V/VF power will be powered by the 115V/400Hz power.

As for the system operation mode, the pros and cons of each type of operation mode has been discussed above. The system is designed to operate in parallel because of the nature of DC power. System stable margin will be increased significantly. Furthermore, this type of system can provide the electric power to all the loads without any interruption.

Based on the discussion above, a possible form of primary power distribution architecture was designed and shown in Figure 5-1. It is a typical twin-engine configuration which employs two main generators and APU generator.

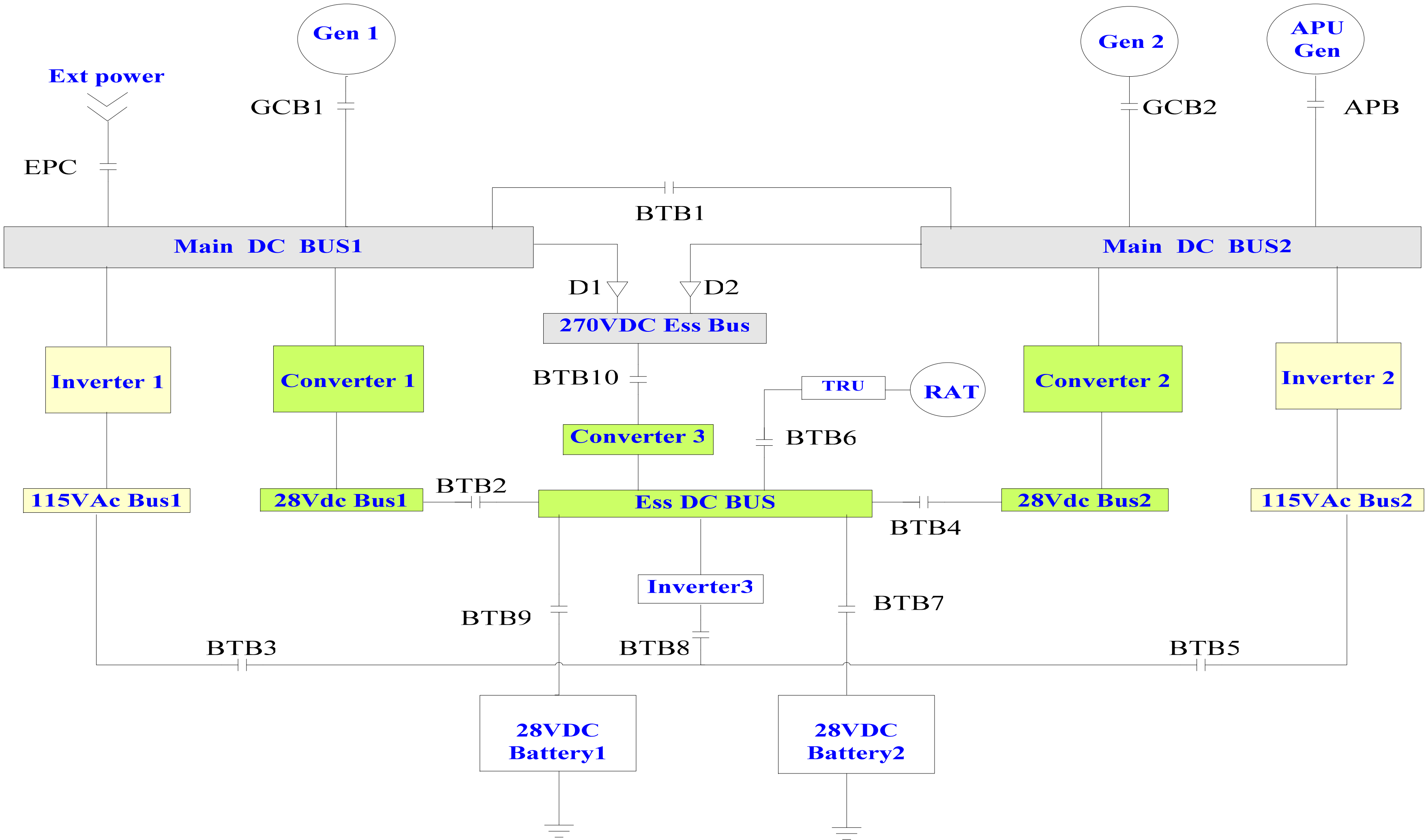


Figure 5-1 Primary Power Distribution Architecture of 270VDC system

5.3.1 System Description

With regard to this system architecture, the two primary power sources run in parallel under normal circumstances. The APU generator will replace one of the main generators in case of the failure of one generator. Meanwhile, the APU generator also can run in parallel with the main generator.

The mainly components of this system are illustrated below:

Two 270VDC brushless DC generators run in parallel to supply the main DC Bus1 and the main DC Bus2.

One APU generator is used as a back up power source during flight and provides power to the power users during ground operation, which makes the airplane to be electrically self-sufficient on the ground.

Two static inverters power the 115VAC Bus1 and 115VAC Bus2 separately. Each one has the capability to power all the essential loads and vital 115VAC loads.

Two converters supply the 28Vdc BUS1, 28Vdc BUS2 independently under normal conditions which can power all the 28VDC loads. One of the converters can supply all the essential loads and vital loads. Both 28Vdc BUS1 and 28Vdc BUS2 feed the Ess DC Bus which supply all the essential loads and vital loads.

Two nickel-cadmium batteries are used to provide emergency power for the vital loads. The low voltage(28V) battery is chosen for this system other than high voltage battery due to the reliability issue. The battery type is the same as the one used in F-22 which consists of 24 cells[30].

One ram air turbine(RAT) driven generator supplies emergency power to the vital loads and part of the essential loads in the event of complete failure of all the generators. As describe in ref[23], the RAT is used to provide sufficient power to the flight critical loads while attempting to restart the engine or divert to the nearest airfield. It is not used as the power source which can power electric loads for long term.

The inverter3 and converter3 are the power conversion equipment which only operates in case of the failure of all the main generators. In the emergency case, the 270VDC power is obtained via converter3 and 115V/400Hz power is obtained through inverter3.

5.3.2 Major Components Sizing

Here, the components' sizing refers to the quantification of the capacity of all the generators and power conversion equipment. The sizing process is based on the load requirement analysis and the following criteria[27]:

1. According to load analysis, the maximum load requirement and the operating period can be decided.
2. Normally, a 33%--50% additional power should be taken into account when sizing the generator.
3. In order to size the generator properly. The overload requirement needs to be taken into account. Normally, the result of 5-minutes analysis is related to the 1.5-times overloading requirement. 5-second analysis is related to 2-times overloading requirement. The ratio between the power requirement of the heaviest load and the system capacity is less than 0.4.
4. Furthermore, if the generator has starting capability, the power requirement of engine starting needs to be taken into account. If the capacity required when staring an engine is more than that of the maximum load requirement, the power generating capacity equals to the power requirement of starting the engine.
5. In terms of the power conversion equipment, the capacities of those equipment are according to the load analysis. Normally, the margin is about 33% to 59%.
6. In civil aircraft, the capacity of APU generator equals to that of a main generator.
7. As regards the capacity of the battery, normally, it can withstand 30-40 minutes.

Based on the sizing criteria mentioned above, the detailed sizing process is shown below:

(a) Main Generator

Under normal circumstance, all the power users are powered by the two generators. Therefore, the nominal generating capacity is determined by the total power requirement of all the continuous loads. Besides, an additional 33% capacity needs to be considered based on the sizing criteria mentioned above. Finally, it is worth to mention that the generator rating is not at the output terminal of the generator but at the point of regulation (P.O.R). Therefore, the following equation is used to sizing the main generator:

$$C = \left(P_{\max}/2\right) \times 1.33$$

Where: C is the capacity of the main generator

$P_{\max}$ is the maximum power requirement of all continuous loads at the P.O.R.

According to the load requirement analysis, the Maximum power requirement is:

$$P\max = P_{270VDC} + \left(P_{115VAC} \times PF / EF_{AC}\right) + \left(P_{28VDC} / EF_{DC}\right)$$

Where: P_{270VDC} is the total power requirement of all continuous 270VDC loads

P_{115VAC} is the total power requirement of all continuous 115VAC loads

P_{28VDC} is the total power requirement of all continuous 28VDC loads

PF is the power factor of AC system

EF_{AC} is the efficiency of the inverter

EF_{DC} is the efficiency of the converter

This calculation is based on the following assumption:

a. the efficiency of all the power conversion equipment is 0.9.

b. the power factor of AC system is of 0.9 lagging.

According to the load analysis mentioned in Chapter4, the maximum continuous power is required at the period when aircraft is at the climb phase or descending phase. Therefore, P_{max}= 374.059 KW

C= 249KW

(b) APU Generator

The function of the APU generator is to replace either or both of the main generators in case of the failure of the main generator in flight and supply the aircraft network when other power sources are unavailable. Therefore, the power supply reliability is affected by the capacity of the APU generator. The capacity of APU generator is normally the same as that of the main generator. This kind of criterion is adopted in the majority of current airliner which can be seen in Table 5-1 [34,45,36].Here, this criterion is also adopted for this case study.

Table 5-1 Generating Capacity of Different Aircrafts

No.	Type of Airliner	Generator	Quantity	Capacity
1	B737	Main generator	2	40KVA
		APU generator	1	40KVA
2	B777	Main generator	2	120KVA
		APU generator	1	120KVA
3	A320	Main generator	2	90KVA
		APU generator	1	90KVA
4	A300	Main generator	2	90KVA
5		APU generator	1	90KVA

(c) Static inverter

As described in section 1.3.1, two state inverters supply all the loads simultaneously. Each of them can supply all the 115V loads except the non-essential 115V loads. Therefore, the capacity is determined by the maximum power requirement of all the essential AC loads and vital AC loads. Furthermore, the margin for the inverter is also taken as 33%.

Therefore, the capacity of the inverter is calculated as follow:

$$C_I = P_{\max - I} \times 1.33 = 0.4 \times 1.33 = 0.532\text{KVA}$$

Where: C_I is the capacity of the static inverter.

$P_{\max - I}$ is the maximum power requirement of all 115V continuous essential loads

In this case study, the capacity is unacceptable because the total capacity of the two inverters can not meet the load requirement of all 115V loads. So, the minimum requirement for these two static inverter is to meet all the power requirement of all 115V loads. Furthermore, additional 33% capacity is also taken into account. Therefore,

$$C_I = \frac{68.7}{2} \times 1.33 = 45.6\text{KVA}$$

(d) Converter The criteria used for sizing the converter is that each of the converter has the capability to supply all the 28VDC loads expect the non-essential 28VDC loads. Meanwhile the stable margin is also set at 133%. So:

$$C_D = P_{\max - c} \times 1.33 = 19.25 \times 1.33 = 25.6KW$$

Where, C_D is the capacity of the converter.

$P_{\max - c}$ is the maximum power requirement of all essential and vital continuous 28VDC loads.

(e) Battery   The function of battery is to power the emergency loads in flight or start APU. The emergency situation refers to the failure of all the generators. From the aircraft point of view, the only choice for the pilot is to do hard landing. Therefore, only the vital load needs to be powered on under this circumstance. According the airworthiness regulation CCAR25 1351[4], the minimum duration for emergency power supply is at least 5 minutes. Normally the capacity expressed in the nameplate is based on one-hour rate. The available power of the battery is not a linear function of discharge current. The higher the discharge current the lower the available capacity[12]. Therefore, all the calculations should be based on one-hour rate. Moreover, the output capacity of a battery also varies with the temperature. Here, the battery sizing is at the normal temperature. Nevertheless, an additional 20% to 25% capacity needs to be taken into account[27]. In this case study, it is assumed that the battery can work for 30 minutes and an additional 25% of capacity is taken into account. Therefore the capacity of the battery is calculated as follow:

$$C_B = \frac{P_v}{24} \times \frac{t}{60} = \frac{4000}{24} \times \frac{30}{60} = 111Ah$$

Therefore, the capacity of each battery is 55.5Ah.

Where: C_B is total capacity of all the batteries

P_v is the total load requirement of all the vital loads.

t is the period of the power supply which is based on the battery (min).

The results of major components sizing is shown in (Table 5-2)

Table 5-2 Sizing Results of 270VDC system

No.	Equipment	Quantity	Capacity
1	Main generator	2	249KW
2	APU generator	1	249KW
3	Converter	2	25.6KW
4	Inverter	2	45.6KVA
5	Battery	2	55.5Ah

5.4 115V/VF System Architecture Design

As described in section 1.3, the system operation mode can be divided into parallel operation and nonparallel operation. In terms of AC system, a number of conditions are required to be well observed for reliable parallel operation[21].

(a) First and foremost, the frequency of all the generators is required to be practically equal.
(b) The electromotive force (EMF) of the generators is required to equal to the line voltage.
(c) The phase sequence of the generator should be identical.

In terms of a wild frequency generating system, the frequency of each generator is proportional to the rotation speed of its own corresponding primary mover. Therefore, the frequency of all the generators can not be maintained at the same value. As a result, the variable frequency AC generators can not run in parallel. For this reason, each main AC busbar employs an external input. The same design was demonstrated in the Latest airliner Airbus-A380 [23].

As shown in Figure 5-2, it is the simplified primary power distribution architecture of 115V/VF system.

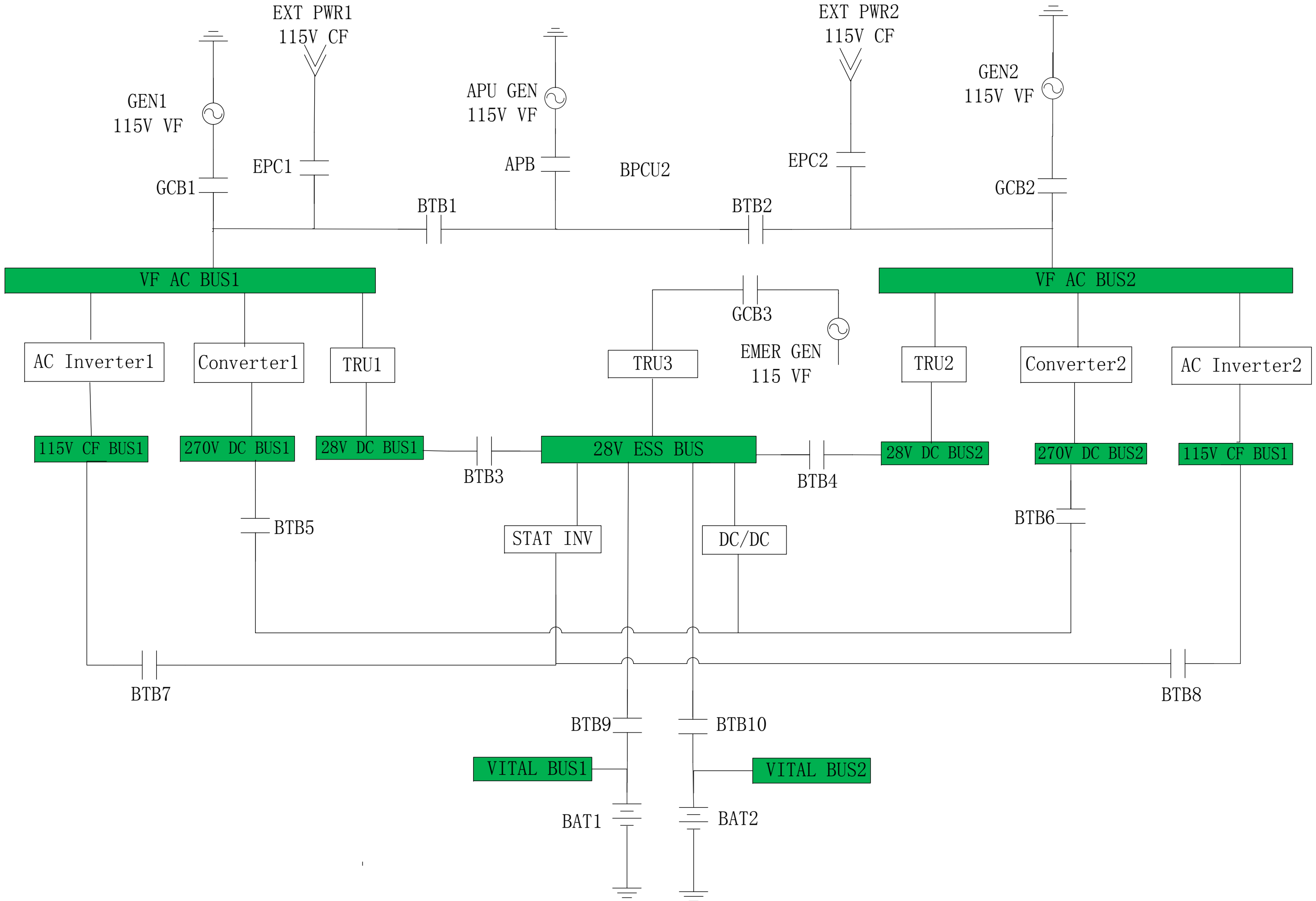


Figure 5-2 Primary Power Distribution Architecture of 115V/VF system

5.4.1 System Description

As regards this system architecture, the two primary power sources run independently under normal circumstance. The APU generator will replace one of the main generators in case of the failure of one generator.

The mainly components of this system are illustrated below:

Two 115V variable frequency generators supply the VF AC Bus1 and the VF AC Bus2 separately.

One APU generator is used as a back up power source during flight and provides power to all the users during ground operation, which makes the airplane to be electrically self-sufficient on the ground.

Two AC inverters are used to convert the variable frequency power into constant frequency(400Hz) power. Those two units power the 115VAC Bus1 and 115VAC Bus2 separately. Each one can power all the essential 115VAC loads and vital 115VAC loads in case of the failure of any one of the inverters.

Two converters power the 270V DC Bus1 and 270V DC Bus2 respectively under normal operation. Any of the converters has the capability to supply all the essential 28vdc loads and vital 28vdc loads.

Two TRUs supply the 28Vdc BUS1, 28Vdc BUS2 independently under normal conditions which can power all the 28VDC loads. One of the converters can supply all the essential loads and vital loads. Both 28Vdc BUS1 and 28Vdc BUS2 feed the Ess DC Bus which supply all the essential loads and vital loads.

Two nickel-cadmium batteries are used to provide emergency power for the vital loads. The battery used in this system is same as the one used in 270VDC system.

The RAT driven generator performs the same function as described in 270VDC system.

The emergency power conversion system consists of TRU3, DC/DC converter and STA INV. Those components normally operate when the main generating system fails.

5.4.2 Major Components Sizing

The sizing criteria used in 270VDC system is also chosen for the VF system sizing. Here, the capacity sizing refers to the rating capacity. Therefore, the continuous load requirement is used for sizing the capacity of power equipment. Those criteria will be briefly restated as follow:

a. Main generator and APU generator. Under normal operational conditions, the two generators can supply all the electric loads. Similarly, an additional 33% capacity is taken into account. As regards the APU generator, the capacity is as much as that of the main generator.
b. Power conversion equipment These equipment include two TRUs, two AC Inverters and two converters. The capacity requirement of those equipment is that all the loads can be powered by different types electric power during normal operation and single equipment has the capability to supply the essential loads and vital loads.
c. Battery The criteria is totally the same as the one used in section 5.3.2

Since the method used here is similar to the one used in 270Vdc system, the author has not presented the detailed calculation process. But, it is worth to notice that the maximum 115V/400Hz load requirement was used when sizing the AC inverter. The maximum requirement of the 115V/400Hz load is regarded as much as 1.5 times the nominal capacity. Therefore, the capacity of Ac inverter equals to maximum load requirement divide by 1.5.

In conclusion, the results are given below (Table 5-3):

Table 5-3 Sizing Results of 115V/VF System

No.	Equipment	Quantity	Capacity
1	Main generator	2	272
2	APU generator	1	272
3	AC Inverter	2	8.6
4	TRU	2	25.6
5	Converter	2	32.8
6	Battery	2	55.5Ah

5.5 Summary

In this chapter, the primary power distribution architecture has been designed. Moreover, the capacity of the major components has been determined.

As regards the system architecture, the parallel operation configuration is considered for 270VDC system. However, the 115V/VF system can not runs in parallel due to its features.

With respect to the capacity of those components, the capacity is determined by the load requirement. In terms of the AC system, the power factor needs to be considered. These are the two reasons why some capacity differences between the two systems occur.

6 Wiring system Design

6.1 Introduction

This section describes the wiring framework of the aircraft-Flying Crane. Wiring system consists of many types of wire according to the functions performed, such as power cable, data bus cable, ignition cable, thermocouple cable and co-axial cable. Due to time reason, it is impossible to study all the wiring system wire by wire. The cables included in this case study are the power cable which runs between power source and power distribution unit. Furthermore, the cable between power distribution unit and ECS are studied because ECS system consumes the majority of generated power.

6.2 Conductor Material Consideration

Two types of material are currently used for conductor in aerospace application, namely copper and aluminium. Copper has a very low specific resistance. The conductivity of aluminium is much lower than that of copper. However, the density of aluminium is just 30% that of copper. If two types of wire are used for the same conditions(current, temperature and voltage drop), the cross section of aluminium wire will be greater than that of copper wire, but the weight of aluminium wire is much lighter than that of copper wire. Even so, the advantages of using aluminium wire are diminished by the following aspects:

1. From the weight point of view. For the same conditions of current, voltage drop and environmental conditions, the cross section of the aluminium wire is greater than that of copper wire. Furthermore, the greater cross section requires more total insulation. Thus the weight saving decreases even the density of aluminium is lower than that of copper.

2 . The mechanical strength of aluminium wire is lower than that of copper wire. Moreover, aluminium has less ductility than that of copper. Therefore, the using of small gauge aluminium wire will be a problem. But it should be noted the wire size limitation. According to the standard MIL-W-5088L, the minimum wire size

for aircraft is AWG-22. As for aluminium wire, any wire whose size is smaller than size 6 are forbidden using in aircraft[15].

3. In addition, if both copper and aluminium wire are used in an aircraft. The galvanic corrosion and differential thermal expansion problem should be considered because they are the dissimilar material. Therefore, the splice fitting method will be more complicated than that of connecting the same kind of conductor which will result in weight penalty [24].

In conclusion, the copper wire is only one considered in this case study based on the comparison mentioned above.

6.3 Insulation Consideration

Generally, wire consists of a conductor surrounded by dielectric material and an outer sheath which is used to protect the conductor from abrasion. The insulation material selection is based on the specific environmental conditions in which the wire operates. Those approved insulation material are polyvinylidene fluoride(PVF), fluorinated ethylene propylene(FEP), polytetrafluoroethylene(TFE), and glass braids [39]. As for a wire, the breakdown voltage is determined by the insulation thickness, insulation material, whether the voltage is ac or dc, and environmental factors such as temperature, pressure, humidity, and how it’s mechanically attached [38]. However, the insulation material and thickness has not been decided in this case study due to lack of information regarding the insulation technology used for 270VDC system.

6.4 Wire Sizing

6.4.1 Sizing Considerations

There are two fundamental requirements for sizing the power cable on aircraft[15]. One is that wires must have the capability to carry the required current without overheating. Another requirement is that the voltage drop in the wires must not exceed the aircraft circuit limit when conducting the required current.

In practice, the environmental conditions also have effects on wires. The following aspects were mentioned in the NASA report[26]. First and foremost, temperature affects the currents rating of wires in two ways. Firstly, the permissible temperature rise will be reduced if the wire works in high temperature conditions. Secondly, the wire resistance is affected by temperature which will also affect the power transmission loss. Besides, the conductor carrying current is also impaired by altitude since the air density varies with the altitude. But in this case study, all these environmental conditions have not been taken into account due to the lack of the sufficient wire information. The only wire information can be obtained is normally at certain environmental condition (Normally 20℃).

6.4.2 Sizing Process

The wire sizing process is shown in Figure 6-1. The detailed procedures of wire sizing are demonstrated in Appendix E. In this case study, the MIL-W-22759/87 wire is adopted and the detailed wire information is obtained at the website of the wire manufacturer Thermax[3].

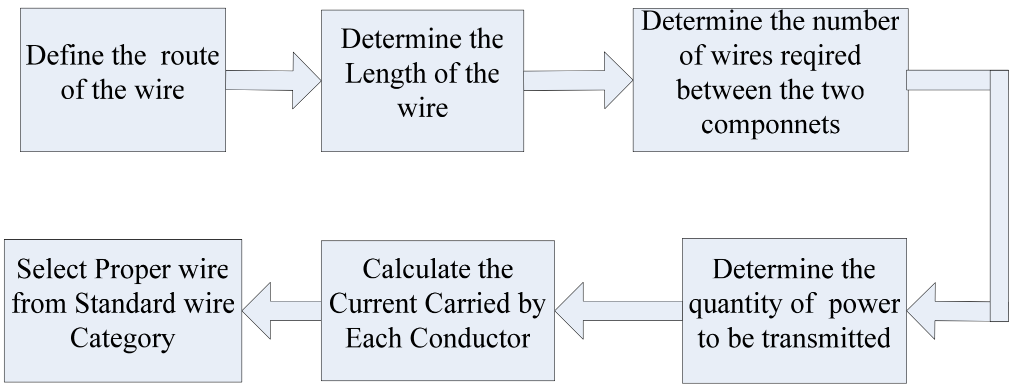


Figure 6-1 Wire Sizing Process

Due to the limited time, the wires used to transmit electric power from different power sources to the power distribution units are studied. Furthermore, the wires that runs between the ECS electric-driven compressor and the PPDU are also studied in this case study.

6.4.3 270VDC System

As mentioned in chapter 3, both metallic and composite materials are used in this aircraft. In terms of metallic parts, the structure is used as the ground return. However, two-wire system is chosen for the composite parts. In terms of this case study, the two wire system is considered for the main generating system as the wing structure is of non-metallic construction.

Based on the method of wire sizing described above, the sizing results of wiring system for 270VDC system are shown in Table D- 2.

6.4.4 115VAC/VF System

As for the electrical system, the three-phase AC power are normally required by the AC power users since those loads whose capacity is greater than 0.5KVA are required to be powered by three-phase balanced power [1]. Normally, the natural phase is grounded to the airplane structure if the structure is of metallic construction. However, since the wing structure of Flying Crane is of composite material, a conductor is required for the main generator which is used to connect the natural phase to the earthing station.

