PROGNOSTIC CONTROL AND LOAD SURVIVABILITY

IN SHIPBOARD POWER SYSTEMS

A Thesis

by

LAURENCE J. THOMAS

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2010

Major Subject: Electrical Engineering

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Approved by:

Chair of Committee,	Karen L. Butler-Purry
Committee of Members,	Deepa Kundur
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ABSTRACT

Prognostic Control and Load Survivability in Shipboard Power Systems.

(December 2010)

Laurence J. Thomas, B.S., Prairie View A&M University

Chair of Advisory Committee: Dr. Karen L. Butler-Purry

In shipboard power systems (SPS), it is important to provide continuous power to vital loads so that their desired missions can be completed successfully. Several components exist between the primary source and the vital load such as transformers, cables, or switching devices. These components can fail due to mechanical stresses, electrical stresses, and overloading which could lead to a system failure. If the normal path to a vital load cannot supply power to it, then it should be powered through its alternate path. The process of restoring, balancing, and minimizing power losses to loads is called network reconfiguration. Prognostics is the ability to predict precisely and accurately the remaining useful life of a failing component. In this work, the prognostic information of the power system components is used to determine if reconfiguration should be performed if the system is unable to accomplish its mission. Each component will be analyzed using the *Weibull Distribution* to compute the conditional reliability from present time to the end of the mission. To determine if reconfiguration is needed, all components to a given load will be utilized in structure functions to determine if a load will be able to survive during a time period. Structure functions are used to show how components are interconnected, and also provide a mathematical means for computing the total probability of a system. This work will provide a method to compute the conditional survivability to a given load, and the results indicate the top five loads that have the lowest conditional survivability during a mission in known configuration. The results show the computed conditional survivability of loads on an all electric navy ship. The loads conditional survivability is computed on high/medium voltage level and a low voltage level to show how loads are affected by failing components along their path.

DEDICATION

To the memory of my late father, Mr. Roland Thomas Jr

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First of all, I would like to give thanks to GOD for allowing me to better myself scholastically and allowing me to keep a level head when research was not very clear to me.

I would like to thank Dr. Karen L. Butler-Purry for giving me the opportunity to be part of her research and guiding me along the right path to finish this work. If it were not for her giving me an opportunity to do this research, this thesis would not have been written.

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I owe the completion of the research to the number of people I encountered while at Texas A&M University. They helped me when times were rough and kept me motivated to complete each task at hand. These people worked in the Power System Automation Lab (PSALers) and they are: Dr. NDR Sarma, Fabian Uriarte, Ayorinnde Akkinikawe, Hamed Funmilayo, James Silva, Tushar Amba, Guyatri Damele, Ebonie Mayhorn, Ariana Amberg, Hariharan Subramanian, Babak Farhangi, and Milad Falahi.

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CHAPTER I

INTRODUCTION

A basic power system consists of power *generation* plants, transmission systems and distribution systems. Electric power can be generated from various types of generation plants such as fossil fuel power plants, nuclear power plants, or hydroelectric power plants. Electric power today is also being generated by renewable sources such as wind, solar, etc. Transmission systems consist of transformers, circuit breakers, and transmission lines to deliver power from the generation power plants to distribution systems. Commercial, residential, and industrial customers are the types of loads served by the distribution system.

Traditionally, reliability has been used on terrestrial systems to improve outage situations. The outages are recorded and used as data to predict when an outage might occur during future years. To improve reliability, energy companies build redundancies throughout a power system. These redundancies are normally placed between the power generation plant and the distribution system. The distribution system may have redundancies also. The whole idea of the redundancy concept is to provide constant power delivery and minimize the number of outages.

The US Navy protects the country on various combatants, cruisers, and submarines which are usually in service for an average 35 years. During the past decade, the concept of an all electric ship has been introduced as the next generation ships. Research on the all electric ship is ongoing to the Navy and to the Texas A&M University Electrical Engineering Department. Navy ships have a power system with similar power system components as traditional terrestrial power system but on a condensed space. Since Navy ships are used during warfare, the Department of Defense needs the power system on ships to be as reliable as possible. To keep the power systems reliable, redundancies are used to maximize the systems' reliability.

This thesis follows the style and format of *IEEE Transactions on Power Delivery*.

1.1 Objective

Research in the Power Systems Automation Lab at Texas A&M University developed reconfiguration techniques for Navy ships. Two techniques were developed for catastrophic events such as faults and cascading faults due to weapon damage. The first reconfiguration technique used an optimization technique that focused on the best configuration for the ship. The second reconfiguration technique focused on load priority at which the algorithm checks for a continuous path back to the source from vital loads. The purpose of this work is to show that reconfiguration can be determined by computing the conditional survivability to each load. The objectives of the work presented in this thesis were to:

1) Develop an algorithm to compute the load survivability using the remaining life of power system components.
2) Develop an approach to determine if reconfiguration in shipboard power systems is needed based on load survivability.

1.2 Motivation

It is imperative to know survivability information because ships are deployed for long periods of time. The more reliable a system is the less the user has to be concerned with maintenance and other problems with the system. The motivation of this work is to ensure that loads are continuously served based on component survivability. The components of the power system are continuously monitored to provide the user with survivability information so that the user will know if a load can be continuously served during a mission.

1.3 Content Overview

In this section, this thesis will be briefly discussed by each chapter. A background and literature review begins the thesis by describing Navy ships and its topology. Chapter II also discusses reconfiguration techniques that were developed in the Power System Automation Lab (PSAL). Reliability, reliability centered maintenance (RCM), and power distribution system reliability techniques are principles are mentioned as well. In chapter III, the modeling principles of structure functions and survivability are stated. The problem formulation is also stated clearly through mathematical representation. Chapter IV demonstrates the structure function method to determine conditional load survivability. The results from the methodology are shown through case studies in chapter V. A summary of the methodology and results are discussed in chapter VI.

CHAPTER II

BACKGROUND AND LITERATURE REVIEW

This chapter presents background information about power systems on Navy ships. It is important that the power system on Navy ships is reliable and able to survive weapon attacks. Survivability can be used to reconfigure a subsystem if is near failure. If a component is near failure, then a ship's topology should change to provide power to essential loads for specific tasks and missions. The definition and concepts of reliability are also discussed in this chapter to build an understanding of how it is used in terrestrial systems for outages and planning for utility companies.

2.1 AC Radial Shipboard Power System

AC Radial Shipboard Power Systems (SPS) are radial distribution systems that are connected in a ring configuration. One reason for this ring structure is to make sure there is continuous power flow to loads at all times. U.S. Navy ships are three phase 460 VAC delta connected distribution systems. The SPS is delta connected ungrounded network. The advantage of ungrounded systems is that line to ground faults do not result in an outage of the grounded feeder. It also improves reliability because the system remains functional if ground faults occur.

There are many components that make up a distribution network on a SPS such as generators, cable, switches, and loads. Generators are the primary source of power, and are also used for emergency purposes. For example, if the primary generator(s) cannot supply the desired power to a system, then a back-up generator will supply the remaining power needed to the system. Transformers are also essential in the ship network. Since SPS is a distribution network, 480/208-120V step-down transformers are used to supply 120 volt single phase loads. Single phase loads consist of lighting, air conditioning, receptacles, etc. Two types of loads exist on a SPS: vital loads and non-vital loads, which are either single-phase or three-phase. Communications, weapons, steering, and other motors are types of vital loads. Automatic bus transfers (ABT) are switches that automatically disconnect vital loads from the primary path and connect the load to the secondary path when it senses the loss of voltage from the primary source. Manual bus transfers (MBT) are identical to ABTs except the switching is done manually. Circuit breakers are protection devices placed throughout the system to protect the power system from overcurrent, undervoltages, etc. Circuit breakers are normally closed and trip when a fault has been detected in the system. Once the fault has cleared, the circuit breakers are closed manually or automatically. Low voltage releases (LVR) are also protection devices that are placed in front of motor loads and automatically starts when power is returned to normal after a fault. The low voltage protector (LVP) is also a protective device that protects motors from high currents. The LVP does not automatically restart after a fault has cleared and an operator must physically reset this device to put the motor back in service. Switchboards are buses that distribute electrical power from the generator to various loads.

2.2 Integrated Power System (IPS)

The integrated shipboard power system (IPS) has some similarities to the AC Radial SPS. In Fig. 2.1, the IPS schematic is shown. This figure shows all components at the high level and all components in each zone. The advanced induction motors are loads at the high voltage level powered by two 36MW generators and two 4MW generators connected by a ring bus. The loads in each zone are powered via *PCM4*s, power converters, which convert AC voltage to DC voltage. The DC zone powers DC loads and AC loads in each zone. The AC loads are powered via DC/AC power converters.

The high voltage subsystem is configured in a ring structure and contains four generators as shown in Fig. 2.1. Each generator is connected to a main and an auxiliary bus, which are interconnected depending on the ship's configuration or mode of operation. The IPS is also a radial distribution system in which the power flows directly from the generator to the load. The IPS is different because it introduces DC buses at the 1kV level. The voltage is decreased by 13.8k/ 4160V AC step down transformers. The 1kV DC is obtained via AC/DC converters. The propulsion motors on the IPS are induction motors that require 4160V AC rated at 18.25MW at full rating. Voltage used by the propulsion motor is obtained through the transformers as described above. The second step-down voltage occurs through a PCM, power converter, which converts AC voltage to DC voltage. 1kV DC is then converted to three voltages via DC/DC converters to supply DC loads of 375VDC, 650VDC, and AC loads from 800VDC power converters.

The four zones on the IPS are energized from PCM4's through two DC buses. The two DC buses are labeled as the port and starboard buses. The power flow is radial and it flows from the bus directly to the load. Six DC/DC converters are used for different DC voltage levels for a given loads. Each DC bus contains three DC/DC converters at each of the voltage levels as described above. The loads are of two types: vital and non-vital. The vital loads are loads that are necessary for the ship to perform its mission. There are two paths available to supply vital loads. In each zone, 800VDC is converted to AC voltage to supply AC loads. AC loads can also be vital or non-vital at which the vital loads have an alternate path to continuously supply such loads. Each zone is interconnected by zone ties.

The IPS is designed in such a way that it can be configured in one of four configuration modes. Each configuration mode changes the way the generators work together through the ring structure. Two generators are rated at 36MW each, and the other two are rated at 4MW each. The Common Bus Mode utilizes the complete ring of the ship and all four generators work together to supply all loads. The Port/Starboard Split Bus Mode provides power by opening breakers to split the ring in half. The Port/Starboard Split Bus Mode divides the ship into an upper region and lower region which generators $MTG1$ and $ATG1$ work together to energize loads connected to the star bus. Generators $MTG2$ and $ATG2$ work together to energize loads connected to the port bus. The Forward/Aft Split Bus Mode separates the generators in half forming a left-hand region (fore) and a right hand-region (aft) pairing generators $MTG1$ and $ATG2$ together to energize the star bus and $ATG1$ and $ATG2$ together to energize the port bus. In the 4-Way Split Bus Mode all generators work separately to energize loads in each zone separately. In this work, no studies were done on the 4-Way Split Bus Mode due to the zone connectivity.