According to the wire sizing criteria and procedures mentioned above, the wire size has been found out. The result is shown in Table D- 1

6.5 Summary

The Chapter mainly depicts the wiring system design for 270VDC system and 115VAC/VF system. Due the lower strength of aluminium wire, only copper wire is considered for this case study. Since the operation condition of Flying Crane is not exactly known, the insulating material has not been specified. During wire sizing process, the power requirements of 5-minute analysis was used to size the conductor as the 5-mintiure load requirement reveals the maximum current need to be transmitted.

7 System Evaluation and Comparison

7.1 Voltage Drop

7.1.1 Introduction

Each regulated power source can only have one point of regulation (P.O.R). The power regulation should be well designed in order to ensure that the power voltage at the input terminals of all loads meets the requirement of aircraft electric power characteristics MIL-STD-704F. Moreover, the voltage drop in conductor directly indicates the power loss in conductor. Therefore, it is worthwhile checking the voltage drop in power transmission cables.

7.1.2 DC or AC Transmission

The voltage drop in a wire is determined by the resistance of the wire. As regards the resistance of a conductor, it is affected by the following two aspects:

a. Temperature Generally, the resistivity of metal increases with temperature. Therefore, the voltage drop also varies with temperature.

b. Power Frequency In terms of alternating current transmission, the skin effect can not be neglected, which produces an increase in effective resistance. This is one of the reasons why DC power transmission is better than AC power transmission since there is no skin effect for DC power transmission. As regards the cylindrical conductor, the resistance caused by skin effect is related to the current frequency and the radius of the conductor.

Having reviewed the factors related to the resistance of a conductor, the voltage drop of each conductor will be assessed. However, the temperature factor is not considered in this project since there is no difference in temperature in terms of these two compared systems. The detailed evaluating process can be seen in Appendix F. Part of the results will be summarized as follow (Table 7-1).

Table 7-1 Voltage Drop

		Power Type	Current (A)	Wire Size	Resistance (Ω)	Voltage Drop(V)
Cable from Generator1 to PPDU1	115V/VF System	115V/VF	324.75	AWG-000	0.006878	2.23
	270VDC System	270VDC	376.48	AWG-0000	0.003186	1.2×2
Cable from PPDU1 to ELMC1	115V/VF System	115V/VF	30.92	AWG-10	0.06512	2.01
		28VDC	215.85	AWG-0	0.005936	1.28
		115V/400Hz	35.13	AWG-8	0.03648	1.28
		270VDC	54.99	AWG-8	0.03648	2.01
	270VDC System	115V/400Hz	33.52	AWG-8	0.03648	0.8
		28VDC	215.85	AWG-0	0.005936	0.8
		270VDC	54.99	AWG-8	0.03648	1.25
Cable from PPDU1 to ACP1	115V/VF System	115V/VF	223.14	AWG-0	0.004511	1.01
	270VDC System	270VDC	260.17	AWG-000	0.002097	0.55

As can be seen from Table 7-1, the voltage drop in the main feeder has slight difference between those types of system. The reason is that two-wire system is adopted for 270VDC system. So, voltage drop will be twice as much as the single wire. As for the cable which runs from PPDU1 to ELMC1, the difference of voltage drop between these two systems is caused by the load current. As regards the cable which runs from PPDU1 to ACP1, the voltage drop in 270VDC system is only half of the one in 115V/VF system. The reason is that the resistance of the wire is different. All in all, the voltage drop is governed by the wire resistance and the carrying current.

7.2 Minimum VA Rating Requirement

7.2.1 Introduction

As far as the aircraft electric power generating system is concerned, the minimum voltamperes rating of a generator not only depends on the load requirement but also depends on the generator itself. The VA rating of a generator directly affects the weight of the generator. In terms of an airframe system, it is always required to be as light as possible since it affects the aircraft performance but also affects the fuel consumption which will give effects on operational cost indirectly. Figure 7-1 shows all the factors which related to VA rating of a generator.

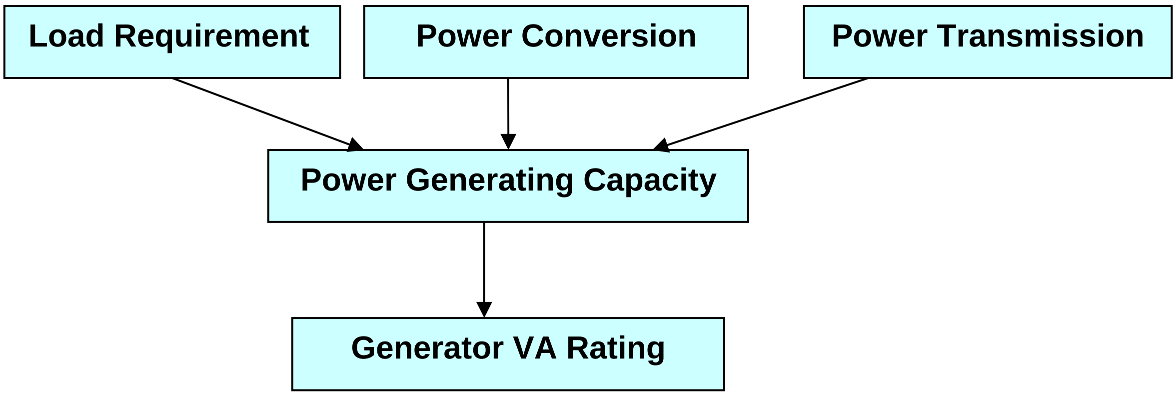


Figure 7-1 Generator VA rating Consideration

As the load requirement is already known, the emphasis is put on the power loss analysis and the generator sizing in this section. Due to time reason, all of these aspects can not be studied in the same level. The differences in generator and power transmission loss will be analyzed in detail.

7.2.2 Power Loss in the Main Feeder

As far as the power transmission loss is concerned, the kind of power loss mainly refers to the I^2R loss in conductor. As described in section 7.1, the resistance of a conductor is different when conducting AC power or DC power, which will cause different power dissipation in the conductor even though the carrying current is the same. In terms the current, it varies with the voltage level for a given power. Taken these two considerations into account, the power loss in conductor can be easily found out.

The Detailed calculation is shown in Appendix G. As the aim of this section is to evaluate the VA requirement of the main generator, the power loss in the cables which are used to transmit the power supplied by the APU generator and external power station is excluded from this study.

7.2.3 VA-Rating Difference in Generator

7.2.3.1 Variable Frequency Generating System

In terms of a VF generator, it does not have either the CSD stage or electronic power conversion stage used in constant generating system. Therefore, the minimum VA rating equals to the power requirement at the output terminal of the generator. Figure 7-2 illustrates considerations of minimum VA rating in terms of a VF generator.

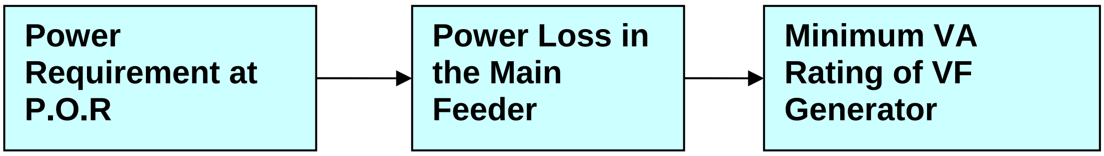


Figure 7-2 Minimum VA Rating of VF Generator

7.2.3.2 270VDC Generating System

As described in chapter1, the case studied here is based on the brushless DC generating system. Generally, this kind of system consists of a synchronous alternator and a rectifier unit. As shown in Figure 7-3, it is a typical configuration of brushless DC generating system, which consists of a three-phase VF synchronous alternator and a three-phase full wave rectification unit. This typical configuration is considered for this project. Other possible configurations are not considered in this project since the technical issues are similar in spite of the differences in rectification unit or the number of phases.

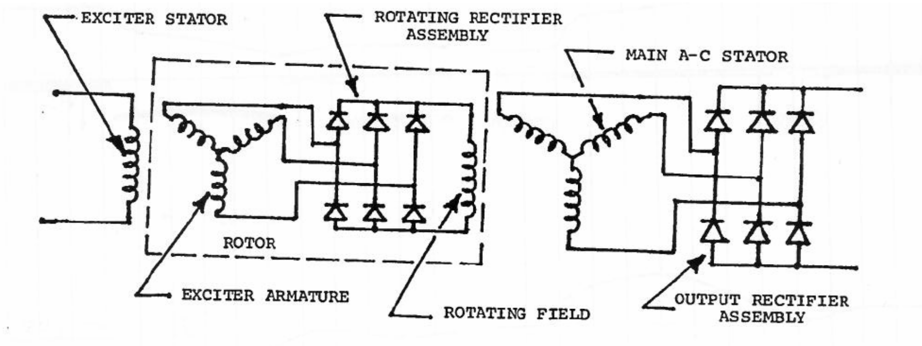


Figure 7-3 Brushless Synchronous Alternator Wiring Diagram(output rectifier assembly included to provide D-C Power)[31]

In terms of the VA rating of a brushless DC generator, the following two aspects needs to be taken into account.

The first One is the 'utilization factor' which reveals the merit of a rectifier circuit. It is defined as the ration of the DC output voltamperes to the input voltamperes. This phenomenon is caused by the different voltage and current waveforms between the two sides of the rectification unit.

The other issue is the imperfect commutation in the rectification circuit. Due to the transient inductance of the generator windings, the current in one arm of the bridge can not instantaneously fall to zero or increase to full value during commutation [40]. Therefore, allowance must be made for the effect of overlap.

As all the technical issues have been considered, the value of the minimum VA rating of these two systems can be obtained. The detailed calculation can be seen in Appendix G. The result is shown below Table 7-2.

Table 7-2 Minimum Rating of the Generator

System	Power Requirement at P.O.R	Power Loss in the Main Feeder	Power Requirement at Alternator
115V/VF	273KVA	3.624KW	275.1KVA
270VDC	249KW	1.531KW	273KVA

From Table 7-2, it can be found that the VA rating of the alternator is nearly the same even the power requirement at the P.O.R is much different. The reason is that the utilization factor and imperfect commutation need to be taken into account for a 270VDC brushless generator.

7.3 Weight

7.3.1 Introduction

Weight is one of the most important factors for aircraft design. System weight not only affects the initial cost of electrical power system but also affects the performance of the aircraft itself. As regards the electric power system, the easiest way to calculate the system weight is to add all the elements' mass together. Since the system design is not conducted in detail in this project, it is impossible to take all elements into account. The scope of mass calculation included in this project is shown as follow Figure 7-4:

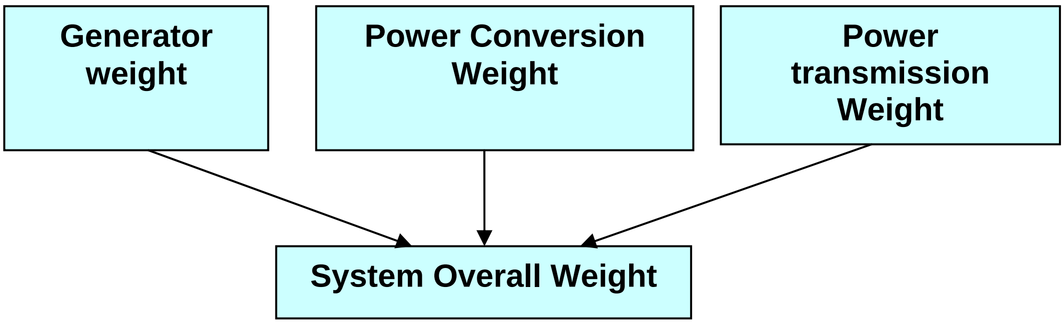


Figure 7-4 System Weight Consideration

The emergency generating system and emergency power conversion system are not taken into account since they are not related to the main power system.

7.3.2 Generator Weight

Here, the notion generator refers to the two main generators and the APU generator. In this case study, we assume that the main generator and the APU generator are the same type. The method used to roughly estimate the weight of generator is shown as follow:

$$W_G = C \times PD_G$$

Where, W_G is the weight of a generator

C is the capacity of a generator

PD_G is the power density of the generator

In practice, it should be noted that the generator weight increase is not directly proportional to the capacity increase [31].

In terms of the 270VDC generator, it consists of a synchronous alternator and a rectification assembly. From the ripple voltage point of view, the output frequency of the alternator is desired to be as high as possible. Simultaneously, the weight of the alternator can be saved as the increase of power frequency. However, the maximum frequency is limited the number of poles and the rotational stress of the rotor. Furthermore, the commutation loss goes up with the increase of power frequency. In ref[5; 8] , it recommends that the optimal frequency range is from 1200 to 2400Hz.. For comparative purpose, the alternator of the 270VDC generator is assumed to be the same type as the VF generator mentioned in this study, whose frequency range is from 360 to 720 Hz. In terms of the specific mass of the alternator, the value 0.35kg/KVA mentioned in ref [8] is selected for this case study since the detailed architecture of the alternator is not concerned in this study.

As for the rectification assembly, it includes rectifier circuit and filter unit. It is difficult to precisely estimate the mass of the rectification assembly. In terms of the rectification circuit, the weight is determined by the diode. The diode selection is based on the current requirement and the voltage threshold. As described in ref[5], the diode assembly weight for a 50KW 200V generator is 7.83kg. As for this case study, as the current rating is higher than that of the 200v/50KW generator. So, a rough estimation for the weight of the diode assembly studied in this project is 10kg.

In terms the filter unit, it would consist of a modified low-pass filter network. In the filter network, the inductance elements occupy the majority of the total mass of the filter unit. The weight of the inductance element is directly related the current. In ref[5], the mass of the filter unit for a 50KW/200V generator is 6.795kg. Therefore, the mass of the filter unit considered in this project is roughly considered to be 15Kg.

Therefore, the generator weight of these two types of system is shown below:

Table 7-3 Generator Mass Comparison Matrix

System	Number of generators	Alternator Capacity(KVA)	Power Density(Kg/KVA)	Rectification assembly Mass (kg)	Weigh t(Kg)
270VDC	3	273	0.35	25	361.65
115V/VF	3	275.1	0.35	/	288.86

7.3.3 Weight of Power Conversion Equipment

As regards the 270VDC system, those power conversion components refer to the L-converter and inverter. However, TRU, H-converter and AC inverter are involved in the VF system.

Since TRU and L-converter perform the same function. Both of them are used to produce 28VDC power. A comparison was taken between TRU and L-converter in ref[8]. It is depicted that the specific weight of converter is lower than that of TRU since a higher frequency is used in the L-converter which will result in mass reduction in the transformer. The power density mentioned in that report are suitable for this case study. It describes that a 4KW 28V TRU weigh 10kg and a 4KW DC/DC switching converter has a mass of 6kg.

In terms of the inverter used in the 270VDC system, the power density of DC/AC inverter reaches 1.03 Kg/KW according to the state of the art power electronics technology[17].

As regards the AC-inverter used in the 115V/VF system, it is assumed to be the same type as the one used in VSCF generating system mentioned in ref [22]. The 30KVA VF-CF inverter unit weigh 29.9kg. The specific weight (0.99KG/KVA) is adopted for this case study.

As for the H-converter, it is assumed to be a rectification unit, which is the same as the one used in the 270VDC generator. Therefore, the same weight power ratio (0.09kg/KW) is used. Then the weight of power conversion equipment is summarized in Table 7-4.

Table 7-4 Power Conversion Equipment Mass Comparison Matrix

System	Equipment	Quantity	Capacity (KW/KVA)	Power Density (Kg/KW, Kg/KVA)	Weight (Kg)
270VDC	Inverter	2	45.6	1.03	93.9
	L-Converter	2	25.6	1.25	64
				SUM	157.6
115V/VF	TRU	2	25.6	2.5	128
	H-converter	2	32.8	0.09	5.9
	AC-inverter	2	8.6	0.99	17
				SUM	150.9

7.3.4 Weight of Power Transmission

As regards the total weight of electric power system, the wiring weight occupies nearly one-to two-thirds of the total electrical system weight[7]. Therefore, it is necessary to compute the total mass of wiring system.

Since the author has not yet found any literature which gives sufficient evidence to show that the wire intended for conventional 115V ac system is still suitable for 270V system without breakdown dangerous even it can withstand a potential of 600volts between conductor and aircraft structure. Therefore, the weight difference in insulation material is neglected in this project. The detailed weight calculation will be given in Appendix D. Table 7-5 shows the wiring weight of these two systems.

Table 7-5 Wiring Mass Comparison Matrix

System	Weight(Kg)
270VDC	336.3
115V/VF	711.3

In summary, the overall weight of 270VDC system is 855.55Kg, whereas, the total mass of the 115V/VF system is 1151.06Kg.

7.4 Reliability

7.4.1 Introduction

As the improvement of technologies, airframe systems become more and more sophisticated. Since the system reliability not only has effects on cost but also affects the flight safety, it is now becoming a design parameter for a system which equals to the importance of functional characteristics. Therefore, it is worth to evaluate the system designed above in terms of mission reliability.

7.4.2 Reliability Definition

The term reliability is defined as the probability of an equipment which are functional under stated conditions for a stated time[14]. In terms of electric power system, the function of electric power system is to supply electric power to all the loads. So in this case study, the reliability is defined as the probability that the system can power all the loads successfully.

7.4.3 System Model

As the system architecture has been designed, it is necessary to evaluate the system mission reliability. Reliability block diagram is a widely used method to conduct system reliability analysis. The detailed system modelling process can be seen in Appendix C.

7.4.4 Comparison

As can be seen in Appendix C, the major difference between these two systems is the configuration of the primary power source. From the system redundancy point of view, the primary power configuration of 115V/VF system is a standby redundant system since the APU generator can not operates simultaneously with the main generators. However, the primary power configuration of 270VDC system can be a standby redundant system or active parallel redundant system. In this case study, the quantitative analysis can not be conducted due to lack of data regarding components' reliability. As for the 270VDC system, if the primary power part is considered to be a standby redundant system, the reliability of primary power source part will be lower than that of 115V/VF system since the reliability of 270VDC generator is inherently lower than VF generator. However, if primary power source part of 270VDC system is considered to be active parallel system, the reliability of this part might not be lower than that of 115/VF system. The reason is that the failure probability of the changeover unit needs to be considered for the standby redundant system.

7.5 Power off-Take

7.5.1 Introduction

In terms of an electric power system, the system efficiency is denoted by the power off-take. It is an important design point for an aircraft. The increase in power-off-take will result in an increase in fuel consumption. Therefore, it is worthwhile evaluating the total system power-off-take.

7.5.2 System Efficiency Consideration

In term of the system power off-take, which includes the power consumed by the electrical loads and the system power loss. With respect to the load requirement, the continuous loads are considered. The power loss in the electric power system can occur in the stage of power generation, power conversion as well as the power transmission. In this case study, what will be discussed are the power generation loss and power transmission loss.

(1) Power Transmission Loss

As for the power transmission loss, which includes the power loss in switchgear, protection equipment and wire. The power loss in switchgear and protection equipment is neglected, since the power dissipation in those components is extremely low. As the voltage drop in each conductor has been examined in section 7.1, it is easy to compute the power dissipation in those wires.

(2) Power Generation Loss

In terms of power generation loss, the two candidates will be discussed respectively.

(a) VF Generating System

It is the simplest generating system among the current generating systems. Besides the power loss in the mechanical part, the main power loss in the alternator mainly refers to the copper loss and the eddy loss. Based on the published literature, the overall efficiency of VF generating system reached to 86%[26].

(b) 270VDC Generating System

Besides the power loss mentioned above, the rectification loss needs to be considered according to the configuration of this type of generating system.

As all the aspects which are related to this issue have been addressed, the detailed power off-take evaluation will be given in Appendix H. The result shows that power extraction of 270VDC is lower than that of 115V/VF system. The overall power loss in 270VDC system in less than that of 115V/VF system.

7.6 Life Cycle Cost

System life cycle cost consists of initial cost and operational cost. As far as the operational cost is concerned, it includes maintenance cost, capital cost and flying cost. Among these factors, maintenance cost and a part of operation cost is related to the availability which is a function of reliability and maintainability and weight. The rest of these factors are insensitive to the exact system type[26].

As regards the initial cost of the 270VDC system will be significantly higher than that of the 115V/VF system at the newly development stage, because it is inevitably to put a large amount of money on developing the new components required by the 270VDC system. In this case study, the main differences between these two systems are the main generator. The high voltage generator and the large capacity high voltage switchgear are the newly components required by the 270VDC system. However, beyond this beginning stage the initial purchase cost will reduce as the improved reliability began to be evident.

In terms of operational cost, the mainly concerned aspects are the flight cost and the maintenance cost. As the 270VDC system is superior to the 115V/VF system in terms of weight and efficiency, the flight cost of 270VDC system will be significantly lower than that of 115VDC system. However, since the 270VDC generator inherently has lower reliability compared to VF generator, the 270VDC system requires more frequent maintenance. So, the maintenance cost of 270VDC system will be higher than that of 115V/VF system. But as the improvement in the reliability of 270VDC generator, the maintenance cost can be reduced.

In summary, even the numerical results have not been given in this study, it can be concluded that the 270VDC system will be superior to 115V/VF system in system life cycle cost as the life span is long enough and this advantage will be more obvious as the longer servicing period.

7.7 Risk

7.7.1 Introduction

As the large amount power is required for MEA or AEA, it is unacceptable to utilize the low voltage power due to the constraints of voltage drop and weight. The higher voltage system will be more efficient for future aircraft. However, the higher voltage system will introduce the electrical discharge problems. Electrical discharge is divided into two types, namely partial discharges(PD) and disruptive discharges[13]. Normally, partial discharge refers to the term ‘corona’.

The following paragraphs will discuss the arcing risk and corona discharge risk in terms of those two systems.

7.7.2 Corona(partial discharge)

In an electric field, air acts as an insulating material. If the potential gradient is large enough, the air which is around the electrode will be ionized and finally create a plasma around the electrode. If the electric field is uniform, the increasing voltage on the gap will cause breakdown among the gap in the form of spark, while the increasing voltage will cause a discharge in the gap at the point with the highest intensity of the electric field if the electric field is non-uniform. The process of electrical breakdown in gases can be seen from Figure 7-5. It is divided into three stages, namely recombination, secondary ionization and breakdown.

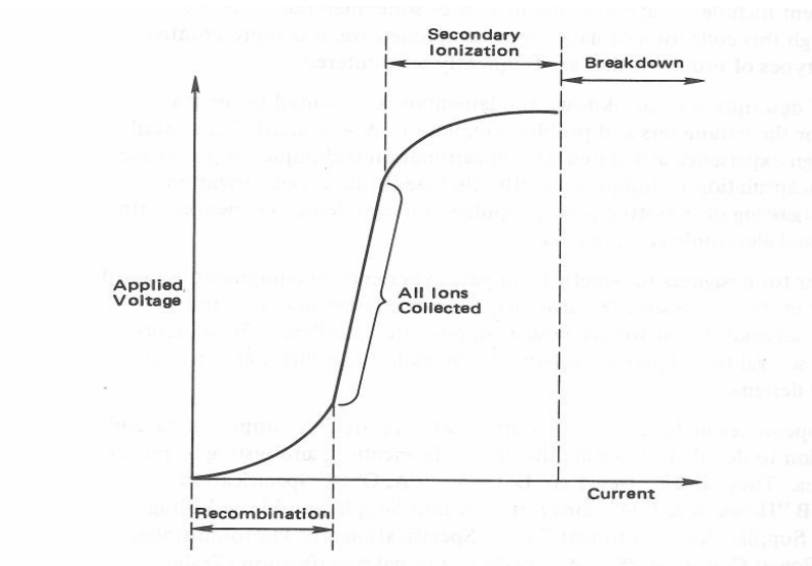


Figure 7-5 Voltage-Current Characteristic for a Gas in a Uniform Electric Field[28]

In the first area which is labelled recombination where the electrons released from a cathode by radiation. Then, this free electron collides with the natural air molecular and produces a new electron and a positive ion. In the second ionization stage, the electrons increase enormously by collision and photo ionization. The amount of electrons is related to the ionization coefficient and the distance at within which the electrons travel. The next region is breakdown. The current increases sharply due to the production of additional electrons at the cathode.

In an aircraft, an electrical discharge risk will occur in air gap which may be between connector pins, between uninsulated busbar or between the insulated cables. According to the Parschen's law, the breakdown voltage varies with the product of air pressure and the distance of the air gap. It can be seen from the Figure 7-6 that the breakdown voltage goes through the minimum value at a certain p.d. product. As for an aircraft, all the air gaps which are under an electric field will pass the minimum twice due to the air pressure variation.

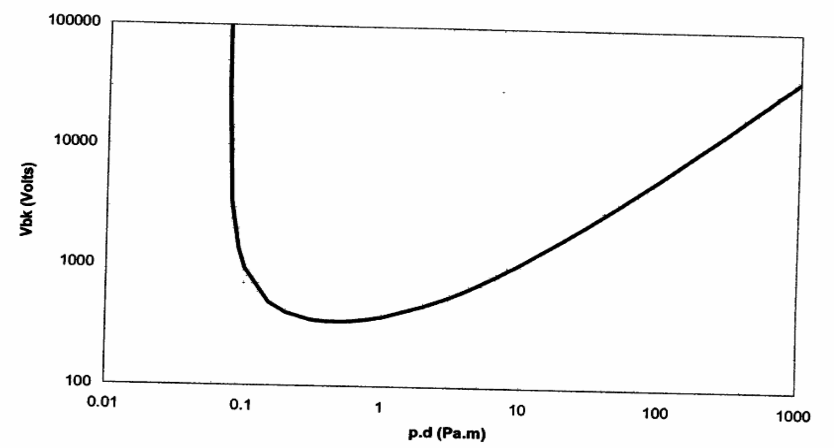


Figure 7-6 Breakdown Voltage in Air for Given Air Pressure-Distance Product [13]

Based on the paschen's law, it can be found that the higher voltage, the higher partial discharge (corona) risk will be at a given air pressure and gap distance conditions. As described in ref[26],"corona-safe voltage levels are considered to be 300volts in unpressurized areas at altitudes up to 30Km(100,000ft) and a max of 700 volts for a base conductor in pressurized areas." According to the aircraft electric power characteristics standard MIL-STD-704F[1], the acceptable voltage threshold of 115V power is 180volts whereas the acceptable voltage of 270V system is as high as 330 volts. Therefore, the 270VDC power is more dangerous than 115VAC power in terms of corona discharge. As for this case study, the 270VDC system is also more dangerous than 115V system since the larger proportion of 270VDC power is used in the system which is based on the 270VDC generating system.