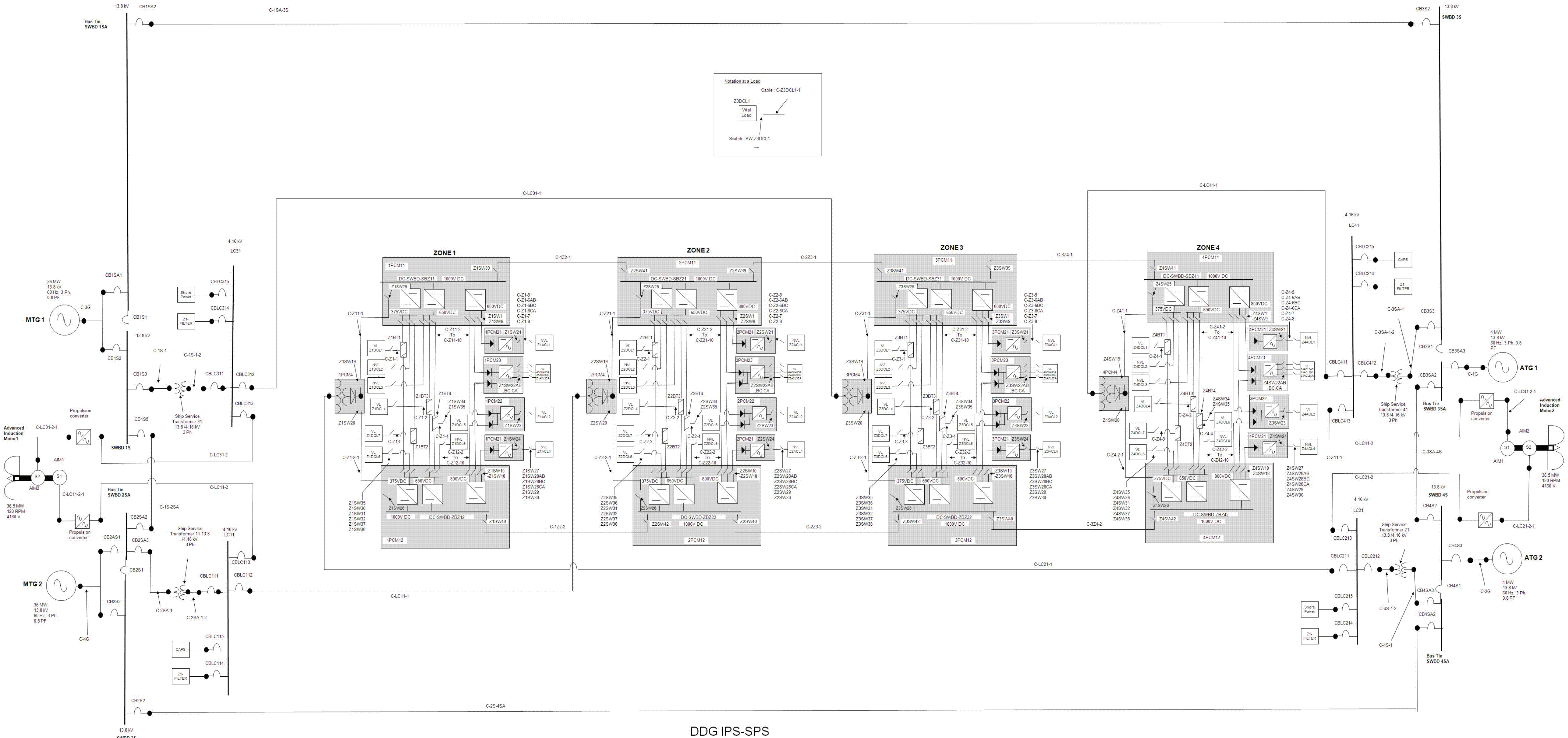

Fig. 2.1 Integrated Shipboard Power System Schematic

2.3 Reconfiguration

Network reconfiguration is the process of altering the topological structures of distribution feeders by changing the open/closed status of sectionalizing and tie switches [1]. The purpose of network reconfiguration is to restore loads that have lost power, balance loads, and minimize power losses. In SPS, network reconfiguration is essential because loads must be continuously supplied if catastrophic events or attacks should occur. There are many different purposes for reconfiguration such as predictive reconfiguration, restoration reconfiguration, and preventive reconfiguration for catastrophic events.

In the Power System Automation Lab (PSAL) at Texas A&M University, two methods for reconfiguration were developed for service restoration on a SPS. One of these two methods discussed below can be used to reconfigure the power system. Method one is an optimization technique that uses an objective function as well as a set of constraints that should not be violated for reconfiguration. The objectives that are accomplished in the optimization technique is to supply as many loads as possible considering their priority and surrounding circumstances along with three constraints: 1) the radial nature of the SPS must be maintained, 2) the current capacities of the generators, cables, and circuit breakers are not to be exceeded, and 3) the voltage should be within tolerable limits [2]. The optimization method considers a graphical representation of the SPS to show all connections to each component. Variables are then assigned to each component as discussed in [2]. The loads in the system are categorized into two categories vital or non-vital. Then these loads are further classified into variable or fixed loads. The variable loads' current can vary from zero to maximum capacity while the fixed loads are either maximum capacity or zero capacity. The overall objective is to maximize the energized loads in case there is a disturbance adhering to constraints of the source node, load node, intermediate node, edge capacity, radiality, and voltage. The results display the capacities of each load and the new path taken to supply the load, and status of the switches in the SPS.

The second method of reconfiguration is a rule-base technique implemented using a program called *EXSYS*. The objective in this case is to restore the loads one by one based on load priority and location [2]. The loads are put into four categories: 1) vital loads on the switchboard, 2) vital loads on the load center, 3) non-vital loads on the switch board, and 4) non-vital loads on the load center. In each category, the *EXSYS* program will check to see where the fault is on a component. Based on the fault location, the program will decide if the load can be restored. If the load(s) can be restored, an alternative path should be found. When alternate path check is initialized, then a bus transfer, load center, or switchboard should be checked for availability. The load cannot be restored if the bus transfer's alternate path has a fault, the switchboard has a breaker fault or the load center has a cable or breaker fault. The *EXSYS* program takes in real time data that includes the fault location(s), out-of-service loads, open breakers, and system topology information [2]. If the load is restorable, then a load flow is run to ensure current capacity and voltage constraints are satisfied. From this given information the loads are restored one by one.

2.4 Reliability

The basic definition of reliability can be stated as the "*quality of measurement*." It can also mean how long a system can repeat an action before an undesirable action occurs. Many utility companies use reliability to perform maintenance on components in a network. Basic reliability terms include availability, duration, failure rate, failure probability, frequency, interruption, mean time between failures (MTBF), mean time to repair (MTTR), reliability, reporting period, restoration, restoration time, service, forced outage, and scheduled outage. These indices provide the utility companies with information about customer load loss, number of customers per outage, and the duration of outage. Reliability of distribution is evaluated in terms of outage rate and outage duration [3]. Utility companies use reliability equations to simplify a network when calculating the outage rates. If the network has components in series or parallel, the components are combined to one equivalent subsystem to carry out the calculations needed to perform outage studies.

2.5 Reliability Centered Maintenance

Reliability centered maintenance (RCM) involves specifying and scheduling electrical preventive maintenance in accordance with the statistical failure rate and/or life expectancy of the equipment being maintained; the most cost-effective way to improve reliability, plant safety, etc [4]. The three steps in RCM are (1) identify the equipment that requires preventive maintenance, (2) specify the different types of maintenance activities, and (3) ensure the preventive maintenance are executed. The three cornerstones are as follows: (1) know when a single failure is acceptable or not, (2) know how to identify hidden failures, and (3) know when a multiple failure analysis is required. RCM comprises a set of tasks generated on the basis of a systematic evaluation that is used to develop or optimize a maintenance program. A single failure analysis exists when there are no hidden failures present. Hidden failures are not evident to operating personnel, and multiple failure analyses are required when single failures are hidden.

Preventive maintenance is a subset of conditioned-directed maintenance and includes using mostly nonintrusive technologies to monitor equipment for precursors. Predictive maintenance is the strategy designed to prevent an unwanted consequence of failure. These two definitions correlate with one another because in order to do preventive maintenance, predictive maintenance has to be implemented first. RCM has two assessments that can be used for preventive maintenance; failure modes and effects analysis (FMEA) and consequence of failure analysis (COFA).

FMEA is not practical because it is essentially capturing all functions in system and subsystem levels. Therefore, there is no guarantee that all functions are captured. The three phases can then be simplified using the COFA assessment. Phase I of the COFA assessment identifies the equipment that must have a preventive maintenance strategy to prevent failure and remain reliable in order to preserve critical equipment functions and minimize any challenge to a plant as a consequence of failure [4]. Phase I also classifies the components into four categories: critical, potentially critical, commitment, and economic components. This is shown at the end of Phase I in Fig. 2.2.Once these components have been identified, the other components are called run-to-failure components. Phase II of the COFA assessment deals with preventive maintenance tasks. The terminology of preventive maintenance includes: condition-directed, time-directed, failure finding, conditioned-based, proactive, reactive, predictive, in situ, on-condition, and surveillances. The COFA assessment uses condition-directed, time-directed and failure finding preventive maintenance tasks to classify components. Condition-directed and time-directed tasks focus on preventing failures at the component level. Failure finding tasks are used to prevent failure at the plant level. Fig. 2.3 describes Phase 2, which decides in which category a component is placed. Phase III of the COFA assessment applies the preventive maintenance task specified in Phase II of the RCM process. Fig. 2.2 shows the three phases of RCM using the COFA assessment.

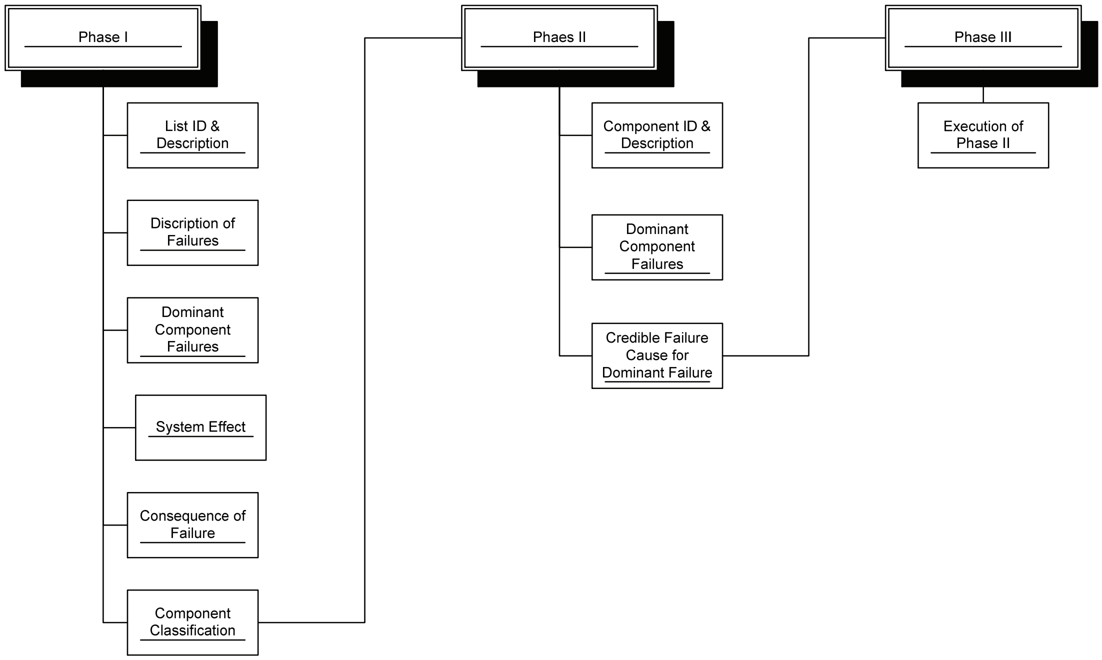

Fig. 2.2 Three Phases of RCM [4]

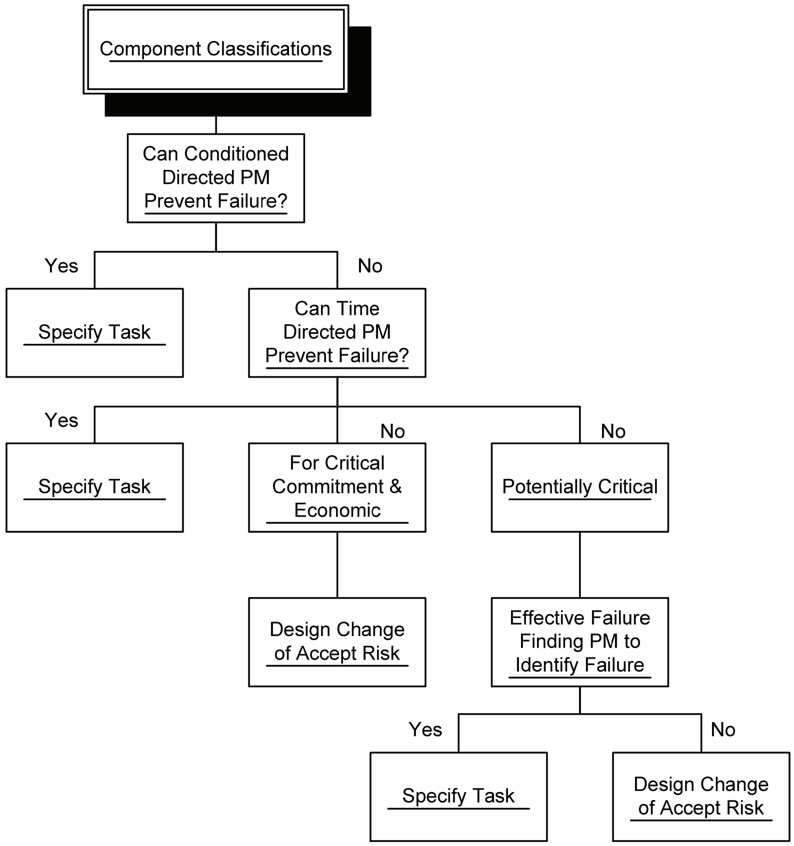

Fig. 2.3 Phase II Logic Tree [4]

2.6 Power Distribution System Reliability

Distribution in a power system is the final stage of delivering electricity to the customer. Voltage levels in distribution systems are normally in the range from 4kV to 34kV. There are three types of distribution systems: (1) radial, (2) loop, and (3) network as shown in Fig. 2.4. The radial system has one electrical path from the source to the load. The loop system has two electrical paths from the source to the load, and the network system has many electrical paths from the source to the load.

The distribution system can be partitioned into two phases, primary and secondary. Primary distribution systems deliver electricity to the substation to distribution transformers while secondary distribution system delivers electricity from distribution transformers to the customer. Most distribution systems are radial because of easier fault current protection, lower fault current over most of the circuit, easier voltage control, easier prediction and control over power flows, and lower cost.

The most commonly used distribution indices include system average interruption frequency index (SAIFI), system average interruption duration index (SAIDI), customer average interruption duration index (CAIDI), and average service availability index (ASAI). Utility companies use SAIFI and SAIDI to benchmark reliability, characterize frequency and duration of interruptions [5]. There are many factors that influence the indices such as weather, load density, age, distribution voltage, physical environment, percent underground and different methods of recording interruptions. Methods to improve reliability in a distribution system include: reducing faults, finding and repairing faults faster, limiting the number of customers from interruptions, and only interrupting customers for permanent faults [5].

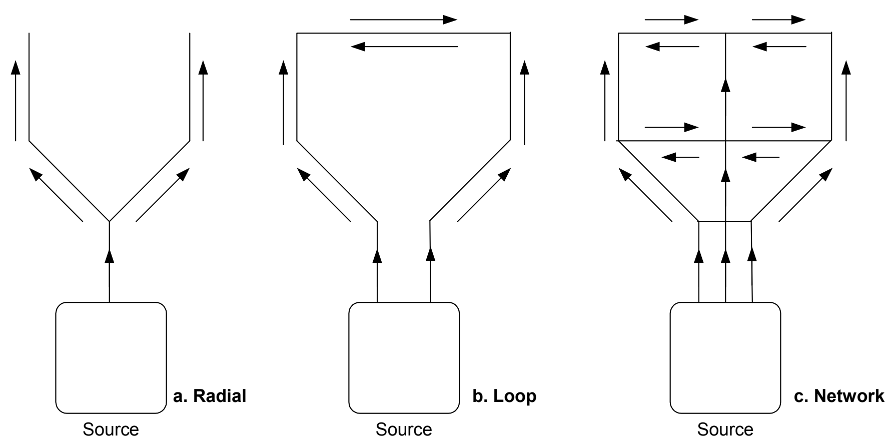

Fig. 2.4 Distribution Systems [5]

2.7 Summary

This chapter presented information about shipboard power systems and distribution systems. It is interesting to note that the IPS is a topology for next generation ships of the future for the U.S. Military, and this ship also integrates power electronics into the system to convert from AC to DC and vice versa to supply loads in a radial path. This chapter provided a definition of reconfiguration and discussed two reconfiguration methods developed in the Power System Automation Lab (PSAL) at Texas A&M University. The two reconfiguration methods use an optimization technique and an expert system based load priority technique for restoration. Reliability techniques were discussed in sections 2.4 through 2.6. In these sections, the basic concepts and definitions of reliability are introduced. Maintenance techniques are also discussed through RCM and distribution reliability. Many utility companies use reliability techniques in different ways. For instance, one company may be concerned with outages, while another may be concerned with the upkeep of hardware.

The concept of reliability can be used reconfigure a SPS while on a mission. The reliability of a system or subsystem is very important to know because loads should be available during catastrophic events. For example, if the communication subsystem fail, seamen would not be able to communicate with an outside source for aid during a mission or an attack was taken place. Before the communication subsystem fails, a prognostic protocol should be called to ensure that the communication subsystem is available during a mission. The prognostic protocol determines the availability of the subsystem for the entire mission.

Chapter II explains basic reliability concepts and background information about power systems on Navy ships. The following chapter will discuss in detail the problem formulation and describe how components fail, and how the remaining life of components is used in computing the conditional reliability for a system.

CHAPTER III

PROBLEM FORMULATION

This chapter provides information about aging electrical components over time, and demonstrates mathematically the computation of remaining life from measured characteristics of each electrical device. The *Arrhenius Model* is used to model thermal stresses on equipment and is combined with a probability density function to compute the reliability of each component. The problem formulation is shown mathematically by structure functions using each component's reliability.

3.1 Life Distribution of Components

A life assessment is performed by monitoring specific characteristics which causes electrical components to fail. The characteristics are used in aging models to predict the remaining life available before a component should be replaced. All electrical equipment fail due to deterioration factors causing the insulating material to deplete or the physical properties to change. Once the insulating material depletes, or the physical properties change at a large magnitude, electrical equipment is near failure or has failed.

The life distribution of electrical components can be modeled using various distributions. The most commonly used distribution of electrical equipment is Weibull distribution because it has a wide family of curves. Also it can be used to model other distributions such as the Normal distribution and the Exponential distribution. The characteristics from the aging components are used in probability distribution functions to show the remaining life distribution of an electrical component. The life distribution shows the point in time where a component is expected to fail. The life distribution is used to compute the survivability of a component at time *t*. The survivability demonstrates the probability that a component is operating at time *t* as well as shown in equation (3.1)

$$f(t) = \left(\frac{\beta}{t}\right)\left(\frac{t}{\alpha}\right)^{\beta} e^{-\left(\frac{t}{\alpha}\right)^{\beta}} \tag{3.1}$$

where:

$f(t)$ = life distribution

β = shape parameter

α = characteristic life

t = time.

A hazard rate is also associated with the probability density function as shown in equation (3.2). The hazard rate is used to show the number of failures per unit of time. The electrical component's life stage can be classified as early life failures, middle of life failures, and end of life failures depending on time. The hazard rate shows numerically how fast a component is deteriorating over a period of time. If the hazard rate exponentially increases, then the component has a chance of failing sooner than expected.

$$h(t) = \left(\frac{\beta}{t}\right)\left(\frac{t}{\alpha}\right)^{\beta} \tag{3.2}$$

where:

$h(t)$ = hazard rate

β = shape parameter

α = characteristic life

t = time.

3.1.1 Aging And Remaining Life of Electrical Equipment

Electrical components age over time and can result a power system being able to perform its mission. As electrical components age, their failure rates increase exponentially. The increase in age also increases the number of inspections and maintenance costs [6]. Deterioration of electrical components can be caused by corrosion, dielectric loss, wear, and moisture retention. All of these deterioration factors impact the physical and mechanical strengths of equipment. When voltage is applied to an electrical component, the insulation breakdown process begins by the acceleration of chemical processes in the dielectric. The dielectric strength is affected by electromagnetic fields which cause corrosion. The movement of mechanical parts erode material in the moving junction by loosening and scratching smooth surfaces. This type of deterioration is found in moving devices such as switches and rotating machines. Heat, one of the leading causes of deterioration, is generated by the electrical losses from components. Heat accelerates physical and chemical mechanisms involved in material deterioration. In the following sections, a description of how electrical components deteriorate due to heat stress, voltage stress, or wear are explained, along with the equations used to compute the remaining life.

3.1.1.1 Transformer

The remaining lifetime of a transformer is said to be measured by the degradation of insulating material [7, 8] which is also called dielectric. The dielectric separates the primary and secondary sides of a transformer and is usually in the form of air or some type of fiber material. Three elements can damage the dielectric in a transformer; hydrolysis (water), oxidation (oxygen), and pyrolysis (heat) [7]. These elements reduce the Degree of Polymerization (DP) which shorten and weaken the fiber. Transformers fail primarily because of fiber reductions caused by high temperatures. There are other factors that cause reductions in dielectric such as overloading and voltage surges. The DP is a measure of the mechanical strength for the transformer. As the transformer degrades, the DP value decreases. When the DP value goes below a threshold value, a transformer has reached the end of its life. The initial DP value is a constant that depends on the class or the type of insulation which is usually given by the manufacturer. The remaining lifetime in time is represented in (3.3) [9].

$$T_{rem} = \frac{1}{A}\left(\frac{1}{DP_{end}} - \frac{1}{DP_{begin}}\right)e^{\left(\frac{13350}{T+273}\right)} = B\left(\frac{1}{DP_{end}} - \frac{1}{DP_{begin}}\right) \tag{3.3}$$

In this equation, T_{rem} is the remaining lifetime, T is the hot-spot temperature in °C, DP_{begin} and DP_{end} are the DP values of the insulation at the beginning of life and the end of life respectively, and A is a parameter that depends on the type of paper and water content [9].

Partial discharge (PD) test is also an indication that dielectric is aging. A PD is an electrical discharge that occurs across a portion of the insulation between two conducting electrodes, without completely bridging the gap. PD is a way to show that the insulation is getting older because as the dielectric degrades, the PD number increases as well as its magnitude. PD is measured by its voltage (mV) or its phase angle. Though there is no way to tell the remaining life of the dielectric through PD, it is a way of showing that the insulating material is degrading and that the transformer needs to be replaced or repaired.

3.1.1.2 Rotating Machines

Generators and motors are two components that are recognized as rotating machines. The insulation life of an electrical winding in rotating machinery is described by incorporating constants based on the class of insulating material and rotating machine power rating, measuring the temperature of insulating material over time, and summing the consumed life [10]. The electrical endurance of insulation materials are temperature and time. The life expectancy of rotating machines is represented by two equations depending on the loading conditions. Equation (3.4) is used if a machine's loading conditions are less than or equal to the rated loading conditions. Equation (3.5) is used if the machine is operated greater than its rated value.

$$L_x = L_{100} \times 2^{\left(\frac{Tc-Tx}{HIC}\right)} \tag{3.4}$$

$$L_x = \frac{L_{100}}{2^{\left(\frac{Tc-Tx}{HIC}\right)}} \tag{3.5}$$

The value of L_x is the percent lifetime at x% load , L_{100} is the entire lifetime of the machine, and the units are in the form of time in hours. T_c is the hot spot temperatures in °C. It can be read from the class of insulation chart, which is provided by the manufacturer. T_x is found by using equation (3.6) below.

$$T = F \times \Delta T + 40 \tag{3.6}$$

T_x is equal to the value of T in °C, F is the rated loss factor in percentage given from the rated life loss factor at various loads table, and ΔT is the allowable temperature rise in °C from the insulation class rating table described in [11]. The parameter *HIC* can also be read from the insulation class rating table. The *HIC* is a constant that depends on the class of insulation being used, and it is known as the halving interval constant.

The rated life of rotating machines can also be determined by its bearings. Manufacturers call the bearing lifetime L_{10} life, which is the time duration when there is a 10% probability of fatigue failure under a given constant load. Fatigue failure occurs in the form of metal chips breaking off from the surface of bearings or rolling elements. The L_{10} life of a bearing is the number of revolutions that can be attained before 10% of the identical bearings would fail. L_{10} is represented in hours given by equation (3.7) [12]. A rotating machine's lifetime is controlled by the operating conditions of the winding (temperature) and bearing (load conditions or rotational speed).

$$L_{10} = \left(\frac{C_r}{P_{eq}} \right)^3 \times \frac{10^6 \cdot 2\pi}{3600 \cdot \omega_r} \tag{3.7}$$

where:

C_r - the bearing's radial load rating specified by the manufacturer (N or lbf);

P_{eq} - equivelant radial load applied to bearing;

ω_r - angular speed of the rotating machine (rad/s);

3.1.1.3 Protective Switching Devices

Isolation switches and transfer switches are two types of protective devices shown in Fig. 3.1. Isolation switches are devices that isolate other critical devices from danger. They are usually in the normally open (N.O.) position or the normally closed (N.C.) position. Isolation switches include circuit breakers (CB), low voltage release (LVR), and low voltage protection (LVP). Relays communicate to circuit breakers engaging them to open or close depending on the settings of the relay. Relays are programmed to check for fault conditions that detect overcurrent, undervoltage, directionality of current, differential impedance, etc to send a trip command to the circuit breaker. LVR and LVP protect motors from low voltages, and trip if the voltage supplied to a motor is below the motors voltage rating. The major difference between the LVR and LVP is that the LVP has to be manually reset to connect the motor to the system when the voltage returns to the acceptable value. The LVR will connect the motor back to the system automatically when voltage has reached the acceptable operating value. Automatic bus transfers (ABT) and manual bus transfers (MBT) are transfer switches (shown in Fig. 3.1 C), that have three conductors for connection. The switches' conductors are connected to the normal path, alternate path, and the load. Transfer switches shift the load to the alternate path when the normal path is unable to supply the load. Like the LVR and the LVP, the ABT and MBT are different in the sense that they are automatically and manually switched back to the normal path respectively, once the normal path can properly supply the required operational value to a desired load.