Another aspect need to be highlighted is that the probability of corona discharge is most likely appears in flight when the aircraft climbs[29]. According to townsend mechanism [25], the breakdown phenomenon only occurs at where the pd product is less than 1,000 torr-cm.

7.7.3 Arcing

Arcing danger is a much greater concern compared to other types of electrical faults since it is difficult to be detected by the overcurrent protection devices. The reason is that the faulted current is limited by its impedance. The arcing discharge produces a large amount of heat which will damage the structure.

Compared to AC system, a DC system is more apt to sustain an arc since there is no natural commutation in a DC system. A comparison experiment has been conducted by RAE [34], the results show that the sustained arc length of the 200V DC system is longer than that of 200V AC system. Meanwhile, the heat generated by the arcing discharge in the DC system is more than that of AC system.

Therefore, the 270DC system is generally more dangerous than 115VAC system. In terms of this case study, the electric power system which is based on the 270VDC generating system is more dangerous than that one which is based on 115V/VF generating system since the larger percentage of 270VDC power is used in the former system. Moreover, more space will be required for the cable installation in terms of the 270VDC system because sufficient clearance between wires and structure is required for the sake of avoiding sustained arc.

7.8 System Comparison

7.8.1 Introduction

As the system performance has been evaluated, the comparison between these two systems focuses on their relative merits. Because all the comparison factors are not of the same importance level for aircraft design, it is necessary to distinguish the importance priority firstly and allocate a weight factor to each comparison aspect. Finally, those two systems will be evaluated and give a conclusion for the selection of electric power system for this case study.

7.8.2 Weight Factor Allocation

As regards a commercial aircraft, safety is the first priority for commercial aircraft design, followed by cost. System performance is less important than other factors. Therefore, the weight factor of each comparison point will be roughly given below (Table 7-6):

Table 7-6 Relative Merit Assigned

Characteristics	merit (percentage)
Reliability	20
Risk	20
Cost	15
Weight	15
Voltage Drop	10
Power off take	10
Minimum VA rating	10

7.8.3 Comparison

The weighting factors mentioned in Table 7-6 are used to compute the system merit for comparison. System merit equation is shown as below:

$$FM = \sum \alpha_i W_i$$

Where, FM is the figure of merit

α_i is the weighting factors.

W is the relative value for a comparison point

In this case study, the relative value given to the comparison point will be in accordance with the following criteria.

(1) If system A is better than system B in term of a comparison point, the relative value for system A is 10 whereas the value for system B is 1 and vice versa.
(2) If the superiority is only valid under certain circumstance, then the relative values for both systems are 5.

Therefore, the figure of merit of each system will be tabulated as below:

Table 7-7 System Comparison

System	Reliability	Risk	Cost	Weight	Voltage Drop	Power off take	Minimum VA rating	Total score
115V/VF	5	10	5	1	1	1	10	4.2
270VDC	5	1	5	10	10	10	1	5.55

As can be seen from Table 7-7, it can be concluded that the 270VDC system is better than 115V/VF system based on what have been discussed in this project.

8 Discussion

8.1 System Architecture Design

In terms of system architecture design, the main difference between these two generating systems is the capability of parallel operation. The power supply quality of 270VDC is better than that of variable frequency system since the 270VDC has the capability to provide uninterrupted power to the loads while the variable frequency system can not provide uninterrupted power. The uninterrupted power is crucial for MEA and AEA since the majority of electronic circuit is sensitive to power interruption. Thus, the 270VDC system is better than 115V/VF system from the power quality point of view.

However, if the generators of the 270VDC system are designed to run in parallel, the system control strategy will be more complex than that of 115V/VF system. Moreover, the overall system capacity is affected by the division circuit accuracy. In this case study, the system overall capacity will be less than 498KW if the two main generators operate in parallel.

8.2 Wiring System

As regards wiring system design, the total number of wires used in 270VDC system is less than that of 115V/VF system. One reason is that those loads whose power requirements are more than 0.5KVA are required to be powered by three-phase balanced power. The other reason is that the load current decreases as the increase of voltage. The possible drawback in wiring system design is that the conventional wire which is originally for 115V system is considered to be suitable for 270VDC system since the insulation technology has not been studied in detail in this project due to time restrictions.

8.3 System Performance

8.3.1 System Weight

With respect to system overall weight, the 115V/VF system is 1.3 times the mass of 270VDC system. However, this figure is not precisely enough since not all the system elements are taken into account.

As far as the weight of generator is concerned, 270VDC generating system is heavier than 115V/VF generating system. Firstly, the power weight ratio of 270VDC generator is lower than that of 115V/VF generator since the rectification unit is required for 270VDC generator. But, the power weight ratio of 270VDC generator can be improved by increasing power frequency. Secondly, the VA capacity of the 270VDC generator is more than that of 115V/VF generator even both of them produce the same amount of output. The reason is that the utilization factor and imperfect commutation need to be considered for the rectification unit.

In terms of the wiring weight, the 270VDC system has an advantage over 115V/VF system. This is also the major merit of utilizing the 270VDC system. There is one limitation in this result. The insulation thickness difference has not been considered, which will cause a difference in mass.

As for the weight of power conversion equipment, there is a slight difference between those two systems. This result is not always valid since the power weight ratio of the power conversion equipment is governed by the state of the arts power electronics technology.

8.3.2 Voltage Drop

As far as the voltage drop is concerned, it reveals the power loss in the conductor. The higher the voltage drop the more power loss in the conductor. For a conductor whose size is bigger than AWG-2, skin effect should be taken into account when it carries AC current. Here, the wire resistance change caused by the temperature has been neglect. In practice, temperature factor should be taken into account.

8.3.3 Minimum VA Requirement

In terms of the minimum VA requirement, the minimum VA requirements for both generators are nearly equal even the power requirement of those two systems is much different at the P.O.R. The reason is that the utilization factor and the imperfect commutation need to be taken into account in terms of the 270VDC brushless generator. In this case study, the commutation overlap angle is not exactly known since the transient inductances of the winds are not known. In practice, this overlap angle can be measured by oscillograph. However, it is important that the lower transient inductance of winds, the smaller overlap angle. However, the lower transient inductance will cause higher fault current. Furthermore, the semiconductor characteristics is also affected by temperature. In this case study, this factor has not been considered.

8.3.4 Power off-take

In terms power off-take, the 270VDC system is superior to 115V/VF system. From the results, it can be seen that the 270VDC system has higher efficiency in power transmission. However, the 270VDC generator has lower efficiency due to the rectification loss. From this point of view, the advantage of utilizing 270VDC will be more obvious if the cable becomes longer. In this case study, the power loss in power conversion equipment has not been considered since the efficiency of the power conversion equipment varies with the exact circuit.

8.3.5 Reliability

As regards the 270VDC system, a quantitative analysis shows that the reliability of primary power part is lower than that of 115V/VF system if both systems are considered to be standby redundant system. However, if the primary power part of 270VDC system is considered to be active parallel redundancy, this result mentioned above might be doubtful. Therefore, the numerical analysis needs to be conducted. In this project, the reliability of the power conversion part has not been considered.

There are some limitations in this reliability analysis. According to the reliability definition, the system reliability is the product of the reliability of each type of power supply. As can be seen from Figure C- 4 to Figure C- 11, there is a common part in these figures, which is the primary power source part. Thus, the resulting system reliability is underestimated. Moreover, the reliability of the power conversion part has not been considered. Meanwhile, since the electrical wires slightly affect the system reliability, the reliability of wires did not be taken into account when building the system reliability model. Finally, some aspects need to be taken into account for reliability analysis in practice, these aspects refer to the component part stresses, the environmental conditions, special operating conditions and so on and so forth[14]. But, all these factors are neglected in this case study.

8.3.6 Life Cycle Cost

A qualitative analysis shows that the 270VDC system has an advantage over 115V/VF system in terms of life cycle cost. But it needs to notice that the initial cost of 270VDC system will be higher than that of 115V/VF system due to the higher risk. Furthermore, some conventional system components are not suitable for 270VDC system. Due to limited time, a numerical analysis can not be conducted at this stage.

8.3.7 System Comparison

The result shows that the 270VDC system is more suitable for future use in MEA and AEA. However, there is still some limitations in the result. The first one is that the value of the relative merit is roughly considered since the some of the aspects are only qualitative analyse. If all the aspects are quantitative analysis, the cost basis method [26] can be used to precisely determine the value of the relative merit. Thus, the more reliable result can be obtained. But one thing need to noted is that the method used in this section is valuable than the numerical results.

9 Conclusion

9.1 Conclusion

This project studied the relative merits of utilizing 270VDC system and made a comparison with the 115V variable frequency system, the all-electric aircraft Flying Crane was chosen for this case study. The results show that the 270VDC system is more suitable for future use in more or all electric aircraft.

With respect to the primary power distribution architecture design, the main difference between these two generating systems is the capability of parallel operation. The power supply quality of 270VDC is better than that of variable frequency system since the 270VDC has the capability to provide uninterrupted power to the loads.

In terms of system wiring system, the total number of wires used in 270VDC system is less than that of 115V/VF system. One reason is that those loads whose power requirements are more than 0.5KVA are required to be powered by three-phase balanced power. The other reason is that the load current reduces as the increase of system voltage.

The main advantages of utilizing 270VDC system are the weight saving as well as power loss reduction in wiring system. However, the 270VDC generator is heavier than 115V/VF generator due to the differences in VA rating and power weight ratio of the generator. From this point of view, the 270VDC system is more suitable for large aircraft rather than the small one due to the difference of the length of wires. Furthermore, this more weight and energy can be saved as the increase of load requirement.

The main disadvantage of utilizing 270VDC system is the higher risk in arcing danger and partial discharge compared to 115V/VF system

As regards the system reliability, the major difference between those two systems designed in Chapter 5 is that the 270VDC system can be designed as either an active parallel system or a standby redundant system while 115V/VF system can only be designed as a standby redundant system. Due to lack of data regarding components' reliability, the numerical result can not be obtained. However, it should be noted that the 115V/VF generator is inherent more reliable than 270VDC generator. Furthermore, the failure probability of the changeover unit needs to be considered for the standby redundant system. Therefore, the precise conclusion can only be got via quantitative analysis.

The limitation of this study is that the only limited components of the electric power system have been studied. Another aspect is that the effects on load when changing the power type have not been studied in this project. In order to obtain a more precise result, those factors need to be considered. An aspect should be noted that the methods used in this project is more valuable than the numerical results since the accurate data of the components is hard to obtained within this limited period.

9.2 Recommendation

The work done in this project addresses some results on the relative merits of utilizing different types of primary power. But all the aspects can not be covered within such short period. Therefore, the author would like to recommend those aspects which are worth to be studied further in the future.

- The numerical cost analysis is worth to be investigated in the future, since this is an every important parameter for a commercial aircraft design.

- In order to get more accuracy weight of the wires, the insulation technology for 270VDC application is worth to be investigated.

- Since the power type of the electric driven compressor is optimized with the primary power source, the performance of the electric driven compressor should be evaluated under these two types of power supply conditions. Moreover, the study scope can be extended to various types of load.

- In chapter 2, two types of 270VDC generating system have been mentioned. In the future, more efforts can be put on the switched reluctance generating system.

- The methods to cope with the arcing and corona discharge are also worth to study further.

- As for the system reliability, the major difference between 270VDC system and 115V/VF system has been mentioned. In order to obtain accurate result, it is worth to conduct the quantitative analysis in terms of active parallel redundant system and standby redundant system.

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APPENDICES

Appendix A-Group Design Project

Environmental Control System Preliminary Design of 130-seat Civil Aircraft Flying Crane

ABSTRACT

This section focuses on the author's work in group design project which is about the environmental control system (ECS) preliminary design. The design philosophy of these two systems is based on all electric aircraft concept.

The design procedures were complied with the system engineering process. The requirement analysis was conducted at the beginning, followed by system function definition. After that, the system architecture design and components initial sizing were performed. Finally, system safety issue was evaluated by means of preliminary system safety analysis (PSSA).

In terms of environmental control system, the all electric environmental control system has been considered. Thus, the pneumatic system has been eliminated. As a result, the efficiency of the engine can be increased. Meanwhile the specific fuel consumption can be reduced. In this preliminary phase, the system architecture has been built and the mass flow rate as well as the air temperature has been determined. The air distribution system also has been designed. Finally, the emergency oxygen system also has been considered.

Keywords:

Environmental, System, Architecture, Pneumatic , Preliminary design.

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T_c

ABBREVIATONS

ACM Air Cycle Machine

ECS Environmental Control System

PSSA Preliminary System Safety Assessment

FTA Fault Tree Analysis

FHA Functional Hazard Analysis

Symbols

M Mass flow rate of air (kg/s)

C_p Specific heat capacity of air at constant pressure(J/kgK)

T_i Inlet temperature (K)

T_e Exit temperature (K)

H_w Heat transfer through the walls (Kw)

H_s Solar heating (Kw)

H_p Sensible heat from occupants (Kw)

H_e Heat from electrical equipment (Kw)

U_i Heat transfer coefficient W/m^2

A_i Surface area (m^2)

T_c Inside cabin temperature (K)

T_s Outside skin temperature (K)

M_a	Flight mach number
T_{amb}	Static temperature of the atmosphere
r	Temperature recovery factor
γ	Specific heat capacity
M_s	mass flow rate from the air conditioning pack
T_s	outlet temperature of the air conditioning pack
T_r	the temperature of the re-circulated air
M_r	mass flow rate of the re-circulated air
M_{in}	mass flow rate supplied to the cabin
T_{in}	inlet temperature of the cabin
ρ	the density of the fluid (kg/m3)
V	The velocity of the fluid (m/s)
A	area of the duct cross-section.
D	Diameter of the duct

I Requirements Analysis

I.1 Airworthiness Requirement

As the airworthiness regulation CCAR25 has been chosen for this project, the relevant airworthiness regulations about environmental control system are : CCAR25.831, CCAR25.832, CCAR25.841, CCAR25.843, CCAR25.1309,CCAR25.1439, CCAR25.1441, CCAR25.1443, CCAR25.1445, CCAR 25.1447,CCAR 25.1449, CCAR 25.1450, CCAR 25.1453.

I.2 Customer Requirement

The fundamental requirement for customer is also low cost. Meanwhile, as regards environmental control system, the passenger comfort is another major aspect which is required by customers.

I.3 Operational Requirement

When designing the environmental control system, the ambient air properties are the fundamental aspect which is directly relevant to the ECS operating parameters. According to the statistical data[13], the extreme conditions which are shown below (Figure A- 1)have been considered for our Flying Crane ECS design.

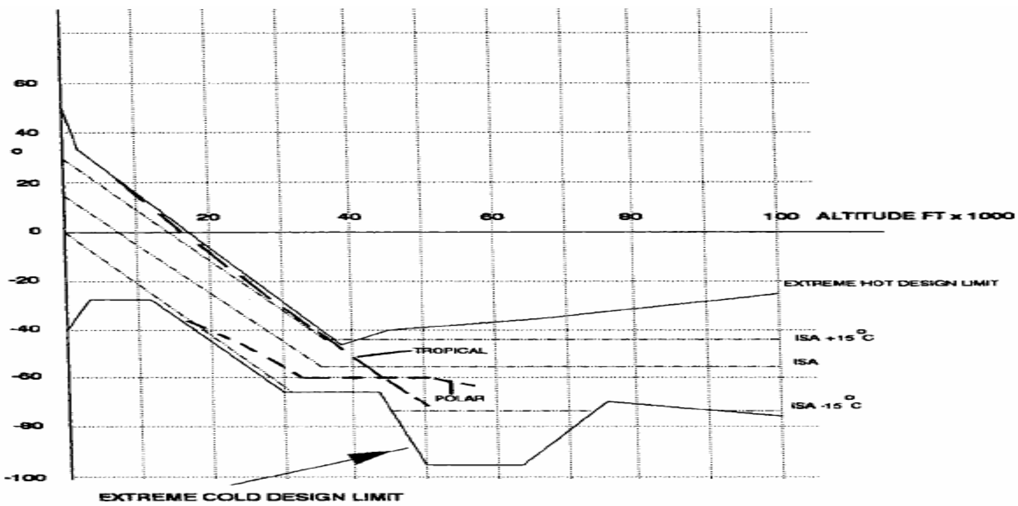

Figure A- 1 Ambient temperature versus altitude[13]

I.4 Performance Requirement

(a) Temperature Requirement

The human body is very sensitive to the temperature and humidity, In order to provide comfortable environment for the occupants, the temperature of the cabin needs to be well controlled, According to the thermal comfort envelope for human occupancy(Figure A- 2), the comfortable temperature generally will be between 20℃ and 26℃.For this reason, the mean temperature of Flying Crane will be 23℃ in order to increase the comfort of the passengers.

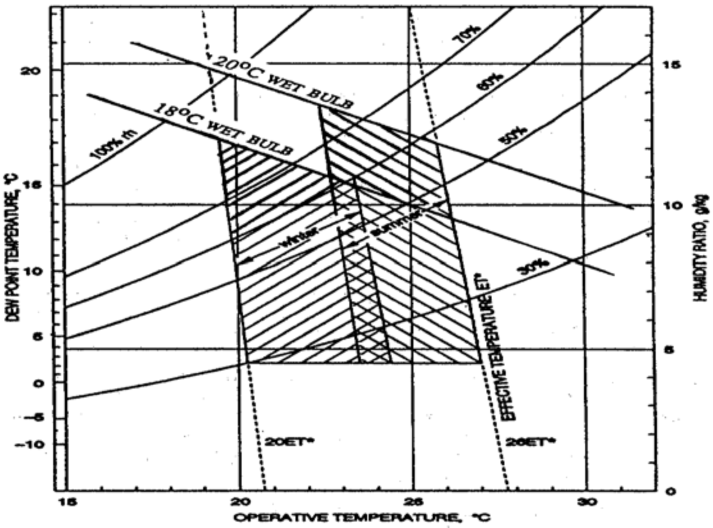

Figure A- 2 Thermal Comfort Envelope[5]

(b) Humidity Requirement

From the airworthiness regulation, there is no specific requirement about the cabin humidity, but humidity is often perceived as the main comfort degradation for the passenger [11]. From the comfort standards, it is recommended that the relative humidity should not be lower than 30%[11].

(c) Contaminants Requirement

According to CCAR25.831 and CCAR23.832, it stipulates the concentration requirement of several types of contaminants.

(d) The cabin pressure will never exceed 8000ft(2400m)at the altitude of service ceiling under normal operation according to CCAR25.

(e) Since rapid pressure change will result in passengers discomfort at eardrum or intestines etc. the cabin pressure change rate is required to be well controlled .It is required that the pressure change rate is limited to no more than 1000ft/min when climbing and 450ft/min when descending[5].

(f) Cabin pressure fluctuation is required to not more than 20mm Hg[8].

(g) Negative pressure should not exceed 0.5psi[7].

I.5 Physical and Installation Requirement

(1) Pressurization valves should be installed at the ice-formation areas.

(2) As regards the outlet valves installation, it should consider that water can not enter the fuselage in the event of aircraft being ditched [7].

(3) Oxygen pressure tanks, ducts and shut off valves should be installed at the place where the probability and hazards of rupture in a crash landing are minimized [2].

(4) Oxygen equipment must never be installed in the same place as oily matter, oil and fuel pipes.

(5) The container should be installed outside the cabin. Furthermore, the distance between container and inflammable material should be at least 1m[8].

(6) The oxygen indicator and pressure gauge should be located at where it is convenient for pilot observation.

I.6 Maintainability Requirement

The following aspects need to be considered.

(a) Accessibility for servicing and inspection.

(b) Means of fault detection need to be considered during system design.

II Function Definition

The primary function of environmental control system is to provide livable conditions for all the occupants. It is can be seen from Figure A- 3, this system contains the following sub-functions.

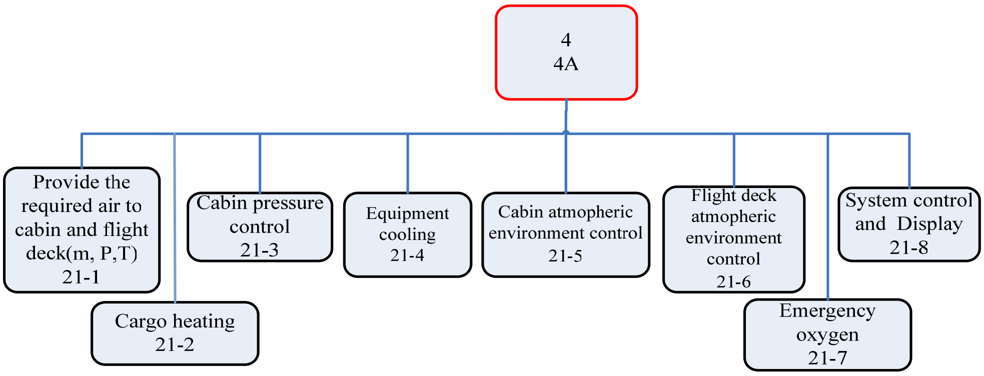

Figure A- 3 ECS Top Level Function

In the graph (Figure A- 3), 4A is the aircraft level function code which stands for aircraft level function-control atmosphere. The following paragraph will describe all these functions respectively.

Provide the required air source: In order to maintain comfortable environment inside of the aircraft, air acts as the media for transferring heat into or out of the cabin. The air properties (P,V,T) are required to meet the requirements.

Cabin pressure control: In order to keep passenger healthy, it is required to maintain the sufficient oxygen partial pressure in lung. This function is designed to maintain cabin air pressure at certain level.

Equipment cooling: Operating electrical/electronic equipment generates heat. Equipment which has been exposed to heat for prolonged periods of time can experience shortened life and premature failure. The equipment cooling system removes the heat through the use of cooling airflow.

Cargo heating: This function is designed to properly keep the temperature of cargo compartment.

Cabin atmospheric environment control: In order to meet the requirement of passenger thermal comfort and health. The cabin air quality (temperature、humidity、contaminants) is required to be well controlled.

Flight deck atmospheric environment control: According to CCAR25.831(f), since the total internal volume of Flying Crane is more than 23m^3, the fight deck and cabin are required to be ventilated independently. So the contents of this function is the same as the cabin atmospheric environment control function.

Emergency oxygen: This is designed to supply supplement oxygen during emergency cases such as depressurization and fire and so on.

System control and display: This function is design to provide the man-machine interface for flight crew.

All of these functions will be implemented by the following three sub-systems, namely air conditioning, pressurization and emergency oxygen system.

III Air Conditioning

III.1 System Architecture Design

III.1.1 Air Supply

The compressed fresh air which comes from ambient air is required for pressurization and the air conditioning system. There are different methods can be used to provide the required compressed airflow.

(1) conventional bleed system
This kind of system has been used in the majority of current commercial aircraft. The compressed air directly comes from the compressor of the jet engine. Most bleed-air systems have at least two extraction ports. One locates near the end of the compressor to get the highest possible pressure when the engine operates at low speed. The other locates near the medium stage of the compressor to get the adequate pressure during normal cruise[1].

This type of system has been used for so many years. The disadvantage of this system is that it is largely effect on engine performance. Also the bleed air could be a contaminated source of the cabin air due to the engine fluids leakage.

(2) Air supplied by the electrically driven compressor
This kind of system provides the required compressed air by utilizing the electric-driven air compressor. In this system, no bleed air is extracted from the engine. This kind of system has been used successfully in the dreamliner B787.

This kind of system is more efficient than the conventional bleed air system, because it avoids excessive energy extraction from the engine. This disadvantage of this kind of system is that additional weight is required since motors are required for this kind of system.

In terms of the design philosophy of Flying Crane, fuel efficiency is considered to be the first priority. In terms of the off-take power, whether it is pneumatic power or shaft power will affects the specific fuel consumption. From the Figure A- 4, it can be found that pneumatic power requires more fuel than that of shaft power for a given amount of off-take power.

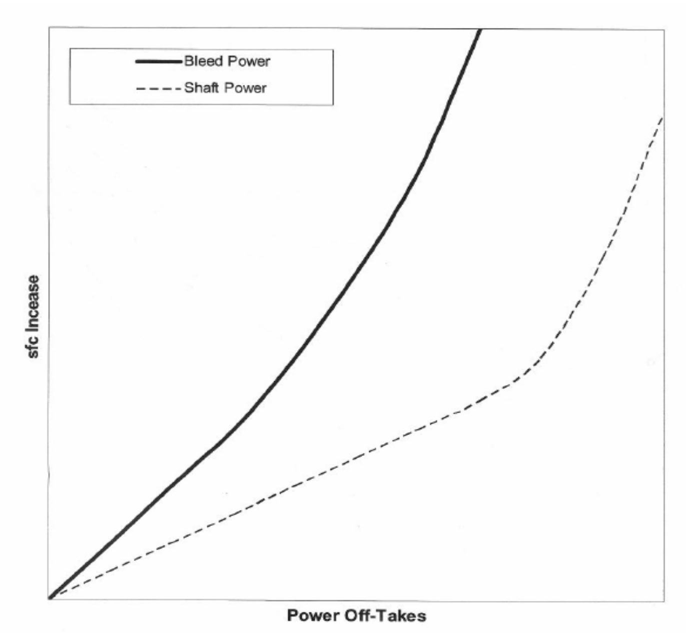

Figure A- 4 Power Off-Takes Versus Specific Fuel Consumption[12]

From what has been discussed above, the required airflow for air-conditioning and pressurization will be provided by electric-driven compressors. Furthermore, in order to save energy, the recirculation system is adopted in the environment control system of Flying Crane.

III.1.2 Method of Air Conditioning

Air taken from the electric-driven compressor is of high temperature and high pressure. It needs to be adjusted to the required value before delivering to the cabin and flight deck. This function is accomplished by air conditioning pack which consists of air cycle machine (ACM), heat exchanger, ozone remover and water separator. As regards ACM, there are many types of ACM which will be discussed below.