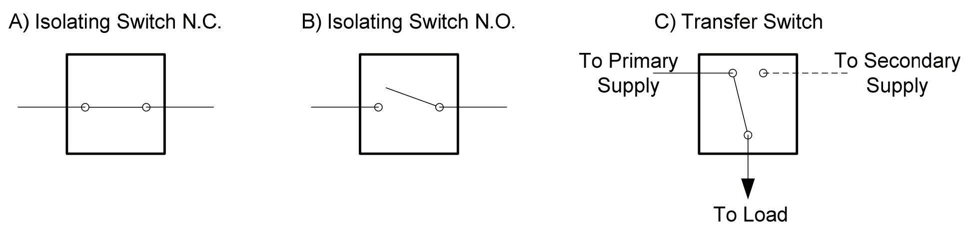

Fig. 3.1 Protective Switches

Switching devices, like any other electrical equipment, age through mechanical, electrical, and thermal stresses. Electrical and mechanical stresses are taken care of by International Standards through durability testing and operation.

Thermal aging of all safety-related materials is assessed and measures are taken to ensure each part can perform its safety-related function until the end of the projected life of the plant. Insulating materials are very sensitive and must be individually considered, taking into account life expectancy and the operating conditions. As insulating materials thermally age, their mechanical properties degrade. The degradation in mechanical properties usually determines the life which is normally limited to 50% reduction in mechanical strength. Switching devices, like other aging electrical components, can be modeled by the *Arrhenius* equation to represent life expectancy. Life expectancy is where the life of the insulating material is determined at a particular temperature with knowledge of the activation energy. The life of insulating materials at any temperature can be modeled by equation (3.8) [13]

$$t_2 = \frac{t_1}{e^{\left\{\left(\frac{A}{K}\right)\cdot\left(\frac{1}{T_1}-\frac{1}{T_2}\right)\right\}}} \tag{3.8}$$

where:

t_1 - Thermal life (years) at temperature T_1;
T_1 - Temperature (K) from thermal life data;
t_2 - Thermal life (years) at temperature T_2;
T_2 - Temperature (K) from thermal life data;
K - Boltzmann's constant;
A - Activation energy (eV).

The parameter values can be obtained by the class of insulation data sheet provided by the manufacturer. Switches also fail due to the movement of the armature and the contact points. Over time, the armature and the contact point(s) begin wear out, creating a hidden failure. Hidden failure can be in the form of a short circuit or open circuit depending on the use of the device. The lifetime of a protective switching device is determined by its operatiing temperature and the normal wear of the switch.

3.1.1.4 Cable

The life expectancy of a cable depends on four factors: operating temperature, dielectric fluid pressurization, dielectric fluid contamination, and mechanical deterioration. The cable insulation will begin to deteriorate if it is operated for temperatures equal to or exceeding 100 °C for extended periods of time. Deterioration due to dielectric fluid pressurization and contamination occurs if the pressure was below its required dielectric fluid pressure, and if moist and harmful particles get inside of a cable structure and damage the insulation over time. A cable can also deteriorate due to improper installation [14]. The useful thermal life of insulation can be estimated by using the *Arrhenius* expression or the reaction rate equation given in equation (3.9) [15].

$$L = Ae^{-\left(\frac{\varphi}{kT}\right)} \tag{3.9}$$

where:

L - thermal life expectancy;

A - material constant;

k - Boltzmann constant;

T - Absolute temperature (K);

φ - Activation energy of the aging reaction (eV).

The values of A and φ are constants that are given by the manufacturer, and the thermal life expectancy is given in hours. The *Arrhenius* model is represented in a graph having coordinates log(L) vs. -1/T, where the model gives rise to a straight line of slope φ/k. This relationship involves changes in the life model and the *Arrhenius* equation becomes equation (3.10) [15].

$$L = Ae^{-\left(\frac{k_1 \log[A]+k_2}{T}\right)} \tag{3.10}$$

where k_1 and k_2 are the regression parameters describing the log(A) vs. φ/k relationship. The degree and the aging rate on insulation depends on the physical and chemical properties of the material, the nature and duration of applied stresses and material processing and treatment during manufacturing and subsequent use in equipment [16].

3.1.2 Arrhenius-Weibull Relationship

The *Arrhenius* equation is a physical acceleration that uses the difference between two temperatures to show how the change in temperature accelerates the age of an item. The *Arrhenius* equation and the Weibull distribution are combined to show the affects of temperature and time on an electrical component where the *Arrhenius* equation is called the life parameter depending on the distribution used. In order to understand how the remaining lifetime can be shown in a distribution, a relationship must be made between the lifetime equations from the above sections and parameters of a probability density function. The equations discussed in the previous sections are a form of the *Arrhenius Rate Equation* as shown in equation (3.11), where L represents a quantifiable life measure such as mean life, characteristic life, median life, etc. C is one of the model parameters to be determined $(C > 0)$, V represents the stress level (in absolute units if temperature), and B is another model parameter to be determined later [17, 18]. The *Arrhenius Rate Equation* is only used when thermal stresses are significant to the degradation of an item.

$$L(V) = Ce^{\left(\frac{B}{V}\right)} \tag{3.11}$$

The *Arrhenius* equation can be written as any life distribution parameter depending on the type of distribution that is used such as the T_{50} parameter for the Lognormal Distribution, the α parameter for the Weibull Distribution, or the $1/\lambda$ parameter for the Exponential distribution [18]. If the desired distribution was the Weibull Distribution as shown in equation (3.12), α would be the parameter to substitute the *Arrhenius* equation where α is known as the scale parameter or characteristic life and β is known as the shape parameter [19]. Equation (3.13) is now formed after substituting equation (3.11) into equation (3.12).

The components described above demonstrate the remaining life by using a form of the *Arrhenius* equation. The remaining life equations are substituted into the Weibull distribution to form the *Arrhenius*-Weibull relationship. The *Arrhenius*-Weibull relationship is shown in Table 3.1 for the electrical components' remaining life described in the previous sections. These relationships are a function of time and thermal stresses which deteriorates the insulation of each component.

$$f(t) = \left(\frac{\beta}{t}\right)\left(\frac{t}{\alpha}\right)^{\beta} e^{-\left(\frac{t}{\alpha}\right)^{\beta}} \tag{3.12}$$

$$f(t,V) = \left(\frac{\beta}{t}\right)\left(\frac{t}{Ce^{\left(\frac{B}{V}\right)}}\right)^{\beta} e^{-\left(\frac{t}{Ce^{\left(\frac{B}{V}\right)}}\right)^{\beta}} \tag{3.13}$$

Table 3.1 Arrhenius-Weibull PDF Model

Component	Arrhenius Model	Arrhenius-Weibull PDF Model
Transformer	$T_{rem} = \frac{1}{A}\left(\frac{1}{DP_{end}} - \frac{1}{DP_{begin}}\right)e^{\left(\frac{13350}{T+273}\right)}$ (3.3) where: T_{rem} - remaining lifetime in hours T - hot spot temperature in °C DP_{begin} - begining insulation values DP_{end} - ending insulation values A - insulation materal constant	$f(t) = \left(\frac{\beta}{t}\right)\left(\frac{t}{\left(\frac{1}{A}\left(\frac{1}{DP_{end}} - \frac{1}{DP_{begin}}\right)e^{\left(\frac{13350}{T+273}\right)}\right)}\right)^{\beta} e^{-\left(\frac{t}{\frac{1}{A}\left(\frac{1}{DP_{end}} - \frac{1}{DP_{begin}}\right)e^{\left(\frac{13350}{T+273}\right)}}\right.}$ (3.14)
Rotating Machines (Generator/Motor) $OC \leq LRC$	$L_x = L_{100} \times 2e^{\left(\frac{Tc-Tx}{HIC}\right)}$ (3.4) where: L_x - percent lifetime at x% T_c - hot spot temperature in °C T_x - rated life loss factor in percentage HIC - insulation materal constant L_{100} - expected lifetime in hours	$f(t) = \left(\frac{\beta}{t}\right)\left(\frac{t}{\left(L_{100} \times 2e^{\left(\frac{Tc-Tx}{HIC}\right)}\right)}\right)^{\beta} e^{-\left(\frac{t}{\left(L_{100} \times 2e^{\left(\frac{Tc-Tx}{HIC}\right)}\right)}\right)^{\beta}}$ (3.15)

Table 3.1 continued

Component	Arrhenius Model	Arrhenius-Weibull PDF Model
Rotating Machines (Generator/Motor) $OC > LRC$	$$L_x = \frac{L_{100}}{2e^{\left(\frac{T_c - T_x}{HIC}\right)}} \quad (3.5)$$ where: L_x - percent lifetime at $x\%$ T_c - hot spot temperature in $°C$ T_x - rated life loss factor in percentage HIC - insulation materal constant L_{100} - expected lifetime in hours	$$f(t) = \left(\frac{\beta}{t}\right)\left(\frac{t}{\left(\frac{L_{100}}{2e^{\left(\frac{T_c - T_x}{HIC}\right)}}\right)}\right)^{\beta} e^{-\left(\frac{t}{\left(\frac{L_{100}}{2e^{\left(\frac{T_c - T_x}{HIC}\right)}}\right)}\right)^{\beta}} \quad (3.16)$$
Switches (CB,BT, & LV)	$$t_2 = \frac{t_1}{e^{\left[\left(\frac{A}{K}\right)\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right]}} \quad (3.8)$$ where: t_1 - thermal life (years) at temperature T_1 - temperature (K) from thermal life t_2 - thermal life (years) at temperature K - Boltzmann's constant A - Activation energy (eV)	$$f(t) = \left(\frac{\beta}{t}\right)\left(\frac{t}{\left(\frac{t_1}{e^{\left[\left(\frac{A}{K}\right)\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right]}}\right)}\right)^{\beta} e^{-\left(\frac{t}{\left(\frac{t_1}{e^{\left[\left(\frac{A}{K}\right)\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right]}}\right)}\right)^{\beta}} \quad (3.17)$$

Table 3.1 continued

Component	Arrhenius Model	Arrhenius-Weibull PDF Model
Cable	$L = Ae^{-\left(\frac{\varphi}{kV}\right)}$ (3.9) where: L - thermal life expectancy, hours k - Boltzmann's constant V - absolute temperature (K) A - insulation material constant φ - activation energy of aging reaction	$f(t) = \left(\frac{\beta}{t}\right)\left(\frac{t}{\left(Ae^{-\left(\frac{\varphi}{kV}\right)}\right)}\right)^{\beta} e^{-\left(\frac{t}{\left(Ae^{-\left(\frac{\varphi}{kV}\right)}\right)}\right)^{\beta}}$ (3.18)

3.1.3 Hazard-Scale Parameter Relationship

The hazard rate, often referred to as the failure rate $h(t)$, of any component can be described as the probability that the component will fail in a time interval $(t, t+\Delta t]$ [20]. In Fig 3.2, the probability is plotted against time to show how the hazard rate changes over time. The hazard rate plot is a piece-wise function known as the *bathtub curve* describing the intervals at which the hazard rate changes. The three intervals at which the curve changes are called the *burn-in period*, the *useful life period*, and the *wear-out period* as shown in Fig. 3.2. T_B and T_P are points at which a component ends the burn in period and useful life period respectively, and T_W is the point at which a component begins the wear-out period. The Weibull shape parameter is chosen depending on what period or interval the component is operating in at that period of time. When the hazard rate is plotted against time using the Weibull hazard rate function, all intervals will take on a different shape. The shape parameter, (β) in the Weibull distribution, has an effect on the change of the hazard rate and what interval a component is operating in at that point in time.