(1)Turbo-fan Air Cycle System.

This kind of system consists of a high speed turbine driven fan, which is used to boost the flow of the coolant air through a heat exchanger. The pros and cons of this type of system are listed below (

Table A- 1).

Table A- 1 Turbo-fan Air Cycle System

Advantage	Disadvantage
No inner cooler requirement, which results in a weight saving and reduction of cooling drag.	High running speed which requires stronger mechanism.
Small in size	Higher air pressure required, at least 70psi[7]
Light weight	

(2) Bootstrap Air Cycle System

This system consists of a primary heat exchanger, a secondary heat exchanger, a compressor and a cooling turbine. Firstly, the compressed air is pre-cooled by a primary heat exchanger. Then the compressor is used to compress the air in order to increase its temperature and pressure. Afterwards the air enters the secondary heat exchanger. Finally, the air enters the turbine section. The advantages and disadvantages of this kind system are listed below (Table A- 2).

Table A- 2 Bootstrap Air Cycle System

Advantages	Disadvantages
Higher efficiency compared to the basic turbo fan system	Very little cooling can be achieved on ground working due to lack of ram air.
Reliable	
Mature technology	
Larger temperature drop can be obtained	

(3) Vapour cycle system

The vapour cycle system is closed-loop. The major parts of this type of system are evaporator and condenser. The fundamental principle of this kind of system is that heat is absorbed by coolant evaporation. The pros and cons of this kind of system are briefly listed below (Table A- 3).

Table A- 3 Vapour Cycle System

Advantages	Disadvantages
Lower Pressure Required	High in mass
More Energy Efficient	Toxic coolant
Low noise output	Maximum operating temperatures of the refrigerants are too low
Ease of moisture removal	

For the reliability and environment friendly reasons, the bootstrap air cycle system is the optimal choice for Flying Crane according to the comparison of these three types of system.

III.1.3 Temperature Control

III.1.4 Zone Control

In order to improve the accuracy of temperature control, the aircraft cabin can have up to seven separate ventilation zone[1]. In terms of the current commercial aircraft, the ECS of A320 has two separate ventilation zones. The ECS of B757 also has two separate ventilation zones as well as the B737. As regards Flying Crane, the cabin is also divided into two separate ventilation zones.

III.1.5 Means of Temperature Control

(1) Pack temperature control
The air conditioning pack provides the means to cool the hot air taken from the electric-driven compressor. This is done by the primary heat exchanger and the secondary heat exchanger. The pack temperature control is achieved by adjusting the cooling medium intake flow rate.

(2) Trim air control
Trim air is directly extracted from the high pressure and high temperature stage of the ECS. Trim air control is a supplement method to control the temperature of each cabin zone. Before delivering to each cabin, the air will be mixed with the trim air in order to adjust the cabin inlet temperature to the desired value.

In conclusion, the method used to control cabin temperature is a combination of pack temperature control and trim air control.

III.1.6 Cargo Heating

Taking Airbus-A320 as reference, the cargo compartment is ventilated by the air both from the trim air and the cabin air.

III.1.7 Equipment Cooling

In order to ensure the safe operation of avionics equipment, adequate cooling for those equipment is required. In a civil aircraft, the heat load of avionics equipment is relatively low. Normally, the avionics equipment is ventilated by the exhaust air from the flight deck.

III.1.8 Emergency Ram Air Inlet

Here, ram air is used for ventilation purpose in the event of the failure of all air conditioning packs. This kind of system only runs when the aircraft descends to an altitude of 10,000ft or even below. Taking the system which is used in Airbus A320[6] as reference, it is decided to shared the inlet ducts with the one which is used for ground inlet.

III.1.9 System Architecture

According to what have been discussed above, the schematic of environmental control system is shown in Figure A- 5. Two electric-driven air compressors provide the air source. Each compressor can provide the required air source. Then, two air conditioning packs are designed to provide the required air for cabin ventilation. In the event of one pack failure, the other one can provides the required air. In the emergency case, the emergency ram air inlet can provide the ambient air for cabin ventilation.

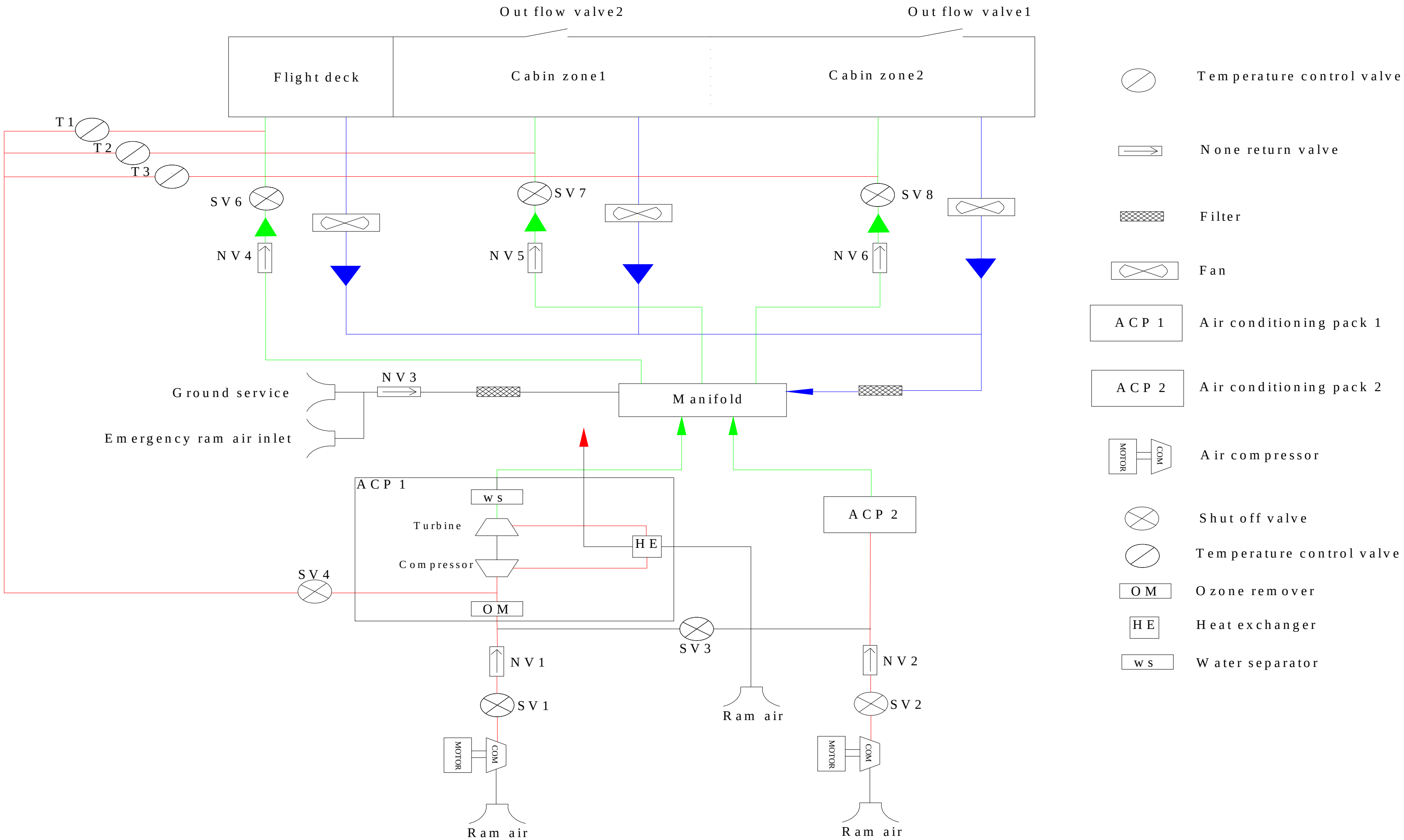

Figure A- 5 Environmental Control System Schematic Diagram

III.2 Initial Sizing

III.2.1 Introduction

The air mass flow rate and temperature are the two most important parameters for an environmental control system, which is not only used to determine the parameters of air conditioning pack but also used to compute the size of air distribution ducts. This section mainly represents the sizing process.

III.2.2 Mass Flow Rate

Flying Crane is a medium to short haul jet liner, which can fly across 2000 nautical miles. The air flow rate is based on maximum aircraft altitude and the associated design conditions. In order to determine the total mass flow rate that has to be supplied to the cabin and flight deck, the following parameters of the aircraft have been considered.

Maximum number of passengers: 150+6(cabin crew)

Service ceiling: 43,000 ft

Cabin altitude: 6,000 ft

Cruise speed: 0.78M

The air flow and inlet temperature is based on the cabin steady state heat balance equation[9]:

$$M \cdot C_P(T_i - T_e) + H_w + H_s + H_p + H_e = 0$$

Where:

M: Mass flow rate of air (kg/s)

C_p: Specific heat capacity of air at constant pressure(J/kgK)

T_i: inlet temperature (K)

T_e: Exit temperature (K)

H_w: Heat transfer through the walls (Kw)

H_s: Solar heating (Kw)

H_p: Sensible heat from occupants (Kw)

H_e: Heat from electrical equipment (Kw)

This equation normally is used to determine the inlet temperature at a fixed flow rate. However, it also enable to determine the mass flow rate with a given inlet temperature.

He   He is generated almost entirely by the electrical equipment which is installed in the cabin and flight deck and dissipated by heat.

$$He = \alpha * (\text{electrical load in cabin})$$

$$\alpha = 0.85 \text{ [15]}$$

H_p: Human body temperature is higher than ambient temperature under normal circumstances. As such, human emit heat by conduction, convection and radiation. Total human heat output varies from about 70w at rest to approximately 650w depending on level of activity.

H_s: The radiation heat from the fuselage is very small and shall therefore not be considered as the emissivity of the fuselage is small and although the radiation heat is proportional to the fourth power of temperature. The temperature of the fuselage is very low. The effects of solar radiation, however are important and should be taken into account.

Typical data are shown below[15]:

transparencies(Sea level)………………………… …..1.2KW/m^2

transparencies(at altitude)…………...………………..1.5KW/m^2

cabin wall(predominantly light colour)…………… ….0.1kw/ m^2

H_w This is the heat transfer through the cabin wall. Normally, the wall consists of inner liner and heat absorbing insulation material. Heat transfer from inside the cabin to the first layer and then is conducted through the first layer, and it is conducted through the second layer as well, and is conducted in the last layer from which heat from skin to outside atmosphere[9; 15].

The heat transfer through the materials can be determined by the following equation:

$$H_w = -\sum_i U_i \cdot A_i \cdot (T_c - T_s)$$

Where:

U_i Heat transfer coefficient W/m^2

A_i Surface area (m^2)

T_c Inside cabin temperature (K)

T_s Outside skin temperature (K)

The typical values of conductivity for different parts of the aircraft are listed below:

windscreen heat conduct coefficient: 6.8 w/m^2 • K

windows heat conduct coefficient: 2.7 w/m^2 • K

wall heat conduct coefficient: 1w/m^2 • K

T_s It is an aerodynamic heating, when the aircraft skin heats up due to friction between itself and air molecules. The skin temperature will rise till it reaches a certain value which is called recovery temperature T_r.

It is determined by the mach number and ambient temperature:

$$T_{skin} = T_r = T_{amb} \cdot \left(1 + r \cdot \frac{\gamma - 1}{2} \cdot M_a{}^2\right)$$

Where,

M_a : flight mach number

T_{amb} : static temperature of the atmosphere

r : temperature recovery factor, =0.9 for dry day

γ : specific heat capacity =1.4

Since the aircraft flies over a wide range of altitude, speed, and ambient conditions, it is necessary to consider the extreme conditions to determine the operational parameters. Therefore, the following cases are considered:

Extreme hot day, ground case

Cold night, ground case

Extreme hot day, flight case

Cold night, flight case

Case1: ground case(Hot day)

Hot day ISA+35℃

H_s: Assume half of the acreage effective

Table A- 4 Heat load H_s-Ground cooling case

Compartment	Transparency(m^2)	Skin(m^2)	Heat load(Kw)
Flight deck	0.5244	31.776	(0.5244×1.2+31.776×0.1)/2= 1.904
Cabin	3.2817	350.399	(3.2817×1.2+350.399×0.1)/2 =19.5

H_p Here, we assume that the heat load for each pilot is 400W and 120W for each passenger.

Table A- 5 Heat Load H_p-Ground cooling case

Compartment	Occupants	Heat load（Kw）
Flight deck	2	400×2=0.8
Cabin	150+6(crew member)	120×156=18.72

H_e : Here, the total cockpit equipment power requirement is from the electric power system load analysis.

Table A- 6 Heat Load H_e-Ground cooling case

Compartment	systems	Heat load（Kw）
Flight deck	Cockpit equipment	2.35×0.85=2
Cabin(estimate)	cabin equipment	5.88×0.85=5

H_w Since aircraft operates on the ground, the skin temperature equals to the ambient temperature.

So: For flight deck: H_w =-0.0353(296.15-323.15) =0.9531Kw

For cabin: H_w =-0.359(296.15-323.15) =9.693Kw

Assume that Cp=1000J/Kg • K

Table A- 7 Heat load H_w –Ground cooling case

Compartment	Window(m2)	Wall(m2)	Coefficient(Kw/K)
Flight deck	0.5244	31.776	0.0353
Cabin	3.2817	350.399	0.359

Here, In order to determine the inlet temperature, the minimum mass flow rate (0.25kg/min/pers) required by CCAR25.831 is used. Based on the cabin heat balance equation, the inlet temperature can be found out:

Table A- 8 Initial Mass Flow Rate and Inlet Temperature-Ground Cooling Case

Compartment	Airflow rate(kg/s)	Temperature(K)
Flight deck	0.0083	-433.5K
cabin	0.65	207K

If the inlet air temperature below 0℃（273K），It is unreasonable. So the mass flow rate should be recalculated as follow:

Table A- 9 Final mass flow rate and inlet temperature-ground cooling case

<table>
<tr><td colspan="2">Inlet temperature(℃)</td><td>0</td><td>5</td><td>10</td></tr>
<tr><td rowspan="2">Mass flow rate(kg/s)</td><td>Flight deck</td><td>0.258</td><td>0.327</td><td>0.449</td></tr>
<tr><td>cabin</td><td>2.464</td><td>3.13</td><td>4.3</td></tr>
<tr><td colspan="2" rowspan="2">Average flow rate (kg/min/pers)</td><td>7.74</td><td>9.81</td><td>13.47</td></tr>
<tr><td>0.947</td><td>1.204</td><td>1.654</td></tr>
</table>

Using the same method, all the required results can be determined in various cases. Here, the minimum mass flow rate is used to determine the inlet temperature. So, the results are shown in Table A-10.

Table A- 10 Final Mass Flow Rate and Inlet Temperature-Other Cases

Case	Compartment	Conditions	Min Airflow rate(kg/s)	Temperature (K)
Case2	Flight deck	cold night(ISA-55℃) Ground Operation	0.0083	181.2
	Cabin		0.6486	287.5
Case3	Flight deck	ISA-55℃(cold night) Cruise speed: 0.78 ma Altitude: 43,000ft	0.0083	190
	Cabin		0.6486	288
Case4	Flight deck	ISA+35℃(hot day) Cruise speed: 0.78 m Altitude: 43,000ft	0.0083	133
	Cabin		0.6486	246.4

From the results above, it can be seen that the inlet temperature is too low which will cause frozen problem and reduce passenger comfort. Then we consider that the mass flow rate needs to increase in order to minimize the value of temperature difference between inlet temperature and cabin inside temperature. Here, we compute the inlet temperature based on the given mass flow rate which increases each time by 0.01kg/min/pers from the 0.25kg/min/pers (the minimum mass flow rate) to 15kg/min/pers. The result is shown in Figure A- 6 and Figure A- 7.

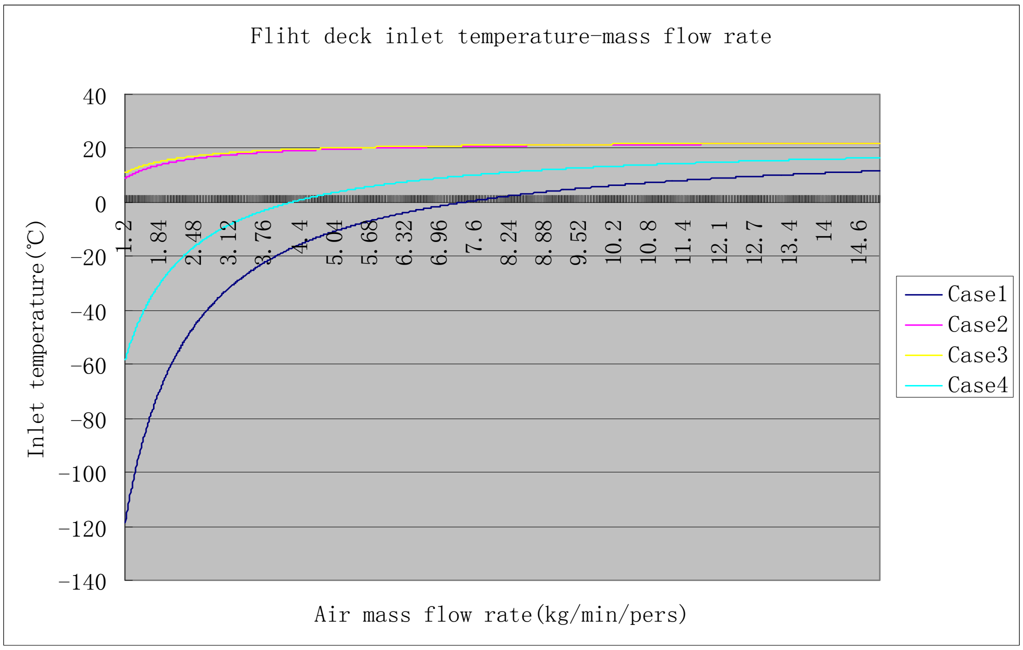

Figure A- 6 Flight Deck Mass Flow and Inlet Temperature

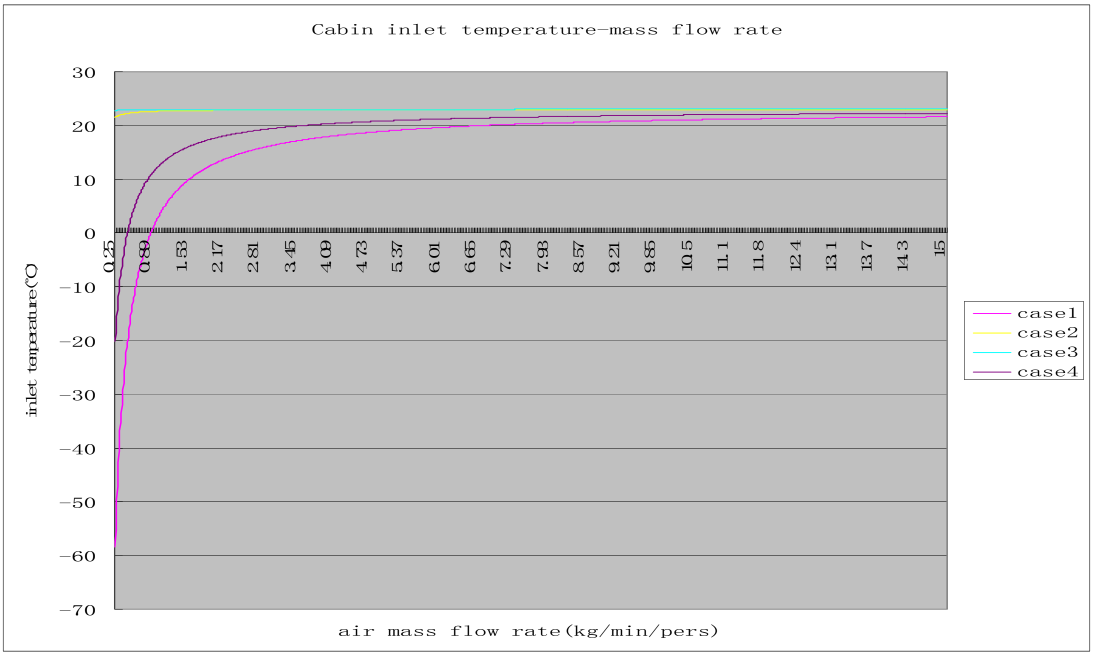

Figure A- 7 Cabin Mass Flow and Inlet Temperature

In terms of thermal comfort of the passengers, it is recommended that the inlet temperature should be higher than 10℃[1]. From Figure A- 6 and Figure A- 7, it can be found that it is required to supply the largest amount of air to cabin in case1 in order to ensure the inlet temperature is higher than 10℃. So, the mass flow rate of case1 is chosen for sizing the air conditioning pack and ducting system.

Therefore, the mass flow rate 1.57kg/min/pers is chosen for the cabin, and 13.06 kg/min/pers is chosen for the flight deck.

In order to save energy, the recirculation system has been considered. Typically the percentage of the amount of the re-circulated air varies from 0% to 55% [1].Here, as regards the Flying Crane, it is firstly considered to use 50% of the cabin air for recirculation. Therefore, 0.785kg/min/pers of fresh air is supplied to cabin and 6.53kg/min/pers of fresh air is supplied to flight deck. These values exceed the minimum fresh air requirement which is required by CCAR25.831.So, it is reasonable.

Based on the following equation[4], the outlet temperature of the air conditioning pack can be found out:

$$M_sT_s+M_rT_r=M_{in}T_{in}$$

Where:

M_s mass flow rate from the air conditioning pack

T_s outlet temperature of the air conditioning pack

T_r the temperature of the re-circulated air

M_r mass flow rate of the re-circulated air

M_{in} mass flow rate supplied to the cabin

T_{in} inlet temperature of the cabin

So, the outlet temperature of the air conditioning pack is -3℃ and the mass flow rate provided by the two air conditioning packs is 2.258kg/s. Each pack provides 1.129kg/s.

IV Pressurization

IV.1 Function Definition

The following diagram (Figure A- 8) shows the pressurization system functional allocation. Here, cabin positive pressure means that the cabin inner pressure is higher than that of outside. On the contrary, negative cabin pressure means the cabin inner pressure is lower than that of outside.

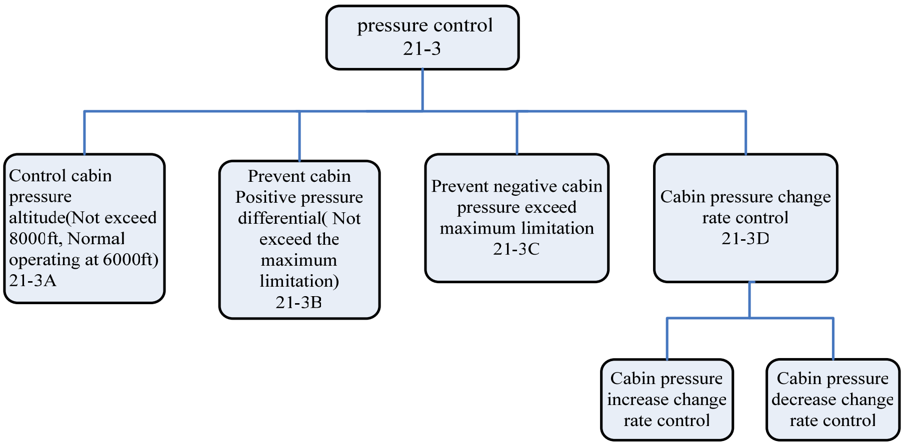

Figure A- 8 Sub-level Functions of Pressurization System

IV.2 Design Consideration

(a) Occupants' health and comfort

Blood oxygen saturation is related to human health directly. However, human blood oxygen saturation is only affected by the oxygen partial pressure (normally, it is required to be no less than 2.3psi. So it is important to control cabin pressure properly.

(b) Aircraft structure weight penalty

Weight is one of the most important factors for an aircraft. Due to the interrelationship between aircraft structure and the pressure difference among internal and external of the cabin, the more pressure difference there is, the stronger the structure would need to be resulting in a greater weight.

According to the system used in the current airliner, the maximum differential pressure of Flying Crane is acceptable, which is 9.4psi.

(c) Cabin Leakage

As we know, cabin is a sealed vessel which consists of many separate parts such as transparent panes, doors and movable parts of canopies. In spite of special methods of sealing seams, it is impossible to ensure that the air can not escape from those seams under certain pressure conditions. The quantity of air leaking from those gaps depends on the cabin pressure, the atmospheric pressure and the sum of the areas of these gaps. So the allowable quantity of air is based on the following considerations:

(1) In normal flight, the total amount of air escape form cabin should not exceed the amount of air supplied to the cabin.

(2) If the cabin lose air supply, it is necessary to ensure that the aircraft can descend to safe altitude without exceeding its maximum pressure change rate.

IV.3 Pressure Control Schedule

The principle of pressurization is that the cabin altitude climes up to its maximum altitude while the aircraft climbs to its cruise altitude. The method for pressurization is to control the cabin inlet airflow rate and the outlet air flow rate. If the amount of air coming into the cabin equals the amount of air going out of the cabin, then the cabin pressure should be maintained at a certain level. If the inlet air flow rate is more than the outlet air flow rate, the cabin pressure will increase and vice versa. In order to ensure passenger and pilot comfort, the cabin pressure change rate should be proper designed in order that the cabin pressure reaches the maximum altitude at the same time as the aircraft reaches its cruise altitude. Another important thing is that the cabin pressure change rate should not exceed the requirement which has been mentioned above.

As regards Flying Crane, the pressure control schedule is shown in Figure A-9 . The pressure change rate is decided by the flight performance.

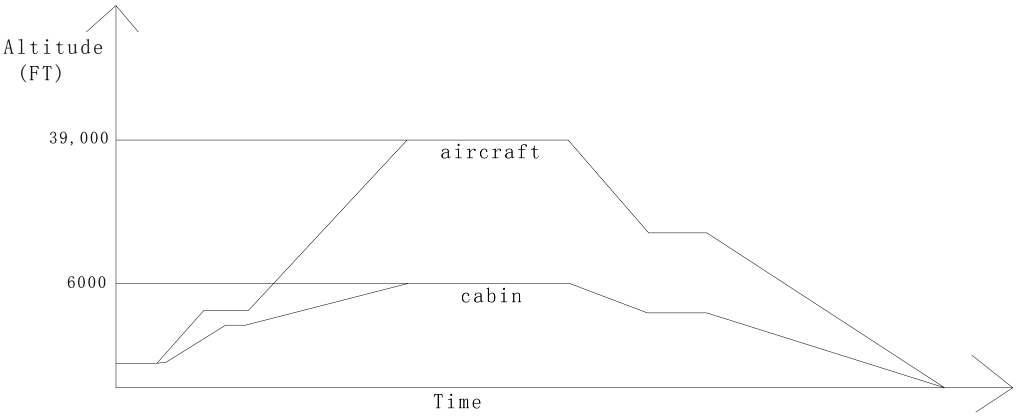

Figure A- 9 Pressure Control Schedule

V Air Distribution

V.1 Introduction

As regards the air distribution system, two aspects need to be concerned, one is the mass flow supplied to each compartment. The other is the ducts which are used to deliver the conditioned air to each zone. This section mainly talks about the ducts parameters design and configuration.

V.2 Design Consideration

When designing the ducting system, it is necessary to consider the following aspects:

(a) It is easy to install and maintenance.

(b) Economy and reliability.

(c) The maximum amount of air and the air velocity need to be concerned. Generally, the allowable air velocity is based on the acceptable noise level in the cabin. Normally, if the ducts are in the cabin, the velocity of 15 to 25 m/sec is acceptable. While the velocity of 100 m/s is acceptable if the ducts are outside of the cabin [8].

(d) The shape of the ducts. As regards the shape of the ducts, there are two types of ducts which are most frequently used in cabin air supply system, namely circular cross-section type and rectangular cross-section type. Compared to the circular cross-section type, the ducts with rectangular across-section are easier to install, but those having rectangular cross-section show a higher pressure loss for the same flow area. So, the circular cross-section is considered to be the best choice for air distribution.

(e) The position of the diffuser needs to be concerned. In the cabin, the passenger thermal comfort is influenced by the air flow pattern. There are two types of flow pattern are considered. One is top-to-down type which means the inlet is at the top level of the cabin and the outlet is at the floor level of the cabin. A good thermal comfort can be achieved by using this kind system. The disadvantage is that the flow pattern is influenced by the contour of the cabin lining. This kind of configuration has been adopted by the majority of civil aircraft. Another is bottom-to-top type. This kind of configuration has been regarded as a solution for getting an optimal flow pattern regardless of the cabin interior layout. But the major disadvantage is that this type of flow pattern includes the downward convection flow direction, with the subsequent difficulty of achieving the cooling demand, and the negative influence of high momentum air flow in the vicinity of seated passenger. Furthermore, contamination on the floor will be carried up into the faces of the passengers.

(f) The position of ducts needs to be concerned. To determine the position of ducts, the space to install the ducts and the thermal conditions needs to be concerned. Normally there are two choices for installing the distribution ducts, namely under the floor and between the ceiling and the structure of the fuselage. The normal configuration is that the distribution ducts are installed on the ceiling and circulation ducts are installed under the floor, the reasons are:

1. Pressure drop can be reduced

2. Temperature losses can be reduced

3. Weight saving, due to ducts being closer to the outlet.

V.3 Ducts Configuration Design

Based on what has been discussed above, the ducts with circular cross section are chosen for the ducting system as first priority. If the space is not enough to install circular cross-section duct, the rectangular ducts can be used. In order to maintain the passenger thermal comfort, the ducts configuration of Flying Crane has been designed as it is shown in Figure A-10. This configuration is similar to that of B747's.

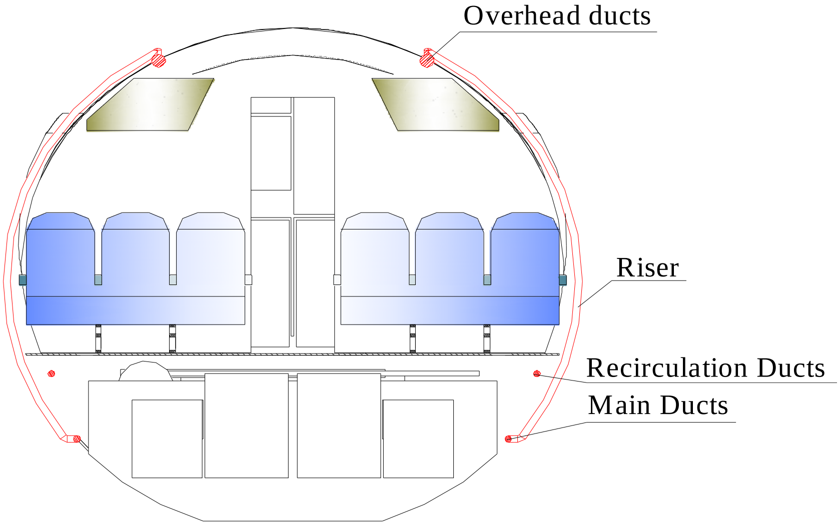

Figure A- 10 Ducts Configuration

The conditioned air provided by ACP is mixed with the re-circulated air in the manifold before delivering to the whole aircraft. Then the mixed air is delivered to the main ducts. Finally, it is transmitted to each compartment via different ducts.

V.4 Ducts sizing

The cross-section areas of these ducts are determined by the velocity of the fluid, the density of the fluid and the mass flow rate. The area of duct is determined by the following formula:

$$M = \rho \cdot V \cdot A$$

Where:

M: The total mass flow rate(kg/s)

ρ: the density of the fluid (kg/m3)

V: The velocity of the fluid (m/s)

A: area of the duct cross section.

Based on the ducting system design, the circular cross section ducts have been chosen for the air distribution system. So, the diameter of ducts can be determined as follow:

$$A=\frac{\pi \cdot D^2}{4}$$

It is worth to note that the value of the air density is not at sea level. The value of air density is chosen as the equivalent value of atmosphere density where the altitude is 6000ft. So,

$$\rho = 1.023 kg/m^3$$

(1) Ducts from ACP to manifold

The mass flow rate of air supplied by each air conditioning pack has been determined in the previous section, which is 1.129kg/s. As far as the velocity of the air is concerned, it has been discussed in the section V.2, The recommended value is 100m/s if the duct is installed outside of the cabin. Therefore, the diameter of the duct can be found out.

$A=0.011m^2$

$D=11.85$ cm

Hence, the duct with the diameter of 12cm is chosen for routing from air conditioning pack to manifold. Thus, the velocity is 97.5m/s.

(2) Main supply ducts

The main supply ducts are used to supply air to different areas. It consists of two ducts. Each one runs along one side of the fuselage and connected to the manifold.

The total mass flow rate is:

$M = M_{cabin} + M_{flight\ deck} + M_{lavatories}$

$M_{cabin} = \frac{1.57 \times 156}{60} = 4.082$ kg/s

$M_{flight\ deck} = \frac{13.06 \times 2}{60} = 0.435$ kg/s

$M_{lavatories} = 1$ kg/s

So, M=5.517 kg/s

Each duct will supply M=2.758 kg/s. These ducts are also installed outside of the can. The air velocity can be as high as 100m/s. Therefore:

A=0.027 m^2 D=18.5 cm

Then, taking D=20cm. Then V=85.8 m/s

(3) Risers and overhead ducts

Those ducts supply air to the two cabin zones, which consist of four ducts. Two of those ducts supply air to the forward cabin zone and the rest supply air to the aft cabin zone. The position of these ducts can be seen in Figure A- 11:

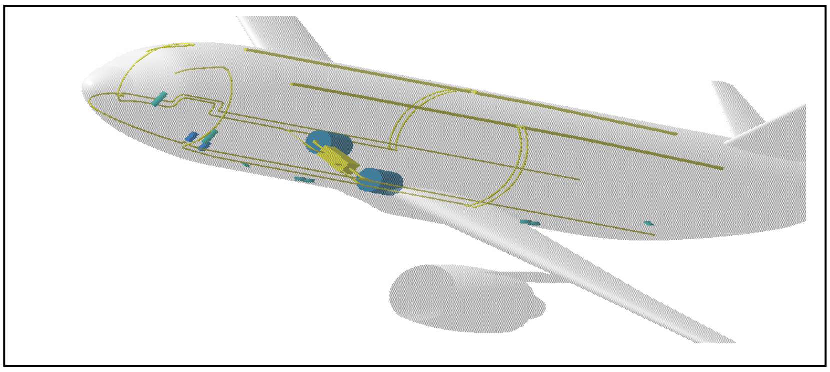

Figure A- 11 Position of the Ducts

Each duct will supply one forth of the cabin mass flow, so

$$M=\frac{1.7\times156}{60\times4}=1.02\ \text{kg/m}$$

As those ducts are installed inside of the cabin, the recommended air velocity range is 15-25m/s, So,

$$V=20\text{m/s}$$

Then, the diameter of the duct can be determined:

$$A=0.05\ m^2\ ,\ D=25.2\text{cm}$$

Then, taking D=26cm. So, V=18.79m/s

As regards the risers, it is decided to use rectangular cross-section ducts since the space is not enough to install the circular ducts.

(4) Ducts for the flight deck

Those ducts supply air to the flight deck compartment. It consists of two ducts. Each one runs along each side of the fuselage. The position of these ducts can be seen in Figure A- 12:

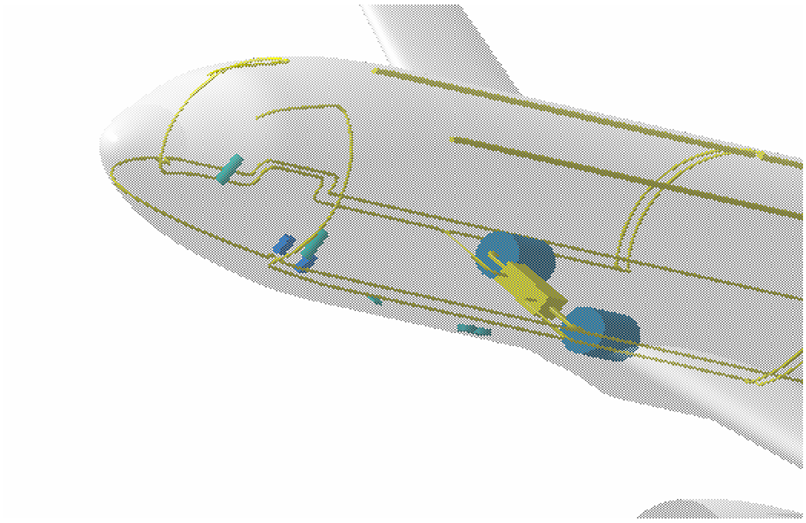

Figure A- 12 Flight Deck Ducts

Each duct will supply one forth of the cabin mass flow, so

$$M=\frac{13.06\times 2}{60\times 2}=0.218 \text{ kg/m}$$

As those ducts are installed inside of the cabin, So,

V=20m/s

Then, the diameter of the duct can be determined:

$A=0.011\ m^2$, D=11.6cm

Then, taking D=12cm. So, V=18.8m/s

(5) Ducts for re-circulating air

This ducting system is used to extract cabin air and supply to the manifold. It consists of two ducts. Each one of these runs along the length of the fuselage. These ducts are installed under the cabin floor. This exact position of those ducts can be seen in Figure A- 13 . Due to half of the air which is supplied to the cabin and flight deck will be re-circulated, therefore,

M=4.517kg/s

Therefore, each duct will supply 2.58kg/s.

Because those ducts are installed outside of the cabin, then,

V=100.

Then, the diameter of those ducts can be found out.

$A=0.022\ m^2$,   D=16.7 cm

Then, taking D=18 cm . So, V=86.8 m/s

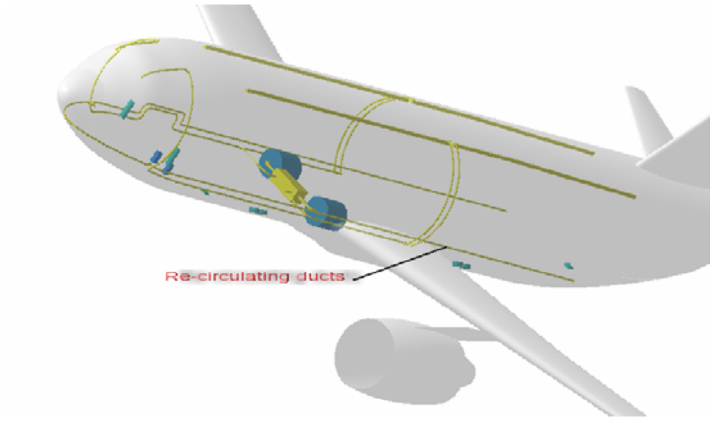

Figure A- 13 Re-circulating Ducts

In summary, all the parameters of the ducting system are summarized as follow (Table A- 11):

Table A- 11 Ducts Parameters

Duct	Area(m^2)	Velocity(m/s)
Ducts from ACP to manifold	0.011	97.5
Main supply ducts	0.027	85.8
risers and overhead ducts	0.05	18.79
ducts for the flight deck	0.01	18.8
Ducts for re-circulating air	0.022	86.8

VI Emergency Oxygen System

VI.1 Introduction

As regards the atmosphere, the oxygen partial pressure falls with increasing altitude. Human will suffer from hypoxia when the altitude is above 4300m (14000ft).So emergency oxygen system is designed to provide sufficient oxygen to flight crew and passengers in the event of pressurization failure.

VI.2 Function Definition

The following diagram (Figure A- 14) shows the emergency oxygen system functional allocation.

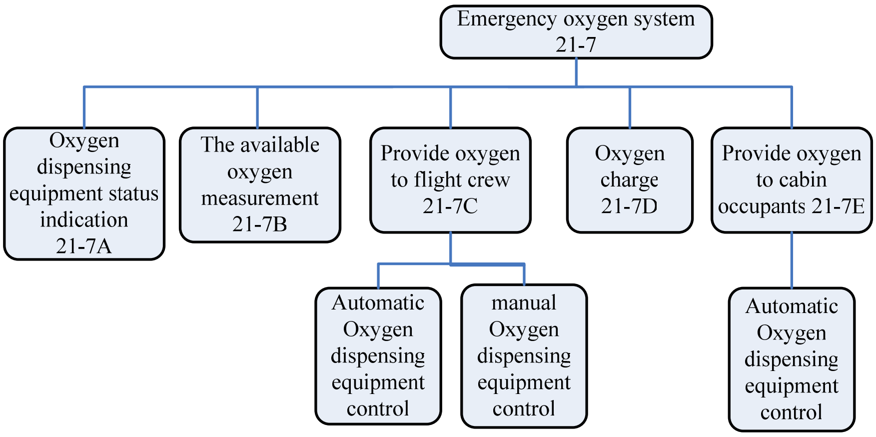

Figure A- 14 Sub-level Functions of Emergency Oxygen System

The available oxygen measurement: According to CCAR25.1441(c), this function is designed to provide the information of the quantity of available oxygen for flight crew.

Oxygen dispensing equipment status indication: This function is designed to provide means for flight crew to know whether the oxygen dispensing equipment is in use or not.

Oxygen charge: This function is designed to provide access for charging oxygen whenever it is necessary. The following graph (Figure A- 15) shows this kind of maintenance panel.

Figure A- 15 Oxygen Servicing Point[14]

Automatic oxygen dispensing equipment control: This function is designed to provide means to deliver oxygen mask for pilots automatically when it is required.

Manual oxygen dispensing equipment control: According to CCAR25 1447(c), a manual means for making oxygen dispensing equipment available immediately in case of automatic system failure.

VI.3 Design Consideration

As regards emergency oxygen system, the following aspects need to be concerned:

- Suitability for high-altitude operation
- Low resistance for breathing
- Simplicity in use.

VI.4 Oxygen Source Type

As regards means of generating oxygen, there are many types of oxygen can be used nowadays, namely high pressure gaseous storage of oxygen, chemical oxygen, liquid oxygen and concentration of outside air. But the methods of generating oxygen which are not suitable for emergency supplies are concentration of outside air and liquid form oxygen [12].The main features of the rest types of oxygen are listed below:

(1) High pressure gaseous storage of oxygen

The advantage is that it is the simplest way to provide oxygen immediately. However, the mass of storage cylinder and the ducts will be heavier compared to the low pressure system.

(2) Oxygen generation by chemical reaction

In this kind of system, Oxygen is produced by chemical reaction. The advantage of this kind of system is that it is relatively low in mass and no extra distribution pipe work.

VI.5 Oxygen Mask

(1) Continuous Flow Oxygen System

The advantage of this system is that it has relatively low resistance for breathing and it is simple to use. The composition of the air/oxygen mixture is not sensibly affected if the mask does not fit well. This disadvantage of this system is that it is waste of oxygen during exhalation.

(2) Diluter Demand System

When using this kind of system the oxygen partial pressure can be maintained constantly by the regulator. With the increasing cabin altitude, the oxygen flow increases such that the oxygen partial pressure can be maintained [3].

VI.6 System Design

VI.6.1 Flight Crew System

Based on CCAR25.1445, a separate oxygen source is required for flight crew. According to the system types discussed above, the high pressure oxygen and diluter demand system is selected for flight crew. In order to increase system safety, a duplicated system is provided. Figure A- **16** shows the system architecture:

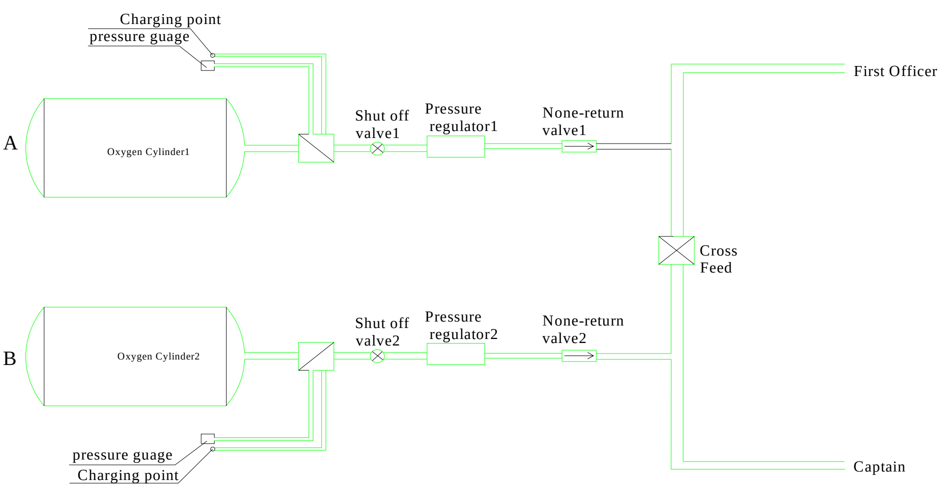

Figure A- 16 Flight Crew Oxygen System Schematic Diagram

The cross feed provides the additional safety feature in case of one channel failure. During normal operation, Channel B is for captain and the other channel is for first officer. The sufficient oxygen is required until the aircraft descend to safe altitude(<10000ft).

VI.6.2 Passenger System

In terms of emergency oxygen system for passenger use, the chemical oxygen system is considered. This system consists of chemical oxygen generator and dispensing units which are contained within service panels at each group of passenger seats. The quantity of oxygen is also determined by the period for aircraft descending to safe altitude. Normally, the system can supply oxygen for at least 15min..

VI.6.3 Cabin Attendants System

At each crew station, one portable oxygen set is installed. The portable oxygen set consists of oxygen cylinder, flow control, pressure reducing valve and mask.

VI.7 System Control and Display

In terms of system display and control, the following contents are the minimum requirement in order to meet the airworthiness regulation.

- Cabin temperature and flight deck temperature
- Cabin altitude
- Cabin pressure differential
- Cabin pressure change rate
- Cabin altitude warning
- The amount of available oxygen information
- Oxygen dispensing equipment status

Furthermore, means need to be taken to allow pilots to set the temperature value of each compartment and cabin pressure change rate. In addition, the use of oxygen dispensing equipment also can be controlled by pilots.

VII Preliminary System Safety Assessment

According to system development processes which is required by SAE4754, safety design is an indispensable part of the system. During the safety assessment, the method used in this project is based on ARP4761, the first step is system function allocation and requirement analysis. The next step is system architecture design and system function hazardous assessment, followed by PSSA which will examine the system architecture whether it can meet the safety requirement or not. In PSSA analysis, the FTA method will be used. Here, we chose one case to demonstrate the process of safety assessment. According to FHA, it can be found that the function of cabin altitude control effects flight safety, its functional hazard has been defined as category Ⅱ (hazardous) . So, this function has been chosen for demonstration. The detailed fault tree analysis can be seen as follow (Figure A- 17):

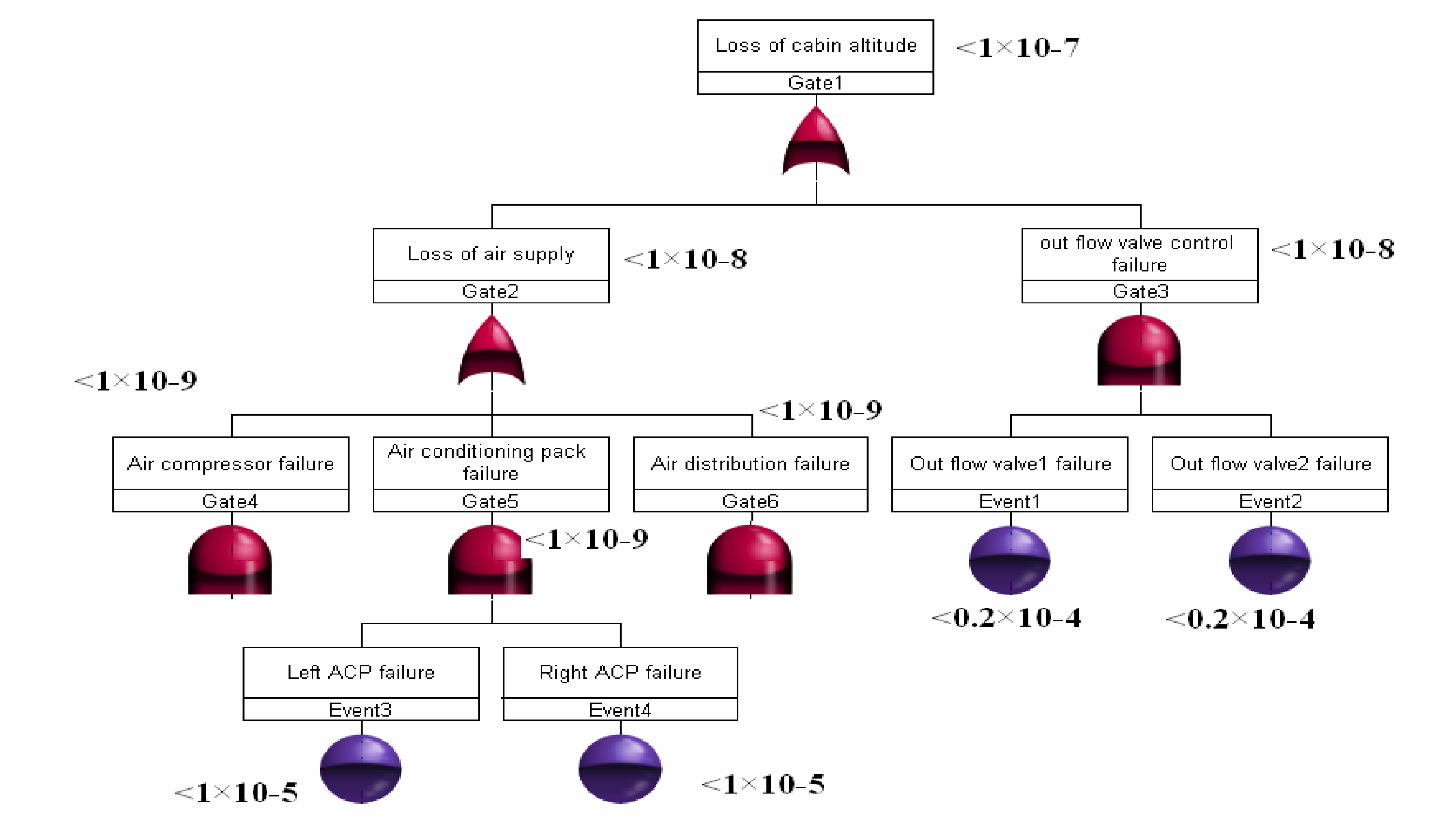

Figure A- 17 ECS Fault Tree Diagram

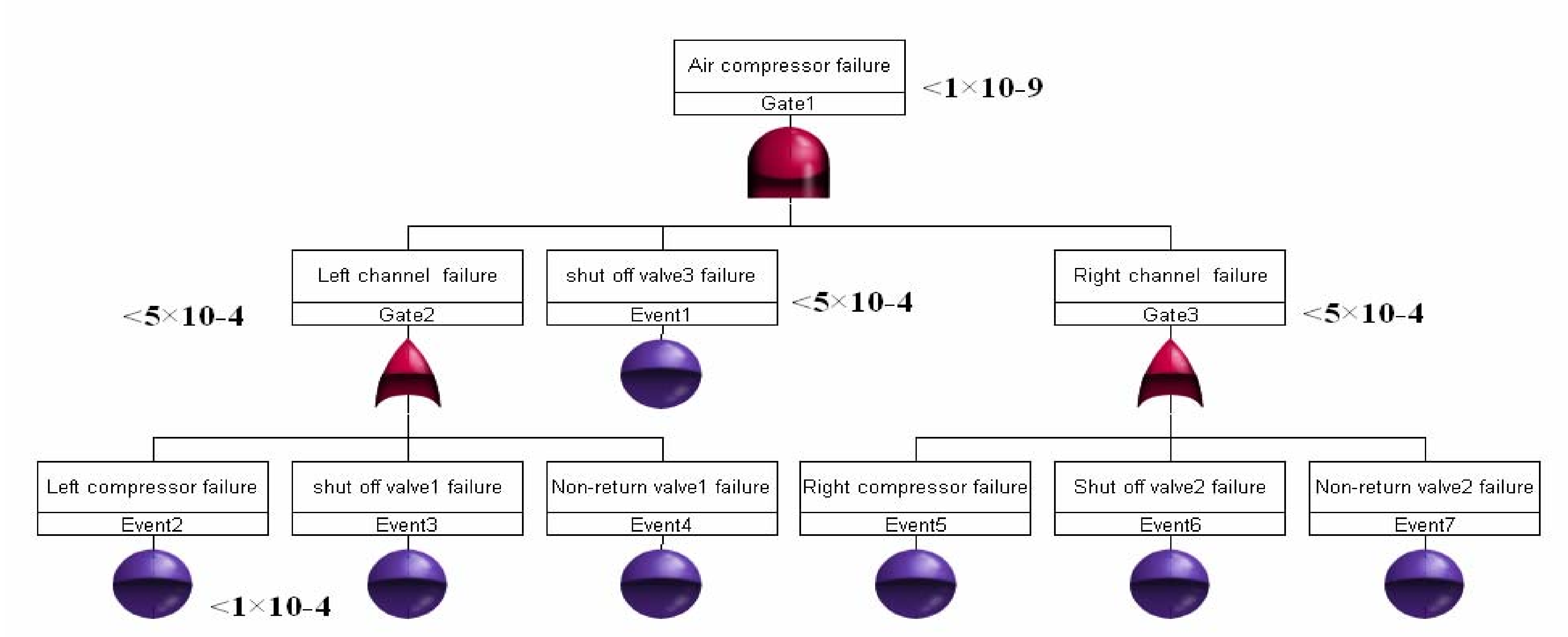

Figure A- 18 ECS Fault Tree Diagram(cont.)