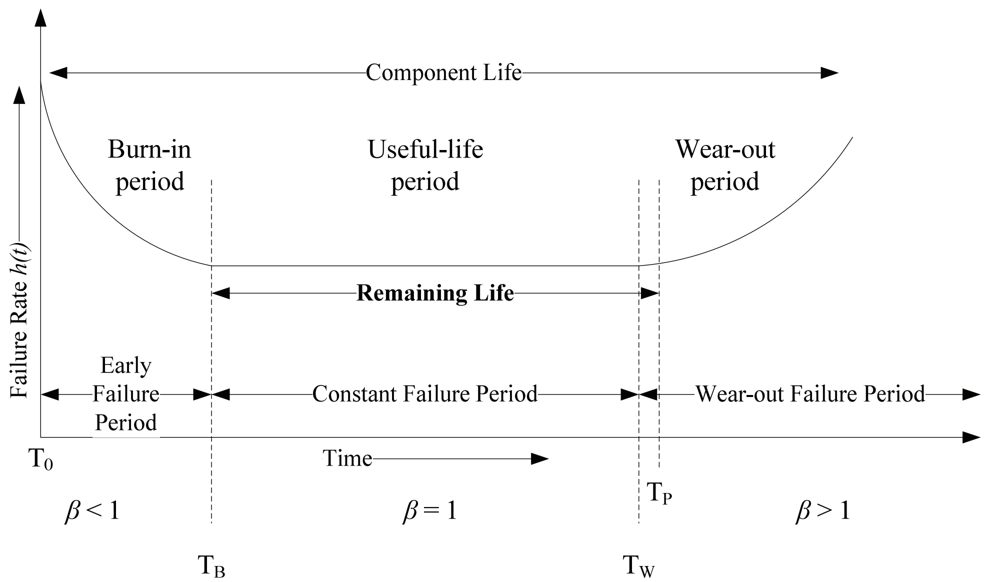

Fig. 3.2 Hazard Rate as a Function of Time

The *burn-in period* is also called the infant mortality period, which has a high failure rate initially. It is characterized by a decreasing failure rate, which begins from T_0 to the burn-in time T_B shown in Fig. 3.2. This period can be due to a result in poor design, the use of substandard components, or lack of adequate controls in the manufacturing process. Early failures can be eliminated from the customer by "burn in" during which time the component is operated at stress levels equal to the intended actual operating conditions. A component is released for actual use only when it has passed through the *burn-in period* [21]. The *burn-in period* is usually modeled using the Gamma or Weibull distribution with the shape parameter $\beta < 1$ [18].

The *useful-life period* is characterized by a constant failure rate and is usually the longest interval of the three periods. The *useful-life period* extends from the burn-in time T_B to the wear-out time T_W also shown in Fig. 3.2. This period is dominated by chance or random failures. This period cannot be eliminated by lengthy burn-in periods or good preventive maintenance practices. In this interval, the component is designed to operate under certain conditions and up to certain stress levels. When these stress levels are exceeded due to random unknown events, a chance of failure could occur. The time when a chance failure will occur cannot be predicted; however, the probability that one will occur during a given period of time within the useful life can be determined by analyzing the equipment design [21]. The *useful-life period* is normally modeled using the Exponential distribution, but the Weibull distribution can be used with $\beta = 1$ [18]. In this period, the remaining life of an electrical component is considered to start from the end of the *burn-in period* T_B to the failure or prognostic time T_P which is usually located in the *wear-out period* given that there are no failures at the component's present time as shown in Fig. 3.2 [22].

The *wear-out period* is characterized by an increasing failure rate resulting in equipment deterioration due to age, which begins from the wear-out time T_W to the end of the components life as shown in Fig. 3.2. The only way to prevent failure due to wear-out is to replace or repair the deteriorating component before it fails [21]. The *wear-out period* takes the shape of the Normal distribution, but it too can be modeled using the Weibull distribution with shape parameter $3 \le \beta \le 4$ [18].

The Weibull distribution can be used to model the entire *bathtub curve* as a function of the shape parameter and the time interval that the component is operating. Throughout the rest of this work, the *useful-life period* and the *wear-out period* will be used because electrical components are only distributed after they have passed the *burn-in period*.

3.2 System Survivability

The system survivability is defined by its individual components' operation and the structure that it follows. A system can be grouped into three basic parts depending on the size of the system. These basic parts of the system are the individual components, subsystems, and the system itself. Each component's survivability is taken into account when determining the system or subsystem's survivability.

3.2.1 Component Survivability

Since the components are assumed to be non-repairable, we are only interested in studying components until the first failure occurs. When the failure occurs, then the component may be repaired or discarded. The state of the component at time t may be described by the state variable $x(t)$:

$$x(t)=\begin{cases}1, & \text{if the component is functioning at time } t\\ 0, & \text{if the component is in a failed state at time } t\end{cases} \tag{3.19}$$

The state variable of a non-repairable component is illustrated in Fig. 3.3 and is a random variable. The *time to failure* of a component is the time elapsing from when the component is put into operation until the component fails the first time.

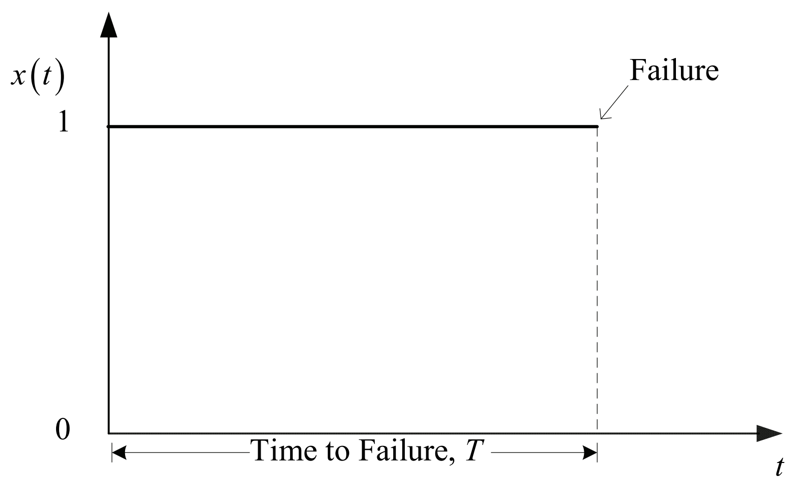

Fig. 3.3 The State Variable and the Time to Failure of a Component [20]

The relationship between the state variable $x(t)$ and time to failure T is illustrated by equation (3.20) where T is a random variable.

$$x(t)=\begin{cases}1, & 0\le t\le T\\ 0, & \text{otherwise}\end{cases} \tag{3.20}$$

Since time to failure can be a discrete variable, it can be approximated by a continuous time variable. Now we will assume that time to failure T is continuously distributed with the probability density function (PDF), $f(t)$, and distribution function $F(t)$. $F(t)$ denotes the probability that the item fails within the time interval $(0,t]$ [20].

$$F(t) = \Pr(T \le t) = \int_0^t f(u)\,du \qquad \text{for } t > 0 \tag{3.21}$$

Assuming the remaining lifetime of electrical components are modeled using the Weibull distribution, the reliability of components are modeled using the mean and standard deviation to illustrate the remaining lifetime of components as a function of time. The Weibull distribution is a successful model for electrical components because it is a flexible distribution with a wide variety of possible failure rate curves [18]. In the Weibull distribution, the scale parameter α and shape parameter β are used to model the appearance of the distribution. The PDF is given by (3.22) where it is a function of time, and remaining lifetime at time t is the value that will signify the percentage of time available until a failure occurs. Assuming that time to failure data of a component fits the Weibull distribution, (3.22) can is used to represent a component's lifetime distribution. Lifetime distribution is the time interval that a component is expected to survive.

$$f(t) = \left(\frac{\beta}{t}\right)\left(\frac{t}{\alpha}\right)^{\beta} e^{-\left(\frac{t}{\alpha}\right)^{\beta}} \tag{3.22}$$

The parameters mean lifetime μ and variance σ^2 are given by the manufacturer, and are used in the Weibull distribution to estimate the parameters α and β . The Weibull mean (3.23) and variance (3.24) equations are used to solve for α and β where the *Gamma Function*, $\Gamma(x)$, is substituted into each equation. The Appendix of [23] demonstrates the steps taken to estimate the parameters α and β.

$$\mu = \alpha\Gamma\left(1 + \frac{1}{\beta}\right) \tag{3.23}$$

$$\sigma^2 = \alpha^2 \left[\Gamma\left(1+\frac{2}{\beta}\right) - \Gamma^2\left(1+\frac{1}{\beta}\right) \right] \tag{3.24}$$

$$\Gamma(x) = \int_0^{\infty} t^{x-1} e^{-t} dt \tag{3.25}$$

Once the component's lifetime distribution is represented as a function, $f(\alpha, \beta, t)$, as described in (3.22), then the cumulative distribution function (CDF), $F(t)$, can be obtained by integrating (3.22) from 0 to t as shown in (3.26). To evaluate $F(t)$, *u substitution* must be used to simplify the expression for integration with $u = \left(\frac{t}{\alpha}\right)^{\beta}$ and $du = \left(\frac{\beta}{t}\right)\left(\frac{t}{\alpha}\right)^{\beta} dt$.

$$F(t) = \int_0^t f(u)\, du = \int_0^t \left(\frac{\beta}{t}\right)\left(\frac{t}{\alpha}\right)^{\beta} e^{-u} \frac{du}{\left(\frac{\beta}{t}\right)\left(\frac{t}{\alpha}\right)^{\beta}} \tag{3.26}$$

The limits are in terms of u as shown in equation (3.27) since integration is with respect to u.

$$F(t) = \int_0^u e^{-u} du \qquad (3.27$$

$$F(t) = -e^{-u} \Big|_{u=0}^{u=\left(\frac{t}{\alpha}\right)^{\beta}} \tag{3.28}$$

$$F\left(t\right) = -e^{-\left(\frac{t}{\alpha}\right)^{\beta}} - \left(-e^{0}\right)$$
$$= -e^{-\left(\frac{t}{\alpha}\right)^{\beta}} + e^{0}$$
$$= -e^{-\left(\frac{t}{\alpha}\right)^{\beta}} + 1 \tag{3.29}$$
$$= 1 - e^{-\left(\frac{t}{\alpha}\right)^{\beta}}$$

Evaluating (3.28) from 0 to u yields (3.29), which is known as the unreliability function. The CDF function represents the summation of area underneath $f(t)$, and displays how failure increases for the change in time *t*. The component's survival also depends on the age of the component.

$$F(t) = 1 - e^{-\left(\frac{t}{\alpha}\right)^{\beta}} \tag{3.30}$$

$F(t)$ minus 1 yields $R(t)$ as shown in (3.31), which is known as the survivability equation. The survivability equation represents the reliability of the component's lifetime over a period of time for $\left(t > 0\right)$ [20]. It can be seen that the component's reliability decreases as time *t* approaches time *T* as illustrated in Fig. 3.4.

$$R(t) = 1 - F(t) = P\left(T > t\right), \qquad \text{for } t > 0$$
$$R(t) = e^{-\left(\frac{t}{\alpha}\right)^{\beta}} \tag{3.31}$$

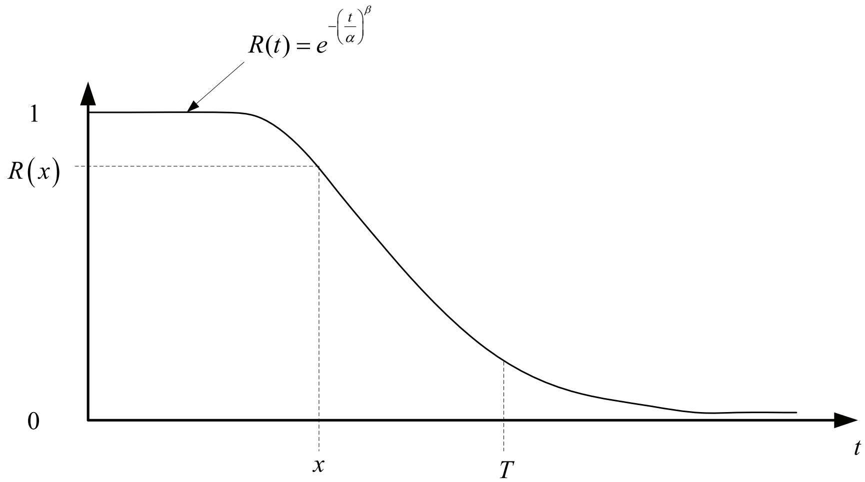

Fig. 3.4 Survivability Plot for Component *i*

Since the *Arrhenius* equation is used to characterize life in any distribution, it can also be used in reliability equations such as equation (3.31). The characteristic life parameter α is equal to $L(V)$ in the *Arrhenius* equation as discussed in section 3.1.2. Since $\alpha = L(V) = Ce^{\frac{B}{V}}$, then the reliability equation (3.31) now becomes (3.32) where V is the thermal stress applied to an electrical component [19]. Equation (3.32) is known as the *Arrhenius*-Weibull Reliability equation because it is a function of thermal stress and time. If the parameter B is positive, then the reliability increases as the temperature decreases [19].

$$R(t,V) = e^{-\left(\frac{t}{Ce^{\left(\frac{B}{V}\right)}}\right)^{\beta}} \tag{3.32}$$

From Table 3.1, in section 3.1.2, the probability density function for each component can be directly related to a reliability equation similar to equation (3.32) when the steps of integration are used as described previously beginning from equation (3.13). Table 3.2 lists the reliability model for each component when its respected *Arrhenius* model is substituted for the characteristic variable α.