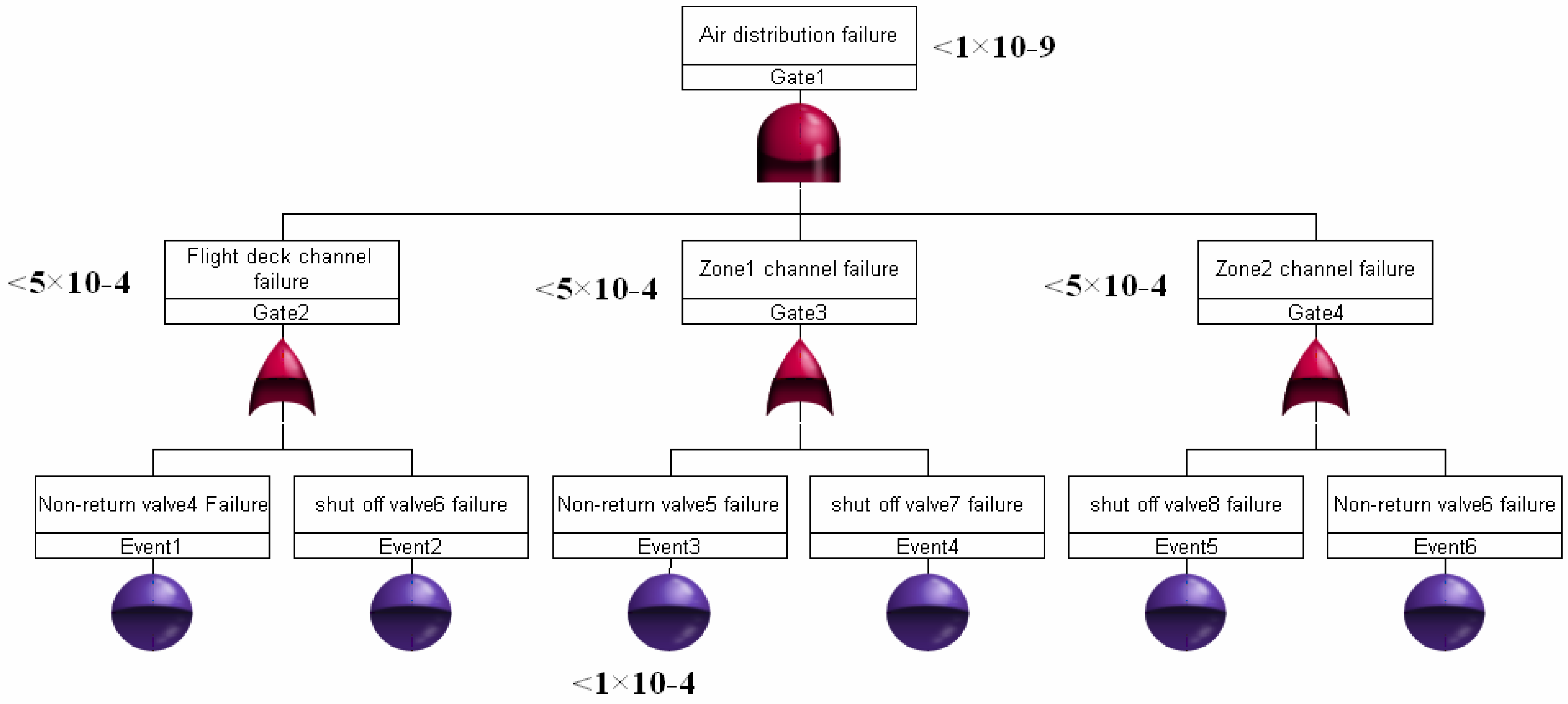

Figure A- 19 ECS Fault Tree Diagram(cont.)

According to the results of FTA, the reliability requirement determined by FHA has been allocated to each component.

It can be found From Figure A- 17 that the failure probability of air conditioning pack should be less than 1×10^{-5} and the failure probability of air conditioning pack should be less than 1×10^{-4}. Due to lack of real product reliability information, other products information has been chosen for reference. In terms of the air conditioning pack, the reliability value of ACP which is used in B747 is 1,000,000 flight hours[10]. As regards the valves, the reliability value of valve which is used in A340 is 100,000 flight hours. Based on these data, all these components' reliability requirement is achievable. So, this system architecture is reasonable.

VIII Conclusion

The design process is complied with the system engineering process. Meanwhile, it is also complied with the airworthiness regulation CCAR-25.

As regards the environmental control system, the design philosophy is all-electric ECS. The heat load analysis has been conducted at the beginning. Then fundamental parameters have been decided according to the heat load. Finally, the ducting system has been considered.

During the design process, the most important procedure is the system safety assessment. The system architecture design is based on the results of the safety assessment. For time reasons, some aspects can not be conducted. Therefore, the following areas need to be considered:

- The Cabin air diffuser configuration needs to be well designed in order to obtain optimal air flow pattern.
- Furthermore, means of cabin air quality control and surveillance need to be studied.
- The detailed system health monitoring and indication needs to be designed.

- The ducts material needs to be considered in order to estimate the mass of the ducting system. Furthermore, the pressure loss needs to be determined.

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Appendix B Load Analysis

First of all, the following definitions need to be given:

- Continuous loads: Those loads that operate longer than 5 minutes.
- Intermittent loads: Those loads that operate less than 5mintus.

Then, the following assumptions should be made before conducting the load analysis:

- The real operating time of an intermittent load is neglected. The operating time of this type of load in is regarded as 5 minutes on average.
- It is assumed that the power factor of AC system is 0.9 lagging.

B.1 Data Collecting

The electrical load requirements come from the results of the group design project[10; 18; 20; 32; 33]. All of these power requirements of each load are the average power requirement. The peak power did not considered in this project. The original data are listed in the tabular form below (Table B- 1,Table B- 2).

Table B- 1 Load Requirement

Systems	Equipment	Voltage(AC/DC)	Working Period(continuous/temporary)							Power requirement(KW/KVA)
			F1	F2	F3	F4	F5	F6	F7	
Electric power system	Electric Load Management Centre	28VDC	C	C	C	C	C	C	C	1.2KW
	Primary Power Distribution Unit	28VDC	C	C	C	C	C	C	C	1KW
Actuation System	Landing Gear Actuator	115VAC/400Hz		T					T	12KVA
										12KW
	Rudder Actuator	270VDC		C	C	T	C		C	2.207KW
	Elevator Actuator	270VDC		C	C	T	C		C	6.98KW
	Aileron Actuator	270VDC		C	C	T	C		C	3.526KW
			Total Primary Flight Control actuation system							**12.713KW**
	Thrust Reverse	115VAC/400Hz							T	13.3KVA
	Tail Horizental Stabilizor Actuator	270v DC			C		C		C	1.556KW
	Slats Actuator	270v DC			C		C		C	12.8KW
	Flaps Actuator	270v DC			C		C		C	2.56KW
	Spoilers Actuator	270v DC			C		C		C	15.36KW
			Total Secondary Flight Control actuation system							**32.276KW**
Environmental Control System	Motor(compressor)	115VAC/400Hz	C	C	C	C	C	C	C	260.17KW
	Miscellaneous Equipments	28vdc	C	C	C	C	C	C	C	5KW
Ice Pretection System	Capacitor Bank	115VAC	C		C	C	C	C		4KVA
	Heater Elements	115VAC	C		C	C	C	C		20KVA
Flight Control Cystem	Primary Flight Control Computers(4)	28DC	C	C	C	C	C	C	C	0.8KW
	Second Flight Control Computers(2)	28DC	C	C	C	C	C	C	C	0.4KW
	Autopilot Computers(3)	28DC	C	C	C	C	C	C	C	0.6KW
	Actuator Control Electronics(4)	28DC	C	C	C	C	C	C	C	1KW
Surveillance System	Weather Radar	28VDC			C	C	C	C		0.8KW
	EGPWS	28VDC		C	C	C	C	C	C	0.5KW
	TCAS	28VDC		C	C	C	C	C	C	0.3KW
Navigation System	ADIRS	115VAC/400Hz	C	C	C	C	C	C	C	0.12KVA
	GPS/ILS Receiver	115VAC/400Hz	C	C	C	C	C	C	C	0.08KVA
	ADF Receiver	115VAC/400Hz	C	C	C	C	C	C	C	0.08KVA
	VOR/Marker Receiver	115VAC/400Hz	C	C	C	C	C	C	C	0.06KVA
	DME	115VAC/400Hz	C	C	C	C	C	C	C	0.06KVA

Table B- 2 Load Requirement (cont.)

Systems	Equipment	Voltage(AC/DC)	Voltage Period(continous/temporary)							Power requirement(KW/KVA)
			F1	F2	F3	F4	F5	F6	F7	
Cockpit and Display System	Display Unit	28VDC	C	C	C	C	C	C	C	1.8KW
		28VDC	C	C	C	C	C	C	C	1.2KW
Commuication System	HF System	28VDC	C	C	C	C	C	C	C	1.5KW
	VHF System	28VDC	C	C	C	C	C	C	C	1.2KW
	SAT System	28VDC	C	C	C	C	C	C	C	0.8KW
	Others For Communication	28VDC	C	C	C	C	C	C	C	0.8KW
	PA(PES)	115VAC/400Hz				C				5KVA
Flight Management System	Flight Management Computer	28VDC	C	C	C	C	C	C	C	0.6KW
Cabin Equipmengts	Heater(Lavatory)	115VAC				C				15KVA
	Coffee Kettle (Galley)	115VAC				C				7.8KVA
	Chiller (Galley)	115VAC				C				2.6KVA
	Oven (Galley)	115VAC				C				12.5KVA
	Light	28VDC	C	C	C	C	C	C	C	1.5KW
	Cargo Door Actuator	270VDC	T							2KW
	Evacuation Equipments	28VDC	C							1KW
	Waste Water Master Heater	115VAC	C	C	C	C	C	C	C	4KW
Propulsion System	APU Starting-Generator	28VDC	T				T			10KW
Fuel System	PUMP, VALVES	270VDC	C							3KW
	PUMP, VALVES	270VDC		C	C	C	C	C	C	12KW
External lighting	Navigation Lights	28VDC	C	C	C	C	C	C	C	0.2KW
	Anti-Collision Beacons	28VDC	C	C	C	C	C	C	C	0.3KW
	Landing/Texiing Lights	28VDC	C						C	0.85KW
	Ice Inspection Lights	28VDC	C	C	C	C	C	C	C	0.3KW
	Emergency Lights	28VDC	C	C	C	C	C	C	C	0.2KW
Fire Protection System	Miscellaneous	28VDC	C	C	C	C	C	C	C	0.4KW
Flight data Record System	Flight Data Record Unit	28VDC	C	C	C	C	C	C	C	0.2KW
Landing Gear System	Nose wheel Steering System	270VDC		T					T	3.8KW
	Breaking System	270VDC							T	27.4KW
Avionic Network	Miscellaneous Equipment	28VDC	C	C	C	C	C	C	C	3.05KW

F1: Ground **F2**: Take off **F3**: Climb **F4**: Cruise **F5**: Descending **F6**: Loiter
F7: Landing **C**: Continuous loads **T**: Intermittent Loads

It is can be found that four kinds of power source are required in electric power system from Table B- 1and Table B- 2, namely,**115V/400Hz AC，115V/VF，28VDC and 270VDC.** Up to now, the power source categories have been determined.

B.2 Load Categories

It is necessary to divide all these loads into different categories based on their functions before conducting further load analysis, because it is the fundament of the power distribution system, Due the limited generating capacity, all the loads can not be powered at all time. In other words, some loads will be shed in the event of power source failure. According to reference [24], all the electric loads have been divided into the following three categories:

a. Vital loads: vital loads are those which are required to operate at any circumstances even after an emergency hard landing.

b. Essential loads: essential loads are those which are required to ensure flight safety in an in-flight emergency situation.

c. Non-essential loads: Non-essential loads are those which are related to flight safety. It can be isolated for load shedding purpose in the emergency situation.

All the loads have been classified as follow:

Table B- 3------------Non-essential Loads

Table B- 4------------Vital Loads

Table B- 5------------Essential Loads

Table B- 3 Non-essential Loads

Systems	Equipment	Voltage(AC/DC)	Working Period(continuous/temporary)							Power requirement(KW/KVA)
			F1	F2	F3	F4	F5	F6	F7	
Actuation System	Secondary F.C. Actuator	270v DC			C		C		C	32.276KW
	Thrust Reverse	115VAC/400HZ							T	13.3K VA
Communicaiton System	SAT System	28VDC	C	C	C	C	C	C	C	800W
	PA(PES)	115VAC/400HZ				C				5KVA
Flight Management System	Flight Management Computer	28VDC	C	C	C	C	C	C	C	0.6KW
Cabin Equipmengts	Heater(Lavatory)	115VAC				C				15KVA
	Coffee Kettle (Galley)	115VAC				C				7.8KVA
	Chiller (Galley)	115VAC				C				2.6KVA
	Oven (Galley)	115VAC				C				12.5KVA
	Light	28VDC	C	C	C	C	C	C	C	1.5KW
	Cargo Door Actuator	270VDC	T							2KW
	Waste Water Master Heater	115VAC	C	C	C	C	C	C	C	4KW
External Lighting	Navigation Lights	28V DC	C	C	C	C	C	C	C	0.2KW
	Landing/Taxiing Lights	28V DC	C						C	0.85KW
	Ice Inspection Lights	28V DC	C	C	C	C	C	C	C	0.3KW
Ice Protection System	Capacitor Bank	115V AC		C	C		C	C		4KVA
	Heater Elements	VF 115V AC		C	C		C	C		20KVA

Table B- 4 Vital Loads

Systems	Equipment	Voltage(AC/DC)	Working Period(continuous/temporary)							ower requirement(KW/KVA)
			F1	F2	F3	F4	F5	F6	F7	
Electric Power System	Primary power distribution unit	28VDC	C	C	C	C	C	C	C	1
	Electric load management centre	28VDC	C	C	C	C	C	C	C	1.2
External Lighting System	Emergency lights	28VDC	C	C	C	C	C	C	C	0.2
Cabin Equipments	Evacuation equipments	28VDC	C							1
Fire Protection System	Miscellaneous	28VDC	C	C	C	C	C	C	C	0.4
Flight Data Record System	Flight data record unit	28VDC	C	C	C	C	C	C	C	0.2

Table B- 5 Essential Loads

Systems	Equipment	Voltage(AC/DC)	Working Period(continuous/temporary)							Power requirement(KW/KVA)
			F1	F2	F3	F4	F5	F6	F7	
Actuation System	LG actuator	115VAC/400HZ		T					T	12KVA
	Primary Flight Control actuator	270v DC		C	C	T	C		C	12.713KW
Environmental Control System	Motor(compressor)	115VAC/400HZ	C	C	C	C	C	C	C	260.17KVA
	Miscellaneous Equipments	28vdc	C	C	C	C	C	C	C	5kw
Surveillance System	Weather Radar	28VDC			C	C	C	C		0.8W
	EGPWS	28VDC		C	C	C	C	C	C	0.5KW
	TCAS	28VDC		C	C	C	C	C	C	0.3KW
Navigation System	ADIRS	115VAC/400Hz	C	C	C	C	C	C	C	0.12KVA
	GPS/ILS Receiver	115VAC/400Hz	C	C	C	C	C	C	C	0.08KVA
	ADF Receiver	115VAC/400Hz	C	C	C	C	C	C	C	0.08KVA
	VOR/Marker Receiver	115VAC/400Hz	C	C	C	C	C	C	C	0.06KVA
	DME	115VAC/400Hz	C	C	C	C	C	C	C	0.06KVA
Cockpit and display system	Display unit	28VDC	C	C	C	C	C	C	C	1.8KW
	Display computor	28VDC	C	C	C	C	C	C	C	1.2KW
Commuication System	HF SYSTEM	28VDC	C	C	C	C	C	C	C	1.5KW
	VHF SYSTEM	28VDC	C	C	C	C	C	C	C	1.2KW
	OTHERS FOR COMMUNICATION	28VDC	C	C	C	C	C	C	C	0.8KW
Fuel System	PUMP,VALVES	270VDC	C							3KW
	PUMP,VALVES(ground refueling)	270VDC	C							20KW
	PUMP,VALVES	270VDC		C	C	C	C	C	C	12KW
Propulsion System	APU STARTING-GENERATOR	28VDC	T				T			10KW
External Lighting	Anti-Collision Beacons	28V DC	C	C	C	C	C	C	C	0.3KW
Flight Control System	Primary Flight Control Computers(4	28DC	C	C	C	C	C	C	C	0.8KW
	Second Flight Control Computers(2)	28DC	C	C	C	C	C	C	C	0.4KW
	Autopilot Computers(3)	28DC	C	C	C	C	C	C	C	0.6KW
	Actuator Control Electronics(4)	28DC	C	C	C	C	C	C	C	1KW
Landing Gear System	Nose Wheel Steering System	270VDC		T					T	3.8KW
	Breaking System	270VDC							T	27.4KW
Avionic Network	Miscellaneous Equipments	28VDC	C	C	C	C	C	C	C	3.05KW

The following paragraph gives the further explanation about how the loads are divided into these three categories. Here, the author just lists part of those loads. Because those loads are important for an aircraft and need to be extensively considered:

1. Cabin equipment According to the aircraft level function, the main function of cabin equipment is to enhance passengers comfort. All the loads except evacuation equipment are not related to flight performance and safety. So, those cabin facilities except evacuation equipment are regarded as non-essential loads.

2. Electric power system equipment The electric power system equipment is related to flight safety directly, because all the equipment is related to power supply. That is why those components belong to vital loads.

3. Actuation system The primary flight control actuation system is divided into essential load category, because the primary flight control actuation system is related to aircraft maneuverability. But the secondary flight control actuation system is regarded as non-essential load, because the function of secondary flight control actuation system is to improve flight performance. As for the landing gear actuator, it is also divided into Essential load category, because it is related to safe landing.

4. Flight control system The flight control system is divided into essential load category, because it is directly related to flight safety.

5. Fuel system The primary function of Fuel system is to provide an uninterrupted supply of fuel to power plants. This system is flight safety critical. So, it is divided into the category of essential load.

6. Avionics system Herein, what we called avionics system includes those sub-systems: communication system, flight management system, surveillance system, navigation system and data bus system as well as cockpit and display system. Those system componnets except for passenger entertainment system、SAT system and flight management unit are mainly for providing

sufficient information to pilots in order to enhance flight safety. So, these loads are divided into essential loads. As for the rest of those equipment, since these are not related to flight safety, those are regarded as non-essential loads.

7. ECS and IPS   The environmental control system is divided into essential load, because the main function of ECS is to provide liveable conditions in the cabin. Whether the system works well or not is relevant to all occupants' lives. As for the Ice protection system, it is divided into non-essential load, because icing encounter is very rare at cruise altitude (39,000ft)[17],and it just operates a short period when descending and climbing. So .the ice protection system is divided into non-essential load.

Appendix C System Reliability Assessment

The reliability block diagram represents the functional relationship of each component of the system. As regards system model, six types of system model are used to analyze simple systems, namely series systems, parallel systems, series-parallel systems, partially redundant systems and standby redundant systems[9]. These types of system model will be briefly reviewed firstly. Meanwhile, the equation which is used to describe the system models will be given.

a. Series systems: In terms of this kind of system, the system failure will occur when any component is fail. In other words, the system will be functional only if all the system components are functional. The system reliability block diagram (RBD) can be seen in Figure C- 1.

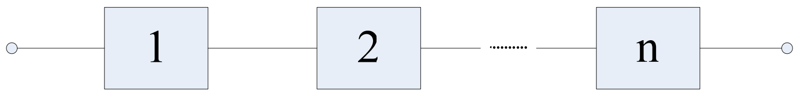

Figure C- 1 Series Model

b. Parallel systems: Compared to the series system, this system will be functional when one of the components is functional. However, the system will fail only after all the components are failed. The RBD is represented in Figure C- 2.

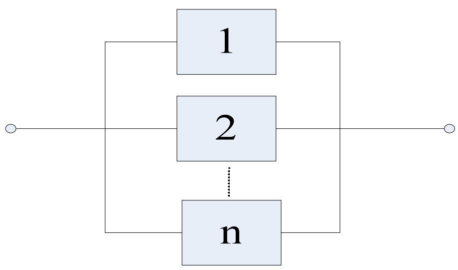

Figure C- 2 Parallel Model

c. Series-parallel systems: As discussed above, series system and parallel system are the basic system models. Series-parallel model is used to analyse more complicated system configuration. The method used to analyse complicated system is to reduce complicated system architecture by combining series and parallel model until the complicated system is reduced to a single equivalent element.

d. Partially redundant systems: In terms of parallel system, it is a kind of full redundancy system. As regards the partially redundant system, the reliability block diagram is the same as the one shown in Figure C- 2. However, the difference between parallel system and partially redundant system lies in the numbers of component required for system success or cause system failure. If a system consists of more than one component, only one component is required for system success in terms of a parallel system. But for a partially redundant system, more than one component is required for system success[19].

e. Standby redundant systems: As for the parallel system, all the branches operate simultaneously. In a standby redundant system, all of the redundant components can not operate simultaneously. One or more redundant branches are in standby mode. As a typical standby system which is shown in Figure C- 3, component A operates continuously while component B is in a standby mode. As regards the changeover unit, it also has effects on the system reliability.

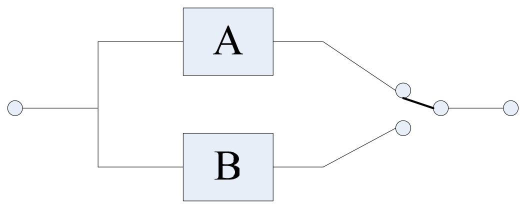

Figure C- 3 Standby Redundant System

As described in chapter 5 and chapter6, the system configuration varies with the system operating conditions which consists of normal condition and abnormal condition. In this case study, the system reliability assessment is only based on the normal operation mode which means that all the system components are functional. The reliability block diagram and reliability calculation of 270Vdc system as well as the 115V/VF system will be given in the following section respectively.

(1) 115V/ VF system

In this type of system, four types of electric power are required by the electrical loads, namely 115V/VF, 115V/400Hz, 28VDC, and 270VDC. Therefore, the system reliability will be the product of the probability of successfully supplying those four types of power. According to the system architecture and the functional relationship between the system elements, the system RDB is divided into the following four parts. Figure C- 4 shows the reliability block diagram of 115V/VF power supply. Figure C- 5 illustrates the reliability block diagram of 270VDC power supply. Figure C-6 depicts the reliability block diagram of 28VDC power supply. Figure C- 7 shows the reliability block diagram of 115V/400Hz power supply.

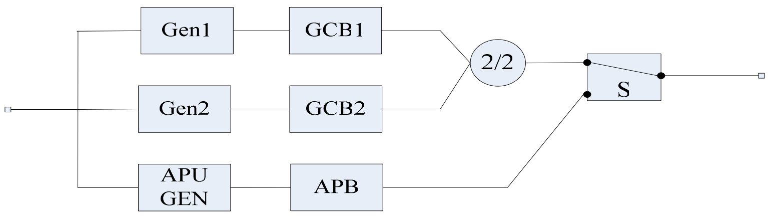

Figure C- 4 RBD of 115V/VF Power Supply (115VAC System)

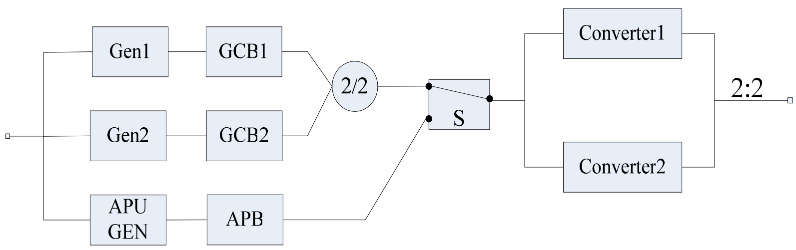

Figure C- 5 RBD of 270VDC Power Supply (115VAC System)

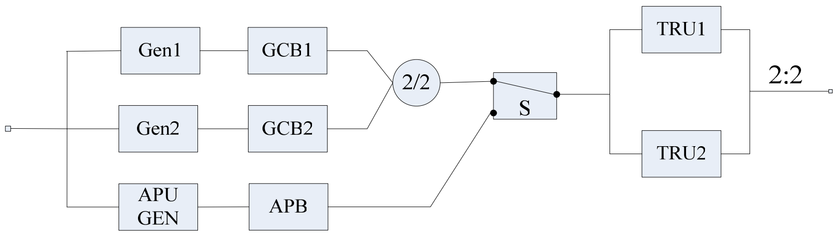

Figure C-6 RBD of 28VDC Power Supply (115VAC System)

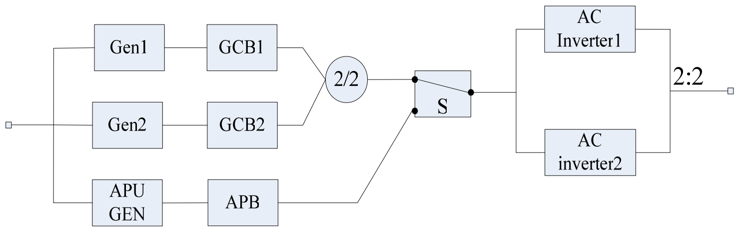

Figure C- 7 RBD of 115VAC/400Hz Power Supply (115VAC System)

As can be seen from Figure C- 4 to Figure C- 7, there is a common part among those diagrams, which is the RBD of primary power supply part (see Figure C- 4). As regards this part, it is regarded as a standby redundant system since the APU generator can not operate simultaneously with the main generators. In terms of the two main generators, it is considered to be a partial redundancy system because a single generator can not supply all loads. As regards the rest part of those diagrams, it is also regarded as a partial redundancy system since the capacity of single conversion equipment is not enough to power all the loads. In these diagrams, the 'S' part stands for the function of a switch. The exact elements of this part vary with the system architecture. Here in 115V/VF system, the RBD of 'S' part is shown as below(Figure C- 8):

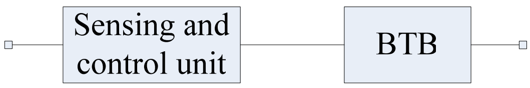

Figure C- 8 RBD of Switch

(2) 270VDC System

In terms of 270VDC system, it provides three types of power source to all the electrical loads, namely 270VDC, 28VDC and 115VAC/400Hz. Therefore, the system success is governed by the success of these three sub-systems. As shown below, Figure C- 9 shows the reliability block diagram of 270vdc system. Figure C- 10 presents the reliability block diagram of 28VDC system. Figure C- 11 presents the reliability block diagram of 115v/400Hz system.

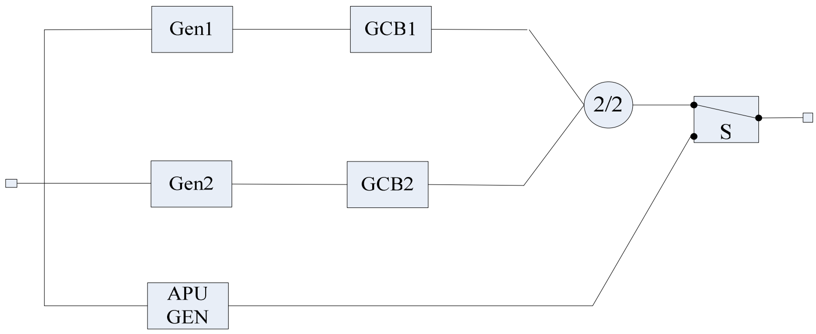

Figure C- 9 RBD of 270VDC Power Supply (270VDC System)

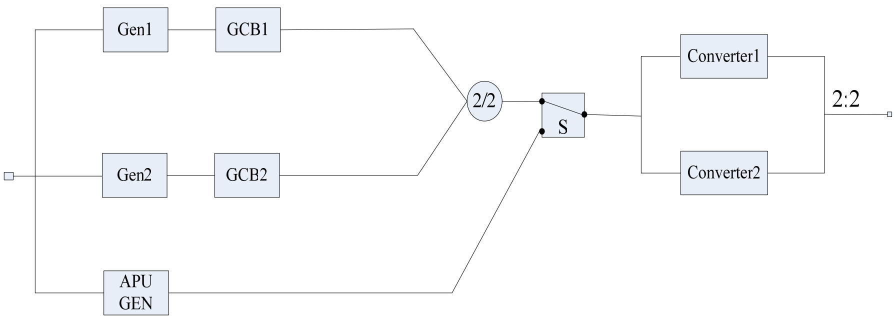

Figure C- 10 RBD of 28VDC Power Supply (270VDC System)

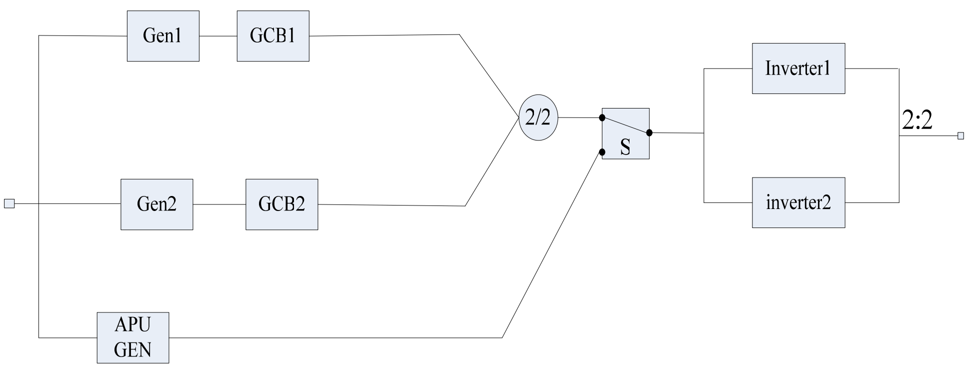

Figure C- 11 RBD of 115VAC/400Hz Power Supply (270VDC System)

Similarly, those diagrams also can be divided into primary power part and power conversion part. Since the diagram of the power conversion part is the same as the one mentioned in 115VAC system, this part will not be explained in detail. As far as the primary power part is concerned, it is similar to the diagrams shows in section (1). The APU generator also acts as a standby power source. Alternatively, the primary power system also can be regarded as a partial redundancy system shown in Figure C- 12 since the all the generators can operate simultaneously to power all the electrical loads.

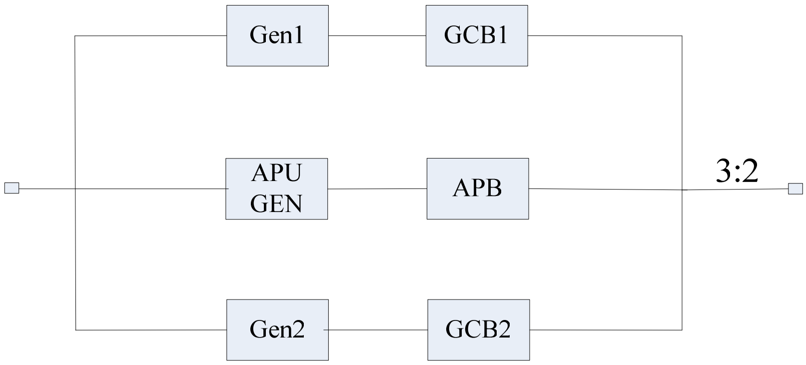

Figure C- 12 Partial Redundancy System of 270VDC Supply (270VDC System)

As for the 'S' part, the detailed diagram is shown in Figure C- 13

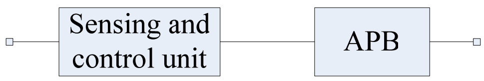

Figure C- 13 RBD of Switch

Appendix D Wiring Weight Evaluation

As the wring system has been designed in chapter 4, the MIL-W-22759/87 wire is selected for this case study. The specific weight of each gage size wire has been given in (Table E- 1). Therefore, the mass of each conductor equals to;

$$W = \rho \times L$$

Where, W weight of each conductor

ρ specific weight of the wire

L Length of the wire

The total weight of wiring system is the sum of all the mass of each conductor. The wiring weight of the two systems will be tabulated as follow respectively.

Table D- 1 115V/AC Wiring System

Relative Position of Components	Number of Wires	Length of the Conductor	Cable Selection	Max.WT (Kg/Km)	Weight (kg)
Cable from generator1 to PPDU1	3	18	2*[AWG-000]	806.5	87.102
Cable for earth return	1	18	2*[AWG-000]	806.5	29.034
Cbele from PPDU1 to ELMC1					
(115V/400Hz)	3	16	AWG-8	85.71	4.11408
(270VDC)	1	16	AWG-8	85.71	1.37136
(28VDC)	1	16	AWG-0	513.4	8.2144
(115V/VF)	3	16	AWG-10	46.72	2.24256
Cable from PPDU1 to ELMC3					0
(115V/400Hz)	3	2	AWG-8	85.71	0.51426
(270VDC)	1	2	AWG-8	85.71	0.17142
(28VDC)	1	2	AWG-0	513.4	1.0268
(115V/VF)	3	2	AWG-10	46.72	0.28032
Cable from PPDU1 to ELMC5					0
(115V/400Hz)	3	10	AWG-8	85.71	2.5713
(270VDC)	1	10	AWG-8	85.71	0.8571
(28VDC)	1	10	AWG-0	513.4	5.134
(115V/VF)	3	10	AWG-10	46.72	1.4016
Cable from Generator2 to PPDU2	3	18	2*[AWG-000]	806.5	87.102
Cable for earth return	1	18	2*[AWG-000]	806.5	29.034
Cable from PPDU2 to ELMC2					0
(115V/400Hz)	3	16	AWG-8	85.71	4.11408
(270VDC)	1	16	AWG-8	85.71	1.37136
(28VDC)	1	16	AWG-0	513.4	8.2144
(115V/VF)	3	16	AWG-10	46.72	2.24256
Cable from PPDU2 to ELMC4					
(115V/400Hz)	3	2	AWG-8	85.71	0.51426
(270VDC)	1	2	AWG-8	85.71	0.17142
(28VDC)	1	2	AWG-0	513.4	1.0268
(115V/VF)	3	2	AWG-10	46.72	0.28032
Cable from PPDU2 to ELMC6					0
(115V/400Hz)	3	10	AWG-8	85.71	2.5713
(270VDC)	1	10	AWG-8	85.71	0.8571
(28VDC)	1	10	AWG-0	513.4	5.134
(115V/VF)	3	10	AWG-10	46.72	1.4016
APU generator to PPDU1	3	20	2*[AWG-000]	806.5	193.56
External power receptacle to PPDU1	3	18	2*[AWG-000]	806.5	87.102
External power receptacle to PPDU2	3	18	2*[AWG-000]	806.5	87.102
Cable from PPDU1 to ACP1	3	9	2*[AWG-0]	513.4	27.7236
Cable from PPDU2 to ACP2	3	9	2*[AWG-0]	513.4	27.7236
				SUM	711.2816

Table D- 2 270VDC Wiring System

Relative Position of Components	Number of Wires	Length of the Conductor	Cable Selection	Max.WT (Kg/Km)	Weight (kg)
Cable from generator1 to PPDU1	1	18	2*[AWG-0000]	1013	36.468
Cable for earth return	1	18	2*[AWG-0000]	1013	36.468
Cbele from PPDU1 to ELMC1					0
(115V/400Hz)	3	16	AWG-8	85.71	4.11408
(270VDC)	1	16	AWG-8	85.71	1.37136
(28VDC)	1	16	AWG-0	513.4	8.2144
Cable from PPDU1 to ELMC3					0
(115V/400Hz)	3	2	AWG-8	85.71	0.51426
(270VDC)	1	2	AWG-8	85.71	0.17142
(28VDC)	1	2	AWG-0	513.4	1.0268
Cable from PPDU1 to ELMC5					0
(115V/400Hz)	3	10	AWG-8	85.71	2.5713
(270VDC)	1	10	AWG-8	85.71	0.8571
(28VDC)	1	10	AWG-0	513.4	5.134
Cable from Generator2 to PPDU2	1	18	2*[AWG-0000]	1013	36.468
Cable for earth return	1	18	2*[AWG-0000]	1013	36.468
Cable from PPDU2 to ELMC2					0
(115V/400Hz)	3	16	AWG-8	85.71	4.11408
(270VDC)	1	16	AWG-8	85.71	1.37136
(28VDC)	1	16	AWG-0	513.4	8.2144
Cable from PPDU2 to ELMC4					0
(115V/400Hz)	3	2	AWG-8	85.71	0.51426
(270VDC)	1	2	AWG-8	85.71	0.17142
(28VDC)	1	2	AWG-0	513.4	1.0268
Cable from PPDU2 to ELMC6					0
(115V/400Hz)	3	10	AWG-8	85.71	2.5713
(270VDC)	1	10	AWG-8	85.71	0.8571
(28VDC)	1	10	AWG-0	513.4	5.134
APU generator to PPDU1	1	20	2*[AWG-0000]	1013	40.52
External power receptacle to PPDU1	1	18	4*[AWG-0000]	1013	72.936
Cable from PPDU1 to ACP1	1	9	2*[AWG-000]	806.5	14.517
Cable from PPDU1 to ACP2	1	9	2*[AWG-000]	806.5	14.517
				SUM	336.31144

Appendix E Wiring System Sizing

The following paragraph gives a sample of wire sizing.

Step1: Define the route of wire:

From left main generator to the left PPDU

Step2: Find out the distance between these two components:

Based on the CAD model of Flying Crane, the distance between the main generator and PPDU can be found out, it is assume that the length of this wire equals to the distance between these two components. According the same assumption, all the information about the wire included in this case study is shown in Table E- 2.

Step3: Find out the number of cables running between these two components:

As for the variable frequency generating system, it is a three phases system， So, N=3

As for the HVDC system, it is an single phase system, therefore, N=1

Step4: Calculate the power to be transmitted:

According to the load analysis, the peak power requirement for the continuous operating loads is 371.52KVA. For the sake of simplicity, it is assumed that each generator provides half of the total power requirement. So:

$$P= 185.76KVA$$

Step5: Calculate the power per cables runs:

It is assumed that the system is balance system. So:

$$P1=P/3=62KVA$$

Step6: Find out the current carried by each conductor:

As the power conducted in each conductor has already known, the current carried by each conductor can be obtained based on the following equation:

For DC and single-phase AC system: I= $\frac{P_{DC}}{U}$

For single-phase AC system: I= $\frac{P_{AC}}{U}$

For AC balanced three-phase system: I= $\frac{P_{AC}}{U \times \sqrt{3}}$

Therefore, the voltage needs to be known. From the standard MIL-W-5088L, it stipulates that "the total impedance of supply and return paths shall be such that the voltage at the load equipment terminals is within the limits of MIL-STD-704[2]". From the MIL-STD-704F, the voltage range has been specified as follow during the normal steady state:

28 volt DC system: 22.0 to 29.0 volts

270 volt DC system: 250.0 to 280.0 volts

115 volt AC system: 108 to 118 volts, RMS

Due to lack of test data, it assumes that all the voltage values at the busbars installed in the PPDU are the nominal value specified in MIL-STD-704F in terms of this case study. Meanwhile, A 1 % voltage drop is taken into account for the cables which runs from PPDU to ELMC. As for the load circuit, the equipment terminal voltage is taken the lowest permissible value defined in the MIL-STD-704 in order to get the maximum current required by the load.

For this sample calculation, the current in the cable which runs from the generator to the PPDU can be found as follow:

I= P/ U= 224080/115= 649.51A

Step7: Choosing the standard cable which meets the current required.

From the reference table (Table E- 1), it is found that no single cable can carry the required current, so two AWG-000 cables have been chosen for this purpose.

Table E- 1 Reference table [14]

S/No	Item #	Conductor Size (AWG)	Stranding	Conductor Diameter Max.(mm)	Insulation Diameter Max.(mm)	Current Carrying Capacity (Amps)	Max. Resistance in Ω/km (Ω/km) @ 20°C	Max. WT (lbs/1000')	Max. WT. kg/km
1	M22759/87-04	[0000]	2109/30	15.37	16	395	0.177	681	1013
2	M22759/87-03	[000]	1665/30	13.72	14.22	335	0.233	542	806.5
3	M22759/87-02	[00]	1330/30	12.09	12.83	285	0.292	432	642.8
4	M22759/87-0	[0]	1045/30	10.8	11.43	243	0.371	345	513.4
5	M22759/87-1	1	817/30	9.65	10.36	210	0.472	289	430
6	M22759/87-2	2	665/30	8.64	9.25	179	0.581	223	331.8
6	M22759/87-4	4	133/25	6.81	7.32	133	0.902	143	212.8
7	M22759/87-6	6	133/27	5.38	5.82	97	1.43	88.3	131.4
9	M22759/87-8	8	133/29	4.29	4.78	71	2.28	57.6	85.71
10	M22759/87-10	10	37/26	2.84	3.23	32	4.07	31.4	46.72
11	M22759/87-12	12	37/28	2.27	2.67	25	6.49	20.1	29.91
12	M22759/87-14	14	19/27	1.76	2.18	18	9.84	12.95	19.27
13	M22759/87-16	16	19/29	1.41	1.85	14	15.6	8.6	12.8
14	M22759/87-18	18	19/30	1.25	1.65	12	20	6.7	9.97
15	M22759/87-20	20	19/32	1	1.4	9	32	4.55	6.77
16	M22759/87-22	22	19/34	0.8	1.19	6	52.5	3	4.46

Table E- 2 Wiring Design of 115VAC System

Relative Position of Components	Voltage(V)	Power (KVA/KW)	Number of wires	Power Per Run(Kw/KVA)	Current in cable	Length of the Conductor	Cable Selection
Cable from generator1 to PPDU1	115.00	224.08	3	74.69	649.51	18	2*[AWG-000]
Cable for earth return						18	2*[AWG-000]
Cbele from PPDU1 to ELMC1							
(115V/400Hz)	113.85	12.00	3	4.00	35.13	16	AWG-8
(270VDC)	267.30	14.70	1	14.70	54.99	16	AWG-8
(28VDC)	27.72	5.98	1	5.98	215.85	16	AWG-0
(115V/VF)	113.85	10.56	3	3.52	30.92	16	AWG-10
Cable from PPDU1 to ELMC3							
(115V/400Hz)	113.85	12.00	3	4.00	35.13	2	AWG-8
(270VDC)	267.30	14.70	1	14.70	54.99	2	AWG-8
(28VDC)	27.72	5.98	1	5.98	215.85	2	AWG-0
(115V/VF)	113.85	10.56	3	3.52	30.92	2	AWG-10
Cable from PPDU1 to ELMC5							
(115V/400Hz)	113.85	12.00	3	4.00	35.13	10	AWG-8
(270VDC)	267.30	14.70	1	14.70	54.99	10	AWG-8
(28VDC)	27.72	5.98	1	5.98	215.85	10	AWG-0
(115V/VF)	113.85	10.56	3	3.52	30.92	10	AWG-10
Cable from Generator2 to PPDU2	115.00	224.08	3	74.69	649.51	18	2*[AWG-000]
Cable for earth return						18	2*[AWG-000]
Cable from PPDU2 to ELMC2							
(115V/400Hz)	113.85	12.00	3	4.00	35.13	16	AWG-8
(270VDC)	267.30	14.70	1	14.70	54.99	16	AWG-8
(28VDC)	27.72	5.98	1	5.98	215.85	16	AWG-0
(115V/VF)	113.85	10.56	3	3.52	30.92	16	AWG-10
Cable from PPDU2 to ELMC4							
(115V/400Hz)	113.85	12.00	3	4.00	35.13	2	AWG-8
(270VDC)	267.30	14.70	1	14.70	54.99	2	AWG-8
(28VDC)	27.72	5.98	1	5.98	215.85	2	AWG-0
(115V/VF)	113.85	10.56	3	3.52	30.92	2	AWG-10
Cable from PPDU2 to ELMC6							
(115V/400Hz)	113.85	12.00	3	4.00	35.13	10	AWG-8
(270VDC)	267.30	14.70	1	14.70	54.99	10	AWG-8
(28VDC)	27.72	5.98	1	5.98	215.85	10	AWG-0
(115V/VF)	113.85	10.56	3	3.52	30.92	10	AWG-10
APU generator to PPDU1	115.00	224.08	3	74.69	649.51	20	2*[AWG-000]
External Power Receptacle to PPDU1	113.85	224.08	3	74.69	656.07	18	2*[AWG-000]
External Power Receptacle to PPDU2	113.85	224.08	3	74.69	656.07	18	2*[AWG-000]
Cable from PPDU1 to ACP1	108.00	144.60	3	48.20	446.29	9	2*[AWG-0]
Cable from PPDU2 to ACP2	108.00	144.60	3	48.20	446.29	9	2*[AWG-0]

Table E- 3 wiring Design of 270VDC System

Relative Position of Components	Voltage(V)	Power (KW/KVA)	Number of Wires	Power Per Run	Current in Cable	Length of the Conductor	Cable Selection
Cable from generator1 to PPDU1	270.00	203.30	1	203.30	752.96	18	2*[AWG-0000]
Cable for earth return						18	2*[AWG-0000]
Cbele from PPDU1 to ELMC1							
(115V/400Hz)	113.85	11.45	3	3.82	33.52	16	AWG-8
(270VDC)	267.30	14.70	1	14.70	54.99	16	AWG-8
(28VDC)	27.72	5.98	1	5.98	215.85	16	AWG-0
Cable from PPDU1 to ELMC3							
(115V/400Hz)	113.85	11.45	3	3.82	33.52	2	AWG-8
(270VDC)	267.30	14.70	1	14.70	54.99	2	AWG-8
(28VDC)	27.72	5.98	1	5.98	215.85	2	AWG-0
Cable from PPDU1 to ELMC5							
(115V/400Hz)	113.85	11.45	3	3.82	33.52	10	AWG-8
(270VDC)	267.30	14.70	1	14.70	54.99	10	AWG-8
(28VDC)	27.72	5.98	1	5.98	215.85	10	AWG-0
Cable from Generator2 to PPDU2	270.00	203.30	1	203.30	752.96	18	2*[AWG-0000]
Cable for earth return			1			18	2*[AWG-0000]
Cable from PPDU2 to ELMC2							
(115V/400Hz)	113.85	11.45	3	3.82	33.52	16	AWG-8
(270VDC)	267.30	14.70	1	14.70	54.99	16	AWG-8
(28VDC)	27.72	5.98	1	5.98	215.85	16	AWG-0
Cable from PPDU2 to ELMC4							
(115V/400Hz)	113.85	11.45	3	3.82	33.52	2	AWG-8
(270VDC)	267.30	14.70	1	14.70	54.99	2	AWG-8
(28VDC)	27.72	5.98	1	5.98	215.85	2	AWG-0
Cable from PPDU2 to ELMC6							
(115V/400Hz)	113.85	12.00	3	4.00	35.13	10	AWG-8
(270VDC)	267.30	14.70	1	14.70	54.99	10	AWG-8
(28VDC)	27.72	5.98	1	5.98	215.85	10	AWG-0
APU generator to PPDU1	270.00	203.30	1	203.30	752.96	20	2*[AWG-0000]
External power receptacle to PPDU1	267.30	406.60	1	406.60	1521.14	18	4*[AWG-0000]
Cable from PPDU1 to ACP1	250.00	130.09	1	130.09	520.34	9	2*[AWG-000]
Cable from PPDU1 to ACP2	250.00	130.09	1	130.09	520.34	9	2*[AWG-000]

Appendix F Voltage Drop Calculation

As described in Chapter 7, the major difference between AC power transmission and DC power transmission is the resistance increase caused by skin effect. But the skin effect can be neglected for the small gage size wire. In ref[29], it is mentioned that "Skin effect has a negligible effect on resistance at 400 Hz for rounder copper conductors smaller than size 2 AWG and for round aluminium conductors smaller than size 0 AWG".

In the following section, the main feeder which runs from the main generator to the corresponding PPDU is taken as sample calculation which is used to respectively demonstrate the methods used to evaluate the voltage drop in terms of DC power transmission and AC power transmission. The voltage drop in other wires will be tabulated in Table F- 2, Table F- 3.

(a) The Main Feeder in 270VDC System

As the main feeder is used to transmit DC power, only DC resistance of the wire needs to be considered. Therefore,

$$\Delta V = I \cdot R_{DC}$$

Where, I is the carrying current of the wire

R_{DC} is the DC resistance of the wire

(1) Determine the Current Carried by Each Wire

As can be seen from Table E- 3, the main feeder consists of two AWG-0000 wires which run in parallel. It is assumed the two wires are identical. Therefore,

I = Phase current/number of wires = $\frac{752.96}{2}$ = 376.48 A

Phase current= (power requirement of each channel at P.O.R)/270V

It needs to mention that the power requirement at P.O.R includes the maximum load generated by the 5-minute analysis requirement and power loss in the power conversion equipment. It is assumed that the efficiency of the power conversion equipment is 0.9.

(2) Calculate the DC resistance of the wire

The DC resistance of the wire calculated here is based on the datas provided by the manufacturer. As can be seen from Table E- 1, the specific resistance of AWG-0000 wire is 0.177 Ω / Km. So,

$$R_{DC} = L \cdot R_S = (18/1000) \times 0.177 = 0.003186\,\Omega$$

Where,

L is the length of the wire

R_S is the specific resistance of the wire in Ω / Km

(3) Calculate the Voltage Drop

As all the parameters used to calculate the voltage drop of the wire have been found out, the voltage drop of the main feeder is:

$$\Delta V = I \cdot R_{DC} = 376.48 \times 0.004194 = 1.58 \text{ V}$$

As the main feeder between the generator and the corresponding PPDU is two-wire system. Therefore, the voltage drop of the main feeder will be twice as much as that of single wire.

(b) The Main Feeder in 115VAC System

As can be seen from Table E- 2, the wire size of the main feeder is AWG-000, the skin effect must be taken into account. Therefore,

$$\Delta V = I \cdot R_{AC}$$

Where, I is the carrying current of the wire

R_{AC} is the AC resistance of the wire

According to ref [16], the AC resistance is determined by the following equation.

$$R_{AC} = R_{DC} \cdot K$$

Where K is the skin effect ration which is determined from the Table F- 1. In terms of x, whereas:

$$x = 2\pi\alpha\sqrt{\frac{2f\mu}{\rho}}$$

Where: α is the radius of the conductor in centimetre

f is the frequency in cycles per second

μ is the relative magnetic permeability. For nonmagnetic material, μ =1

ρ is the resistivity in abohm-centimeter

(1) Determine the Current Carried by Each Wire

As can be seen from Table E- 2, the main feeder of each phase consists of two AWG-000 wires which run in parallel. It is assumed the three wires are identical. Therefore,

I = Phase current/number of wires = $\frac{649.51}{2}$ = 324.75 A

Phase current= power carried by each phase/115V

It needs to mention that power carried by each phase includes the maximum load generated by the 5-minute analysis requirement and power loss in the power conversion equipment. It is assumed that the efficiency of the power conversion equipment is 0.9.