Table 3.2 Arrhenius-Weibull Reliability Model

Component	Arrhenius Stress Model (Equation)	Arrhenius Stress – Weibull Reliability Model (*R(t)*)
Transformer	$T_{rem} = \frac{1}{A}\left(\frac{1}{DP_{end}} - \frac{1}{DP_{begin}}\right)e^{\left(\frac{13350}{T+273}\right)}$ (3.3)	$R(t) = e^{-\left(\frac{t}{\frac{1}{A}\left(\frac{1}{DP_{end}}-\frac{1}{DP_{begin}}\right)e^{\left(\frac{13350}{T+273}\right)}}\right)^{\beta}}$ (3.33)
Rotating Machines (Generator/Motor) $OC \leq LRC$	$L_x = L_{100} \times 2e^{\left(\frac{T_c - T_x}{HIC}\right)}$ (3.4)	$R(t) = e^{-\left(\frac{t}{\left(L_{100}\times 2e^{\left(\frac{T_c - T_x}{HIC}\right)}\right)}\right)^{\beta}}$ (3.34)
Rotating Machines (Generator/Motor) $OC > LRC$	$L_x = \frac{L_{100}}{2e^{\left(\frac{T_c - T_x}{HIC}\right)}}$ (3.5)	$R(t) = e^{-\left(\frac{t}{\left(\frac{L_{100}}{2e^{\left(\frac{T_c - T_x}{HIC}\right)}}\right)}\right)^{\beta}}$ (3.35)
Switches (CB,BT, & LV)	$t_2 = \frac{t_1}{e^{\left[\left(\frac{A}{K}\right)\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right]}}$ (3.8)	$R(t) = e^{-\left(\frac{t}{\left(\frac{t_1}{e^{\left[\left(\frac{A}{K}\right)\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right]}}\right)}\right)^{\beta}}$ (3.36)
Cable	$L = Ae^{-\left(\frac{\varphi}{kT}\right)}$ (3.9)	$R(t) = e^{-\left(\frac{t}{\left(Ae^{-\left(\frac{\varphi}{kT}\right)}\right)}\right)^{\beta}}$ (3.37)

Each component in the power system is modeled by its conditional survivability function $P(T > t + x \mid T > x)$. The conditional survivability function is the probability a component will survive another *t* time units given that it has survived for *x* time units. The conditional reliability function follows equation (3.38) when $P(T > x) \neq 0$ and $T > t$ [24].

$$P(T > t + x \mid T > x) = \frac{P(T > t + x, T > x)}{P(T > x)} \tag{3.38}$$

Since $\{T > t + x\} \subset \{T > x\}$, it follows that $\{T > t + x\} \cap \{T > x\} = \{T > t + x\}$. Thus, $P(T > t + x, T > x) = P(T > t + x)$ and $P(T > t + x \mid T > x)$ is given by the conditional probability law shown in equation (3.39).

$$\begin{aligned} P(T > t + x \mid T > x) &= \frac{P(T > t + x)}{P(T > x)} \\ &= \frac{R(t + x)}{R(x)} \end{aligned} \tag{3.39}$$

The component survivability is found by evaluating (3.31) at x and $t + x$ as given in (3.40) and (3.41), respectively.

$$P(T > x) = R(x) = e^{-\left(\frac{x}{\alpha}\right)^{\beta}} \tag{3.40}$$

$$P(T > t + x) = R(t + x) = e^{-\left(\frac{t+x}{\alpha}\right)^{\beta}} \tag{3.41}$$

Thus the survivability of component *j*, P_j, is defined as shown in equation (3.42).

$$P_j(T > t + x \mid T > x) = \frac{R(t + x)}{R(x)} = \frac{e^{-\left(\frac{t+x}{\alpha}\right)^{\beta}}}{e^{-\left(\frac{x}{\alpha}\right)^{\beta}}} \tag{3.42}$$

Fig. 3.5 shows a component conditional reliability plot given that it has already survived for *x* time units. This figure is derived from Fig. 3.4 after time has advanced *x* time units where $T > t$ and *T* represents the end of life of a component.

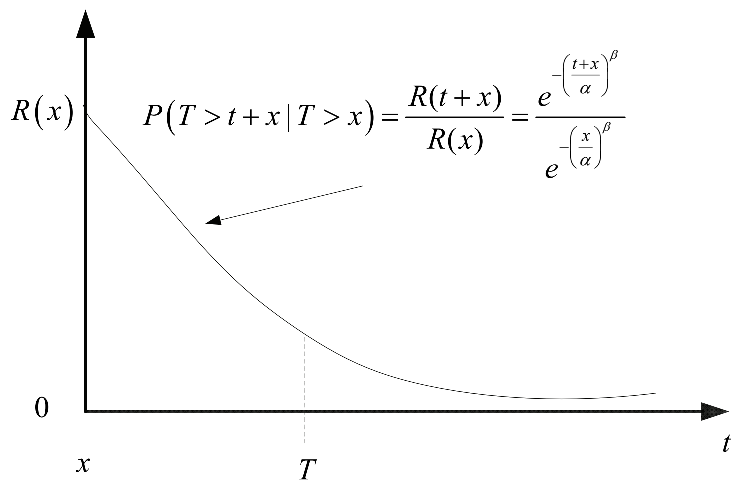

Fig. 3.5 Conditional Survivability Plot Given *x*

When thermal stresses are applied to an electrical component, then the *Arrhenius equation* is substituted for the scale parameter α in (3.42) where $\alpha = L(V) = Ce^{\frac{B}{V}}$. The conditional survivability equation is shown in (3.43) where *V* is the applied thermal stress to an electrical device [19].

$$P(T > t + x \mid T > x) = \frac{R(t+x, V)}{R(x, V)} = \frac{e^{-\left(\frac{t+x}{Ce^{\left(\frac{B}{V}\right)}}\right)^{\beta}}}{e^{-\left(\frac{x}{Ce^{\left(\frac{B}{V}\right)}}\right)^{\beta}}} \tag{3.43}$$

3.2.2 Structure Function Representation of a System

Structure functions are used to show how a system or subsystem is interconnected and which components are critical in a system. Structure functions are also used to compute reliability indices to show the probability that a component fails or survives. Structure functions are mathematical expressions that represent the topology of systems or subsystems that are composed of *n* components numbered from 1 to *n*. The state of component *i*, for $i = 1, 2, \ldots, n$ can then be described by a binary variable from equation (3.19).

$\vec{x}(t) = (x_1(t), x_2(t), \ldots, x_n(t))$ is called a state vector [20]. The state of a system can be described as a binary function as well where $\phi(\vec{x}(t)) = \phi(x_1(t), x_2(t), \ldots, x_n(t))$ and (3.44) holds if the structure function is non-decreasing in each vector argument and such that each component is relevant.

$$\phi(\vec{x}(t)) = \begin{cases} 1, & \text{if the system is functioning} \\ 0, & \text{if the system is in a failed state} \end{cases} \tag{3.44}$$

A system is said to be *monotone* under the following two conditions:

1) its structure ϕ is non-decreasing in each argument, and
2) $\phi(0) = 0$ and $\phi(1) = 1$.

The first condition means that a system cannot deteriorate (the system cannot change from a failed state to a functioning state) by improving performance of a component (replacing a functioning component by a failed component) [25]. The second condition states that if all components in a system are in a failed state then the system is in a failed state, and if all components in a system are in a functioning state then the system is in a functioning state.

A system is said to be *coherent* if all its components are relevant and the structure function is non-decreasing in each argument [20]. It is seen that if ϕ is *coherent*, then it is also *monotone*, and if component *i* is irrelevant, then

$$\phi(1_i, x) = \phi(0_i, x), \qquad \text{for all } (\cdot_i, x)$$

where $(1_i, x)$ represents a state vector where the state of the i^{th} component = 1, $(0_i, x)$ represents a state vector where the i^{th} component = 0 [20, 25]. Therefore, *coherent* structure functions describe the relevancy of components that are used in a specific structure.

A system is considered to be a series configuration if all components are interconnected end- to- end as shown in Fig. 3.6. Series systems only function if all components are functioning properly, providing a continuous path from point *A* to point *B*. A series structure is represented by (3.45) where $\phi(\vec{x})$ is called the *structure function of the system/subsystem* or *structure* [20].

$$\phi(\vec{x}(t)) = \prod_{i=1}^{n} x_i(t) \tag{3.45}$$

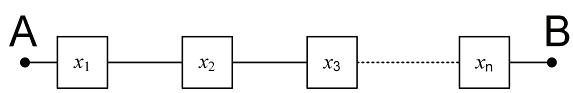

Fig. 3.6 Series Block Structure

A system is considered to have a parallel configuration if all components are interconnected as shown in Fig. 3.7, and the system will still function if there is at least one path available from point *A* to point *B*. A parallel structure, $\phi(\vec{x}(t))$ is represented by (3.46) [20].

$$\phi(\vec{x}(t)) = 1 - \prod_{i=1}^{n} (1 - x_i(t)) \tag{3.46}$$

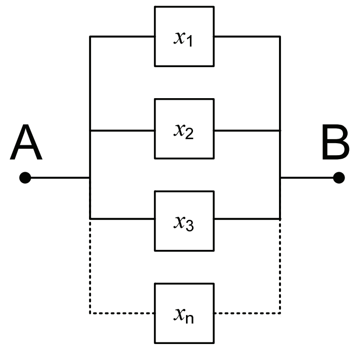

Fig. 3.7 Parallel Block Structure

Structure functions can have a combination of series and parallel structures to describe the topology of an entire system. An example of the combination of both structures is shown in Fig. 3.8. Series - parallel structure functions are represented by equation (3.47).

$$\phi\left(\vec{m}(t),\vec{z}(t)\right)=\left(\prod_{i=1}^{n} m_i(t)\right)\left(1-\prod_{j=1}^{p}\left(1-z_j(t)\right)\right) \tag{3.47}$$

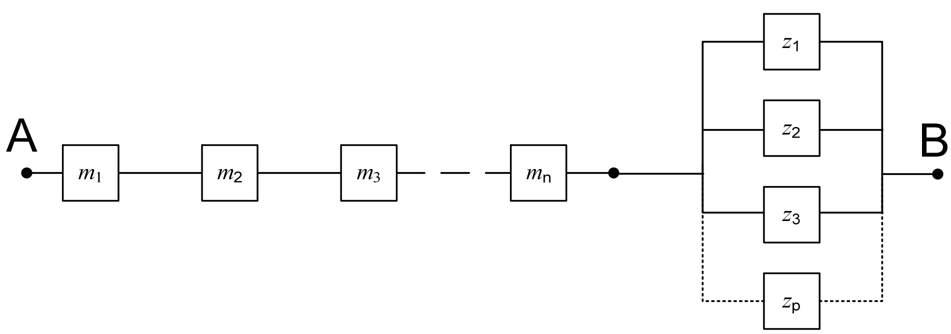

Fig. 3.8 Series and Parallel Block Structure

3.2.3 System Representation Using Structure Functions and Component Remaining Life

Let us consider a system that consist of mutually independent and non-repairable components, and the system's probability is based upon each component's probability. Recall the component conditional survival function given by (3.42). By definition, the reliability can be described as an expectation and/or probability as shown in equation (3.48). Since the system is defined as a structure of *i* components, then the reliability of the system is defined as the structure of *i* reliabilities in a system as shown below [24].