(2) Calculate the AC resistance of the wire

In terms of the DC resistance of the main feeder.

$$R_{DC} = L \cdot R_S = (18/1000) \times 0.233 = 0.004194\,\Omega$$

In terms of the power frequency f, the maximum frequency of the generated power (720Hz) is used in order to get the maximum value of the AC resistance. The radius of the wire can be obtained from Table E- 1. As the wire is made from copper, the copper resistivity ρ can be got from ref[16]. So:

$$x = 2\pi\alpha\sqrt{\frac{2f\mu}{\rho}} = 2\times\pi\sqrt{\frac{2\times720\times1}{1720}} = 3.9$$

Therefore, the skin effect ration can be obtained from the reference table(Table F- 1).

$$K = 1.64$$

So, $$R_{AC} = 1.64 \times 0.004194 = 0.006878\,\Omega$$

(3) Calculate the voltage drop

As all the parameters used to calculate the voltage drop of the wire have been found out, the voltage drop of the main feeder is:

$$\Delta V = I \cdot R_{AC} = 324.75 \times 0.006878 = 2.23\text{V}$$

In this case study, it is assumed that the three-phase AC system is balanced. Therefore, there is no current in the neutral phase. So, the voltage drop of the main feeder is the same value as that of single wire.

Table F- 1 Skin-Effect Ratios [16]

x	K	K'	x	K	K'	x	K	K'	x	K	K'
0.0	1.00000	1.00000	2.9	1.28644	0.86012	6.6	2.60313	0.42389	17.0	6.26817	0.16614
0.1	1.00000	1.00000	3.0	1.31809	0.84517	6.8	2.67312	0.41171	18.0	6.62129	0.15694
0.2	1.00001	1.00000	3.1	1.35102	0.82975	7.0	2.74319	0.40021	19.0	6.97446	0.14870
0.3	1.00004	0.99998	3.2	1.38504	0.81397	7.2	2.81334	0.38933	20.0	7.32767	0.14128
0.4	1.00013	0.99993	3.3	1.41999	0.79794	7.4	2.88355	0.37902	21.0	7.68091	0.13456
0.5	1.00032	0.99984	3.4	1.45570	0.78175	7.6	2.95380	0.36923	22.0	8.03418	0.12846
0.6	1.00067	0.99966	3.5	1.49202	0.76550	7.8	3.02411	0.35992	23.0	8.38748	0.12288
0.7	1.00124	0.99937	3.6	1.52879	0.74929	8.0	3.09445	0.35107	24.0	8.74079	0.11777
0.8	1.00212	0.99894	3.7	1.56587	0.73320	8.2	3.16480	0.34263	25.0	9.09412	0.11307
0.9	1.00340	0.99830	3.8	1.60314	0.71729	8.4	3.23518	0.33460	26.0	9.44748	0.10872
1.0	1.00519	0.99741	3.9	1.64051	0.70165	8.6	3.30557	0.32692	28.0	10.15422	0.10096
1.1	1.00758	0.99621	4.0	1.67787	0.68632	8.8	3.37597	0.31958	30.0	10.86101	0.09424
1.2	1.01071	0.99465	4.1	1.71516	0.67135	9.0	3.44638	0.31257	32.0	11.56785	0.08835
1.3	1.01470	0.99266	4.2	1.75233	0.65677	9.2	3.51680	0.30585	34.0	12.27471	0.08316
1.4	1.01969	0.99017	4.3	1.78933	0.64262	9.4	3.58723	0.29941	36.0	12.98160	0.07854
1.5	1.02582	0.98711	4.4	1.82614	0.62890	9.6	3.65766	0.29324	38.0	13.68852	0.07441
1.6	1.03323	0.98342	4.5	1.86275	0.61563	9.8	3.72812	0.28731	40.0	14.39545	0.07069
1.7	1.04205	0.97904	4.6	1.89914	0.60281	10.0	3.79857	0.28162	42.0	15.10240	0.06733
1.8	1.05240	0.97390	4.7	1.93533	0.59044	10.5	3.97477	0.26832	44.0	15.80936	0.06427
1.9	1.06440	0.96795	4.8	1.97131	0.57852	11.0	4.15100	0.25622	46.0	16.51634	0.06148
2.0	1.07816	0.96113	4.9	2.00710	0.56703	11.5	4.32727	0.24516	48.0	17.22333	0.05892
2.1	1.09375	0.95343	5.0	2.04272	0.55597	12.0	4.50358	0.23501	50.0	17.93032	0.05656
2.2	1.11126	0.94482	5.2	2.11353	0.53506	12.5	4.67993	0.22567	60.0	21.46541	0.04713
2.3	1.13069	0.93527	5.4	2.18389	0.51566	13.0	4.85631	0.21703	70.0	25.00063	0.04040
2.4	1.15207	0.92482	5.6	2.25393	0.49764	13.5	5.03272	0.20903	80.0	28.53593	0.03535
2.5	1.17538	0.91347	5.8	2.32380	0.48086	14.0	5.20915	0.20160	90.0	32.07127	0.03142
2.6	1.20056	0.90126	6.0	2.39359	0.46521	14.5	5.38560	0.19468	100.0	35.60666	0.02828
2.7	1.22753	0.88825	6.2	2.46338	0.45056	15.0	5.56208	0.18822	∞	∞	0
2.8	1.25620	0.87451	6.4	2.53321	0.43682	16.0	5.91509	0.17649			

Table F- 2 Voltage Drop in VF System

Relative Position of Components	Number of Wires	Length of the Conductor	Current per Phase	Cable Selection	Current of per wire	Resistance in Ω/Km(20℃)	Resistivity (abohm-cm)	Radius(cm)	Maximum Frequency(Hz)	Relative Magnetic Permeability	X	K	R_{DC} (Ω)	R_{AC} (Ω)	Voltage Drop(V)
Cable from generator1 to PPDU1	3	18	649.51	2*[AWG-000]	324.7536232	0.233	1720	0.686	720	1	3.9	1.64	0.004194	0.006878	2.23
Cable for earth return	1	18		2*[AWG-000]	0		1720	0.686	720	1	3.9	1.64	0	0	0.00
Cbele from PPDU1 to ELMC1							1720			1	0.0		0	0	0.00
(115V/400Hz)	3	16	35.13	AWG-8	35.13	2.28	1720	0.2145	400	1	0.9	1	0.03648	0.03648	1.28
(270VDC)	1	16	54.99	AWG-8	54.99	2.28	1720	0.2145	0	1	0.0	1	0.03648	0.03648	2.01
(28VDC)	1	16	215.85	AWG-0	215.85	0.371	1720	0.54	0	1	0.0	1	0.005936	0.005936	1.28
(115V/VF)	3	16	30.92	AWG-10	30.92	4.07	1720	0.142	720	1	0.8	1	0.06512	0.06512	2.01
Cable from PPDU1 to ELMC3					0.00		1720			1	0.0	1	0	0	0.00
(115V/400Hz)	3	2	35.13	AWG-8	35.13	2.28	1720	0.2145	400	1	0.9	1	0.00456	0.00456	0.16
(270VDC)	1	2	54.99	AWG-8	54.99	2.28	1720	0.2145	0	1	0.0	1	0.00456	0.00456	0.25
(28VDC)	1	2	215.85	AWG-0	215.85	0.371	1720	0.54	0	1	0.0	1	0.000742	0.000742	0.16
(115V/VF)	3	2	30.92	AWG-10	30.92	4.07	1720	0.142	720	1	0.8	1	0.00814	0.00814	0.25
Cable from PPDU1 to ELMC5					0.00		1720			1	0.0	1	0	0	0.00
(115V/400Hz)	3	10	35.13	AWG-8	35.13	2.28	1720	0.2145	400	1	0.9	1	0.0228	0.0228	0.80
(270VDC)	1	10	54.99	AWG-8	54.99	2.28	1720	0.2145	0	1	0.0	1	0.0228	0.0228	1.25
(28VDC)	1	10	215.85	AWG-0	215.85	0.371	1720	0.54	0	1	0.0	1	0.00371	0.00371	0.80
(115V/VF)	3	10	30.92	AWG-10	30.92	4.07	1720	0.142	720	1	0.8	1	0.0407	0.0407	1.26
Cable from Generator2 to PPDU2	3	18	649.51	2*[AWG-000]	324.755	0.233	1720	0.686	720	1	3.9	1.64	0.004194	0.006878	2.23
Cable for earth return	1	18		2*[AWG-000]	0	0.233	1720	0.686	720	1	3.9	1.64	0.004194	0.006878	0.00
Cable from PPDU2 to ELMC2							1720			1	0.0	1	0	0	0.00
(115V/400Hz)	3	16	35.13	AWG-8	35.13	2.28	1720	0.2145	400	1	0.9	1	0.03648	0.03648	1.28
(270VDC)	1	16	54.99	AWG-8	54.99	2.28	1720	0.2145	0	1	0.0	1	0.03648	0.03648	2.01
(28VDC)	1	16	215.85	AWG-0	215.85	0.371	1720	0.54	0	1	0.0	1	0.005936	0.005936	1.28
(115V/VF)	3	16	30.92	AWG-10	30.92	4.07	1720	0.142	720	1	0.8	1	0.06512	0.06512	2.01
Cable from PPDU2 to ELMC4					0.00		1720			1	0.0	1	0	0	0.00
(115V/400Hz)	3	2	35.13	AWG-8	35.13	2.28	1720	0.2145	400	1	0.9	1	0.00456	0.00456	0.16
(270VDC)	1	2	54.99	AWG-8	54.99	2.28	1720	0.2145	0	1	0.0	1	0.00456	0.00456	0.25
(28VDC)	1	2	215.85	AWG-0	215.85	0.371	1720	0.54	0	1	0.0	1	0.000742	0.000742	0.16
(115V/VF)	3	2	30.92	AWG-10	30.92	4.07	1720	0.142	720	1	0.8	1	0.00814	0.00814	0.25
Cable from PPDU2 to ELMC6					0.00		1720			1	0.0	1	0	0	0.00
(115V/400Hz)	3	10	35.13	AWG-8	35.13	2.28	1720	0.2145	400	1	0.9	1	0.0228	0.0228	0.80
(270VDC)	1	10	54.99	AWG-8	54.99	2.28	1720	0.2145	0	1	0.0	1	0.0228	0.0228	1.25
(28VDC)	1	10	215.85	AWG-0	215.85	0.371	1720	0.54	0	1	0.0	1	0.00371	0.00371	0.80
(115V/VF)	3	10	30.92	AWG-10	30.92	4.07	1720	0.142	720	1	0.8	1	0.0407	0.0407	1.26
APU generator to PPDU1	3	20	649.51	2*[AWG-000]	324.755	0.233	1720	0.686	720	1	3.9	1.82614	0.00466	0.00851	2.76
External power receptacle to PPDU1	3	18	656.07	2*[AWG-000]	328.0339628	0.233	1720	0.686	400	1	2.9	1.28644	0.004194	0.005395	1.77
External power receptacle to PPDU2	3	18	656.07	2*[AWG-000]	328.0339628	0.233	1720	0.686	400	1	2.9	1.28644	0.004194	0.005395	1.77
Cable from PPDU1 to ACP1	3	9	446.29	2*[AWG-0]	223.1466049	0.371	1720	0.54	720	1	3.1	1.35102	0.003339	0.004511	1.01
Cable from PPDU2 to ACP2	3	9	446.29	2*[AWG-0]	223.1466049	0.371	1720	0.54	720	1	3.1	1.35102	0.003339	0.004511	1.01

Table F- 3 Voltage Drop in 270VDC System

Relative Position of Components	Number of Wires	Length of the Conductor	Current per Phase	Cable Selection	Current of per wire	Resistance in Ω/Km(20℃)	Resistivity (abohm-cm)	Radius (cm)	Maximum Frequency(Hz)	Relative Magnetic Permeability	X	K	R_{DC} (Ω)	R_{AC} (Ω)	Voltage Drop(V)
Cable from generator1 to PPDU1	1	18	752.96	2*[AWG-0000]	376.48	0.177	1720	0.7685	0	1	0.0	1	0.003186	0.003186	1.20
Cable for earth return	1	18	752.96	2*[AWG-0000]	376.48	0.177	1720	0.7685	0	1	0.0	1	0.003186	0.003186	1.20
Cbele from PPDU1 to ELMC1															
(115V/400Hz)	3	16	33.52	AWG-8	33.52	2.28	1720	0.2145	400	1	0.9	1	0.03648	0.03648	1.22
(270VDC)	1	16	54.99	AWG-8	54.99	2.28	1720	0.2145	0	1	0.0	1	0.03648	0.03648	2.01
(28VDC)	1	16	215.85	AWG-0	215.85	0.371	1720	0.54	0	1	0.0	1	0.005936	0.005936	1.28
Cable from PPDU1 to ELMC3															
(115V/400Hz)	3	2	33.52	AWG-8	33.52	2.28	1720	0.2145	400	1	0.9	1	0.00456	0.00456	0.15
(270VDC)	1	2	54.99	AWG-8	54.99	2.28	1720	0.2145	0	1	0.0	1	0.00456	0.00456	0.25
(28VDC)	1	2	215.85	AWG-0	215.85	0.371	1720	0.54	0	1	0.0	1	0.000742	0.000742	0.16
Cable from PPDU1 to ELMC5															
(115V/400Hz)	3	10	33.52	AWG-8	33.52	2.28	1720	0.2145	400	1	0.9	1	0.0228	0.0228	0.76
(270VDC)	1	10	54.99	AWG-8	54.99	2.28	1720	0.2145	0	1	0.0	1	0.0228	0.0228	1.25
(28VDC)	1	10	215.85	AWG-0	215.85	0.371	1720	0.54	0	1	0.0	1	0.00371	0.00371	0.80
Cable from Generator2 to PPDU2	1	18	752.96	2*[AWG-0000]	376.48	0.177	1720	0.7685	0	1	0.0	1	0.003186	0.003186	1.20
Cable for earth return	1	18	752.96	2*[AWG-0000]	376.48	0.177	1720	0.7685	0	1	0.0	1	0.003186	0.003186	1.20
Cable from PPDU2 to ELMC2															
(115V/400Hz)	3	16	33.52	AWG-8	33.52	2.28	1720	0.2145	400	1	0.9	1	0.03648	0.03648	1.22
(270VDC)	1	16	54.99	AWG-8	54.99	2.28	1720	0.2145	0	1	0.0	1	0.03648	0.03648	2.01
(28VDC)	1	16	215.85	AWG-0	215.85	0.371	1720	0.54	0	1	0.0	1	0.005936	0.005936	1.28
Cable from PPDU2 to ELMC4															
(115V/400Hz)	3	2	33.52	AWG-8	33.52	2.28	1720	0.2145	400	1	0.9	1	0.00456	0.00456	0.15
(270VDC)	1	2	54.99	AWG-8	54.99	2.28	1720	0.2145	0	1	0.0	1	0.00456	0.00456	0.25
(28VDC)	1	2	215.85	AWG-0	215.85	0.371	1720	0.54	0	1	0.0	1	0.000742	0.000742	0.16
Cable from PPDU2 to ELMC6															
(115V/400Hz)	3	10	35.13	AWG-8	35.13	2.28	1720	0.2145	400	1	0.9	1	0.0228	0.0228	0.80
(270VDC)	1	10	54.99	AWG-8	54.99	2.28	1720	0.2145	0	1	0.0	1	0.0228	0.0228	1.25
(28VDC)	1	10	215.85	AWG-0	215.85	0.371	1720	0.54	0	1	0.0	1	0.00371	0.00371	0.80
APU generator to PPDU1	1	20	752.96	2*[AWG-0000]	376.48	0.177	1720	0.7685	0	1	0.0	1	0.00354	0.00354	1.33
External power receptacle to PPDU1	1	18	1521.14	4*[AWG-0000]	380.28	0.177	1720	0.7685	0	1	0.0	1	0.003186	0.003186	1.21
Cable from PPDU1 to ACP1	1	9	520.34	2*[AWG-000]	260.17	0.233	1720	0.686	0	1	0.0	1	0.002097	0.002097	0.55
Cable from PPDU1 to ACP2	1	9	520.34	2*[AWG-000]	260.17	0.233	1720	0.686	0	1	0.0	1	0.002097	0.002097	0.55

Appendix G Minimum VA Rating Assessment

The system power requirement at P.O.R has been discussed at the Chapter5, which can be seen in Table G- 1 Power Requirement at P.O.R. The sizing criteria used in these two systems are the same. The power loss in power conversion equipment has been taken into account when sizing the system capacity at P.O.R. It is assumed that the efficiency of all power conversion equipment is 0.9.

Table G- 1 Power Requirement at P.O.R

System	Power Requirement Per Channel
270VDC	249KW
115V/VF	272KVA

Note, the system power factor is assumed at 0.9 lgging.

Therefore, the minimum VA rating of the generator is determined by the power loss in the main feeder and the generator itself.

a. 115V/VF System

(1) Power Loss in the Main Feeder

As can be seen from appendix E, the main feeder of each phase consists of two AWG-000 wires. The following calculation is based on single wire. Therefore, the total power loss in the main feeder equals the product of the power loss in single wire and the number of wires. As the resistance of the main feeder has been assessed in appendix F, the power loss in each wire can be easily obtained via the following equation:

$$P_{Loss} = I^2 \cdot R$$

Where, P_{Loss} is power loss in each wire of the main feeder

I is the current carried by each wire of the main feeder

R is the resistance of the wire

In terms of the current I, it is determined by the power required at the P.O.R and the voltage. In this case study, the voltage at the P.O.R is the nominal value defined in MIL-STD-704. Therefore,

$$I = \text{power carried by each wire} \Big/ \text{voltage at P.O.R}$$

The main feeder consists of three phases and each phase is comprise of two AGW-000 wires Moreover, an additional 33% capacity has been considered as the system stable margin in chapter5 , therefore,

$$\text{power carried by each wire} = \left(272 \big/ 1.33\right) \Big/ 6 = 34\text{KVA}$$

So, $$I = 34 \times 1000 \Big/ 115 = 296\text{A}$$

As a result, the power loss in each wire of the main feeder will be:

$$P_{Loss} = I^2 \cdot R = 296^2 \times 0.00688 = 0.604 \text{ KW}$$

The total power loss in the main feeder is:

$$P = P_{Loss} \times 6 = 3.624 \text{KW}$$

So, Minimum VA rating of the variable frequency generator will be:

$$C_{\min} = \sqrt{\left(272 \times \sin\left(\arccos(0.9)\right)\right)^2 + \left(3.624 + 272 \times 0.9\right)^2} = 275.1 \text{KVA}$$

b. 270VDC System

In terms of the 270VDC system, all the factors which are related to the VA capacity of the generator have been described in chapter7. Therefore, the analysis follows the procedures showed in Figure G- 1.

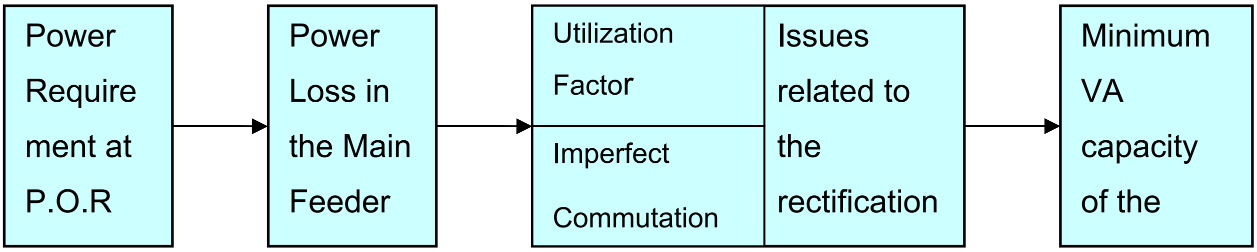

Figure G- 1 Minimum VA requirement of 270VDC Generator

(1) Power Loss in the Main Feeder

Here, the main feeder used in 270VDC system consists of positive line and negative line since the wing is of non-metal material. Each line consists of two AWG-0000 wires. The method used to calculate the power loss in the main feeder is the same as the one used in 115V/VF system. The main differences between these two systems are the resistance of the main feeder and the carrying current. The resistance is each wire can be obtained in Table F- 3. Therefore, power carried by each wire is:

$$P = \left(249/1.33\right)/2 = 93.6KW$$

So, the current carried by each wire is:

$$I = 93.6 \times 1000/270 = 346A$$

As a result, the power loss in each wire is:

$$P_{Loss} = I^2 \cdot R = 346^2 \times 0.003186 = 0.382\ KW$$

So, the total power loss in the main feeder is:

$$P = P_{Loss} \times 4 = 1.531KW$$

(2) Minimum VA Capacity Required by the Rectification Circuit

As described in Chapter 7, two issues affect the input capacity of a rectification circuit, which is also equivalent to VA capacity of the alternator.

As regards the utilization factor, it is determined by the follow equation:

$$\lambda = \frac{V_d I_d}{\sqrt{3} V_a I_a} \text{ [8]}$$

Where, V_d is the output voltage of the rectification unit

I_d is the output current of the rectification unit

V_a is the RMS value of the stator line voltage

I_a is the RMS value of line current

However, the relationship between input and output of the rectification circuit in terms of voltage and current is shown below:

$$V_d = \sqrt{2} V_a \frac{2m}{\pi} \sin\left(\frac{\pi}{2m}\right) \text{ [8]}$$

$$I_d = I_a \sqrt{\frac{m}{2}} \text{ [8]}$$

Where, m is the number of stator phases

In this case study, the number of stator phases is three. So, the utilization of this rectification unit is:

$$\lambda = \frac{3}{\pi} = 0.955$$

In terms of the effect of imperfect commutation which is caused by the generator windings, it will cause a reduction in output voltage. The voltage drop is determined by the following equation[8]:

$$\Delta V_d = \frac{1}{2} V_d (1 - \cos U)$$

Where, U is the overlap angle

So, the new output voltage is:

$$V_{dn} = \frac{1}{2} V_d (1 + \cos U)$$

In this case study, it is assumed that the overlap angle is 20° as the transient reactance of the windings and characteristics of the diode is not known. So,

$$V_{dn} = \frac{1}{2} V_d (1 + \cos U) = 0.96 V_d$$

Therefore, the VA rating of the alternator will be:

$$C = \left({C_o}/{\lambda} \right) / 0.96$$

Where, C_o is the power requirement at the output terminal of the DC generator.

In terms of this case study, the VA rating the alternator is:

C=((249+1.531)/0.955)/0.966 = 273KVA

Appendix H Power off-Take Evaluation

As all the considerations have been mentioned in chapter 7, the following section will compute all the transmission loss and generating loss respectively. Finally, the value of system power off-take can be got. For the comparison purpose, the following assumptions will be given firstly:

(1) The alternator of the 270VDC generator is assumed to be the same as the one used in 115V/VF system.
(2) The VF generating system efficiency value 86% mentioned in ref[26] is adopted for this case study.

The following calculation is on single channel basis.

(1) Power Transmission Loss

The resistance of each wire has been found out in Appendix F. As can be seen from the results, there is no difference in the wire resistance when conducting AC power or DC power if the wire size is smaller than AWG-2. For comparison purpose, those wire whose size is bigger than AWG-2 will only be taken into account. As the calculation method has been demonstrated in Appendix F, So, the author only gives the calculation procedures:

(1) Calculate the power loss in the wires between ECS electric driven compressor and the PPDU.
(2) Determine the total power requirement at the P.O.R, which includes the power loss in the wire which is used to power the electric driven compressor.
(3) Determine the current conducted in the main feeder
(4) Calculate the power loss in the main feeder.

The power transmission loss of these two systems will be tabulated below:

Table H- 1 115V/VF System Transmission Loss

Relative Position of Components	Number of Wires	Current per Phase	Cable Selection	Current of per wire	R_{AC} (Ω)	Power Loss(KW)
Cable from generator1 to PPDU1	3	596.63	2*[AWG-000]	298.32	0.006878	3.67
Cable for earth return	1	0	2*[AWG-000]	0.00	0	0.00
Cable from PPDU1 to ACP1	3	446.29	2*[AWG-0]	223.15	0.004511	1.35

Table H- 2 270VDC System Transmission Loss

Relative Position of Components	Number of Wires	Current per Phase	Cable Selection	Current of per wire	R_{DC} (Ω)	Power Loss(KW)
Cable from generator1 to PPDU1	1	693.74	2*[AWG-0000]	346.87	0.003186	0.77
Cable for earth return	1	693.74	2*[AWG-0000]	346.87	0.003186	0.77
Cable from PPDU1 to ACP1	1	520.34	2*[AWG-000]	260.17	0.002097	0.28

(2) Power Generation Loss

With respect to generation loss, the main difference between these two systems is that the rectification loss needs to be taken into account in terms of 270VDC generator. According to ref[6], the rectification loss is determined by the following equation:

$$P_{loss\_D} = i_{av\_D} \cdot V_D \cdot N$$

Where, N is the number of pulses within an interval

V_D is the voltage drop across the semiconductor

i_{av_D} is the average current across the semiconductor

In this case study, the power diode is considered for the rectification device, which normally presents a conduction drop in the order of 0.7V. According to the 270VDC generator architecture presented in Figure 7-4, the parameter N and i_{av_D} can be determined as follow:

N = 6 (three-phase full wave rectification)

$$i_{av\_D} = I_D / 6$$

Where, I_D is the output current of the rectifier.

I_D is determined by the total power requirement at the P.O.R, which includes the power loss in the wire used to power the electric-driven compressor, So,

$$I_D = 693.7 \text{ A}$$

In terms of the full-wave rectification, two diodes are required to operate at the same time. Therefore,

$$V_D = 1.4\text{V}$$

So,

$$P_{loss\_D} = 6 \times \frac{693.7}{6} \times 1.4 = 0.971\text{KW}$$

As all the power loss has been found out, the power off-take of these two systems is tabulated as follow:

Table H- 3 Power off-take

System	Power requirement at the P.O.R	Power loss in the main feeder	Power Loss in the rectifier	Efficiency	Power off Take
270VDC	187.31	1.54	0.971	0.86	220.7
115VAC	205.84	3.67	0	0.86	243.11