$$E\left[x_i\right] = P\left(x_i = 1\right) = R_i\left(t\right) \qquad \text{for } i = 1, 2, \ldots, n \tag{3.48}$$

To determine the probability that the system will survive another *t* time units given that it has survived for *x* time units, the conditional survivability of each component is used [24]. Let $\phi\left(x_1\left(t\right), x_2\left(t\right), \ldots, x_n\left(t\right)\right)$ be a random structure function where the random state variables each take values in the set $\{0,1\}$ [20]. Recall the state variables $x_i(t)$ for $i = 1, 2, \ldots, n$ are independent and take on only values of 0 or 1. Thus equation (3.49) is given for fixed $t \geq 0$.

$$E\left[\phi\left(x_1\left(t\right), x_2\left(t\right), \ldots, x_n\left(t\right)\right)\right] = P\left(T_i > t\right) = \phi\left(R_1\left(t\right), R_2\left(t\right), \ldots, R_n\left(t\right)\right) \tag{3.49}$$

Recall the conditional survivability of a component is the probability that a component survives for another *t* time unit, given that it has survived for *x* time units. The conditional survivability for a system is shown in equation (3.50).

$$P_{sys}\left(T > t + x \mid T > x\right) = \frac{\phi\left(R_1(t+x), \ldots, R_n(t+x)\right)}{\phi\left(R_1(x), \ldots, R_n(x)\right)} \tag{3.50}$$

3.3 Reconfiguration/Control

In the previous section, the conditional reliability for a load is given by equation (3.50). This equation lets the operator know the condition of the path to a load given that all components have survived for x amount of time units. This equation is also used to get prognostic information about the path for a given mission. Missions are described by how long a ship will be in a particular configuration, or how long will particular loads will be used over a period of time. The missions can be broken into three parts such as early life, middle of life, and end of life as components age.

In this work, the Navy ships' lifetime is assumed to be thirty-five years; therefore, each component can have a maximum life of thirty-five years, although some components may have a longer lifetime. It is assumed that after thirty-five years, a Navy ship is decommissioned or totally overhauled. Operators on the ship would need to know the condition of the ship to decide whether reconfiguration is required during a mission. The operator would also decide whether a ship's condition is acceptable to perform that particular mission. For instance, if the operator is in a particular configuration in the early stages of life, then a reliability of 0.5 may be acceptable for all loads and reconfiguration may not be needed. If loads were to go below the 0.5 threshold, the operator would reconfigure the loads to keep the system's loads available if they will be needed during a mission. Since there are three life periods, there would be three threshold values that an operator would use to determine if reconfiguration is needed.

The IPS is controlled by the opening and closing of various switches, bus transfers, and circuit breakers. The known conditional survivability of the supply path to each load can be used to determine whether or not the path can be improved. Based on the survivability of the path to each load, reconfiguration may possibly be performed to improve a system's overall survivability. The information used in computing the conditional survivability leads to an indication that there is a possible failure or low survivability during a mission. If the conditional survivability of the supply path to a load is close to zero, then there is a possibility that the load will not be served. To avoid this situation, prognostic information must be known to alert the operator that there may be a problem during a particular mission. Reconfiguration is needed to improve the load's chances of survival during a time period. By knowing prognostic information, control actions can be performed on the ship, therefore improving the chances of survival for each load in an entire mission.

3.4 Summary

This chapter presented the problem formulation mathematically and information about the remaining life of electrical components and how they fail. In this work, thermal stresses are used to show that all components fail when they are over stressed. It is also important to note that thermal stresses are not the main contribution to failure. Wear-out and mechanical stresses are essential in the failure of components. The *Arrhenius Model* is the model to show the aging of electrical components due to thermal stresses and it can be substituted into the Weibull Distribution to make a relationship. The relationship is made through the lifetime or characteristic parameter. This chapter also gives a relationship between the hazard rate and the shape parameter from the Weibull Distribution. In section 3.1.3, the shape parameter determines how fast a components deteriorates over a period of time. Using the Weibull probability density function, the reliability equation was derived. A system is represented by series, parallel, or series-parallel structures. The reliability of each relevant component in a structure is used to compute a system's reliability.

In this chapter, the remaining life of each electrical component is used in the *Arrhenius*-Weibull distribution to compute the conditional survivability of a system. The following chapter will discuss in detail the solution methodology and the steps taken to build a system starting with individual components.

CHAPTER IV

SOLUTION METHODOLOGY

The methodology to determine if reconfiguration is needed based on prognosis information for individual component's lifetime distributions under normal operating conditions. From the lifetime distributions, their survivability is calculated based on when the component was installed. The survivability function for each component is used in the system's structure function to compute the conditional survivability to each load in both the HV/MV and LV levels. Fig. 4.1 depicts the proposed methodology for computing the subsystem survivability for each load and $PCM4$ modules.

The process begins by loading the values of characteristic life (α) and shape parameter (β) for each component, present time (*x*), mission time (*t*), and configuration information into an external database. The present time, *x*, and mission time, *t*, are inputs that are used to compute the present reliability $R(x)$, and the conditional reliability $R(x+t)$, for each component. The inputs listed above are shown in Fig. 4.1 module one. The mode of operation is determined and the computation process follows input module. The next step is to compute the reliability at present time for all components in module two. The present time reliability of each component is used to later in each structure to compute load survivability. Next in module three, the reliability at mission time given the present time is computed for each component in the shipboard power system. The mission time reliability of each component is also used later in each structure to compute load survivability.

Module four in Fig. 4.1 begins the process of determining the structure function of the shipboard power system. When the mode of operation is determined, then the structure function is known. The present time and mission time reliability values are used from modules two and three are used in the structure functions to compute the load's present time survivability and mission time survivability. The present time and mission time are used to compute the conditional survivability to each load in module five. Module five is the final computation to each load. The final step is to determine if reconfiguration is needed based on the conditional survivability to each load and the threshold set by the operator. This algorithm will compute all conditional survivability values in each mode of configuration, and are ranked by the top five lowest conditional survivability values at the LV level. The loads in the HV/MV level are all ranked in no specific order because there are only six loads. The system's structures are explained in detailed at both HV/MV level and LV level in next section.

4.1 System Interpretation

There are many ways that the IPS can be described by a structure function. In this work, the system is divided into two levels: the generator and ring level which is the HV level of the ship and within the zones which is the LV level of the ship. The load survivabilities for each load is computed. The load survivability of each PCM4 module and propulsion motor are computed at the HV/MV level. The load survivability of the other loads are computed in the DC zonal level. The ship is split into three levels at which structure functions are determined. The HV and MV structure functions form a series configuration to each *PCM4* and propulsion motor resulting in equation (4.1) where K represents the total number of *PCM4*'s and *AIM*s shown in Fig. 4.2. Fig. 4.2 shows a high level view of the SPS without displaying the LV loads explicitly. Each *PCM4* and *AIM* is circled and labeled to show the different paths from the generators (*MTG1*, *MTG2*, *ATG1*, and *ATG2*).

$$\phi_k\left(\overline{X}\right)=\left(HV_k\right)\left(MV_k\right) \qquad \text{for } k=1 \text{ } to \text{ } K \tag{4.1}$$

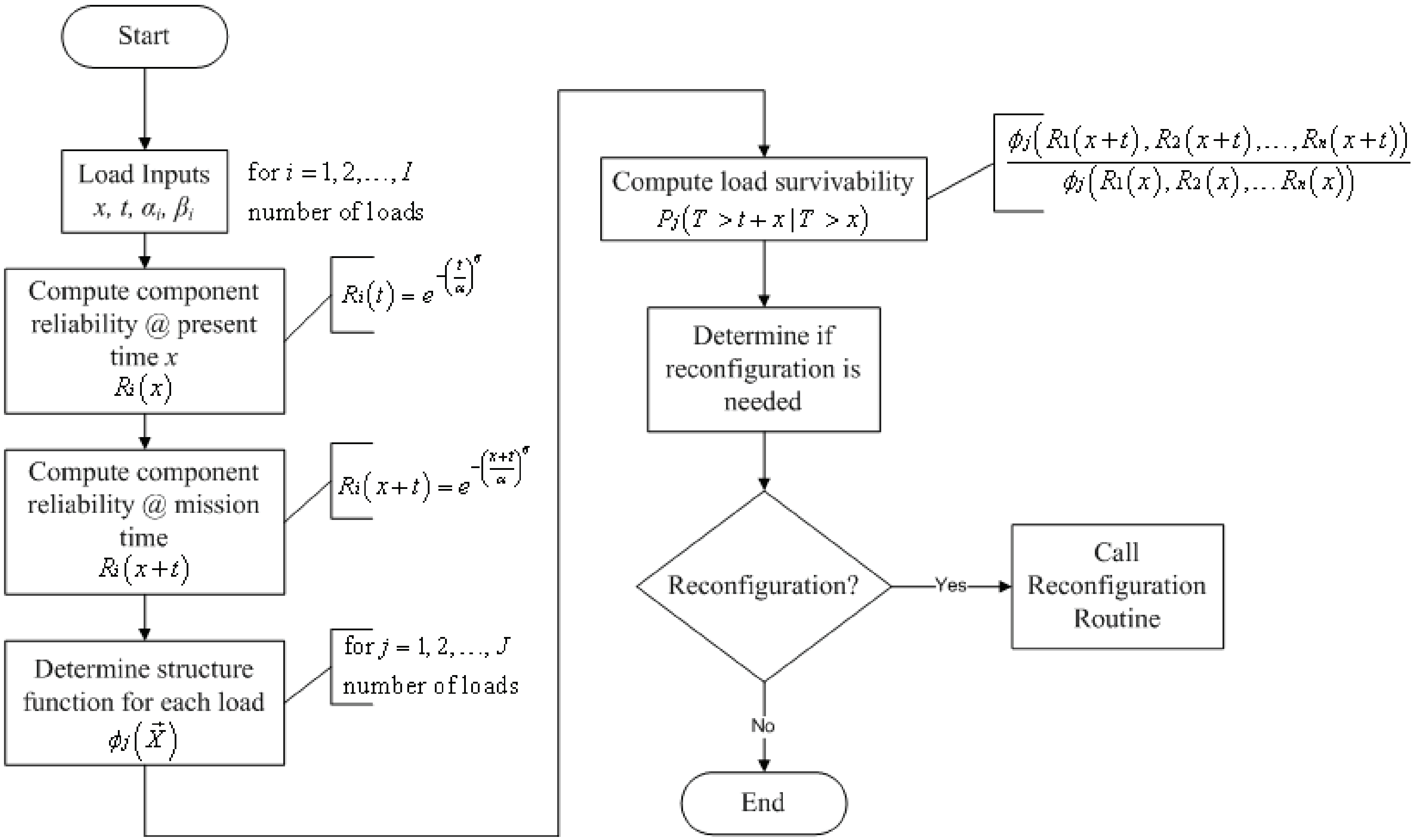

Fig. 4.1 Load Survivability Solution Methodology

Next it is determined whether there is an available path to each of the vital and non-vital loads per zone where the *PCM4*s act as sources to these loads. The loads are shown in Fig. 2.1 where the *PCM4*s serve as sources to the loads. This will be determined by the LV structure function shown in equation (4.2) where J represents the total number of loads.

$$\phi_j\left(\overline{X}\right)=\left(LV_j\right) \qquad \text{for } j=1 \text{ to } J \tag{4.2}$$

The LV structure will consist of components from a *PCM4* to each of the loads in the each zone. In the sections *below*, the formulation of the HV, MV, and the LV structure functions are discussed in sections 0, 4.3, and 4.5, respectively.

4.2 HV System Structure Function

The HV structure consists of generators, circuit breakers, and cables that begin from the generator to the main and/or the auxiliary buses. The ring cables are also a part of the HV structure because they connect all generators to the main and auxiliary buses as shown in Fig. 4.2. Buses $SWBD1S$, $SWBD1SA$, $SWBD2S$, $SWBD2SA$, $SWBD3S$, $SWBD3SA$, $SWBD4S$, and $SWBD4SA$ are used to designate which generators are used for each load. The HV structure function is formulated for each of the four modes of operation connecting the generator to each switchboard or bus. The modes of operation are the Common Bus Mode, Port/Starboard Split Bus Mode, Forward/Aft Split Bus Mode, and the 4 Way Split Bus Mode. In the following subsections these modes of operation will be discussed for HV structure for the *PCM4*s and propulsion motors. The 4 Way Split Bus Mode was not studied because the topology information was not available to understand its operation.

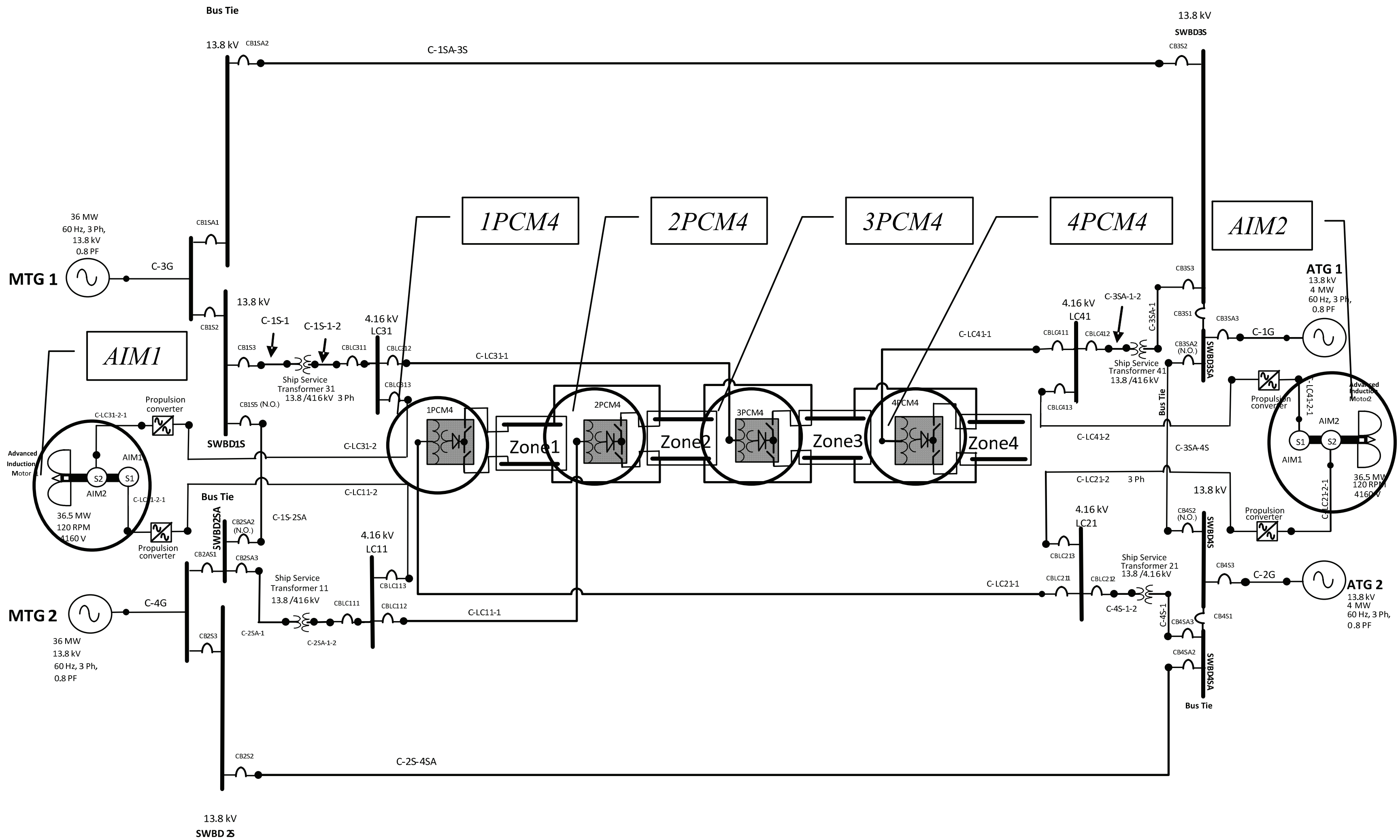

Fig. 4.2 Notional All Electric Common Bus Mode Schematic

4.2.1 Common Bus Mode

The Common Bus Mode topology is configured such that the four generators are connected to the ring structure energizing all buses. The ring structure consists of circuit breakers and cables as shown in Fig. 4.3. In Fig. 4.3, the Common Bus Mode is shown highlighting the ring structure and all paths to each switchboard from generator $ATG2$ .The generators, along with the ring structure, are used to energize power electronic devices called *PCM4s* that convert AC voltage to DC voltage. The *PCM4*s are labeled $1PCM4$, $2PCM4$, $3PCM4$, and $4PCM4$, which supply each zone as shown in Fig. 4.3. The propulsion system also has the same HV structure as the PCM4s. The propulsion system is made up of two propellers at which two induction motors per propeller are used (see Fig. 4.2). The Advanced Induction Motor 1 (*AIM1*) consist of two induction motors labeled *S1* and *S2* as shown on Fig. 4.3. Similarly, the Advanced Induction Motor 2 (*AIM2*) also consists of two induction motors *S1* and *S2* also shown in Fig. 4.2. To avoid confusion between induction motors S1 and S2, $AIM1_{S1}$, $AIM1_{S2}$, $AIM2_{S1}$, and $AIM2_{S2}$ are used to specify which induction motor is being discussed. In the case of the propulsion system, the decision whether reconfiguration is needed will be made. In Fig. 4.3, the path to *1PCM4* is shown by arrows. The paths are labeled HV for the high voltage level and MV for the medium voltage level.

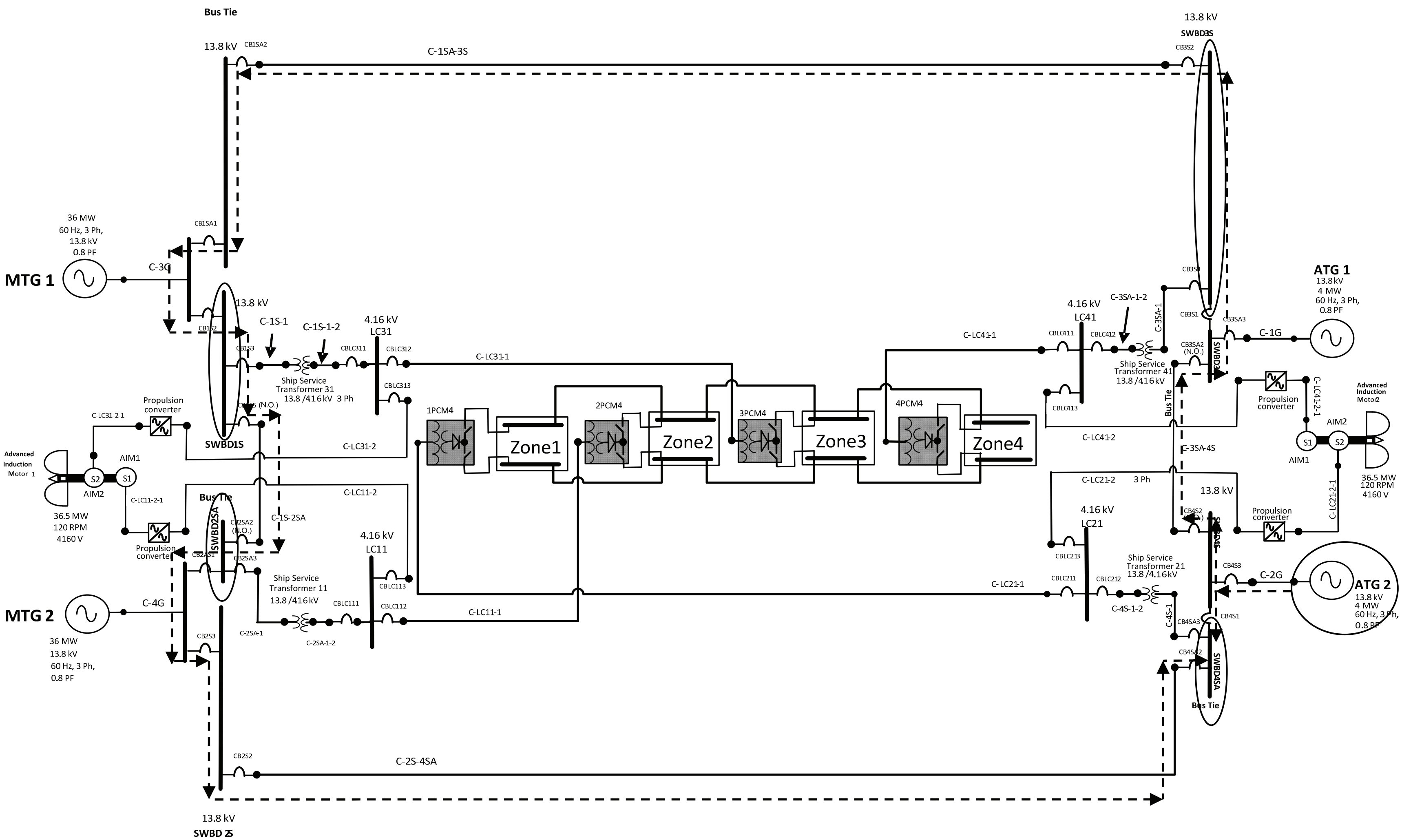

Fig. 4.3 HV Common Bus Mode Schematic

The Common Bus Mode is the only configuration at which all the components in the ring are used. The ring structure is a series structure used in each HV structure as shown in equation (4.3). For simplicity of the ring equation, four different equations are used in this thesis. When the ring is being used, all components will be used as a series structure together when demonstrating a HV structure in the common bus mode.

$$Ring = (Ring_{A1})(Ring_{A2})(Ring_{B1})(Ring_{B2}) \tag{4.3}$$

where:

$$(Ring_{A1}) = (CB4S1)(CB4S2)(C3SA4S)(CB3SA2)$$
$$(Ring_{A2}) = (CB3S1)(CB3S2)(C1SA3S)(CB1SA2)(CB1SA1)$$
$$(Ring_{B1}) = (CB1S2)(CB1S5)(C1S2SA)(CB2SA2)$$
$$(Ring_{B2}) = (CB2SA1)(CB2S3)(CB2S2)(C2S4SA)(CB4SA2)$$

The structures to each $PCM4$ and AIM consist of two structures in series; the HV structure and MV structure. In this section, the Common Bus HV structure functions are presented. In order to find all possible paths to *1PCM4* and $AIM2_{S2}$, one source at a time must be chosen. The first source that will be selected is *ATG2* and an imaginary sink is placed at bus $SWBD4SA$. Next, the path to the sink is traced from the source placing each component that is encountered into a series structure. The first set of components in this structure are *ATG2*, *C2G*, *CB4S3*, and *CB4S1*. This set of components are labeled $Path_{A1}$ as shown in equation (4.4).

$$Path_{A1} = (ATG2)(C2G)(CB4S3)(CB4S1) \tag{4.4}$$

The second series structure involves components from the ring structure as shown in equation (4.3). To obtain the second series structure, the process will begin with the same source and end at the same sink placing the notable components in a series structure. This set of components are *ATG2*, *C2G*, *CB4S3*, and all the components listed in equation (4.3) except for component *CB4S1* because it is not encountered in this path. This series path will be set equal to $Path_{A2}$ as shown in equation (4.5). Also in equation (4.5), component *CB4S1* is also in the ring structure. To eliminate this component from $Path_{A2}$

it will be divided from the ring structure to cancel the component's relevance in this path. $Path_{A1}$ and $Path_{A2}$ can be combined into one equation called $Path_A$ as shown in equation (4.6) by factoring the common components and adding the different components.

$$Path_{A2} = (ATG2)(C2G)(CB4S3)\left(\frac{(Ring)}{(CB4S1)}\right) \tag{4.5}$$

$$Path_A = (ATG2)(C2G)(CB4S3)\left[(CB4S1) + \left(\frac{(Ring)}{(CB4S1)}\right)\right] \tag{4.6}$$

The *OR* logic is represented by the *OR* logic symbol in equation (4.6), and where each path from source to load represents a parallel structure function as shown in equation (3.46). The same process with each generator to the sink was used to determine the remaining paths. Since all four generators are connected to bus $SWBD4SA$ through the ring, a total of two paths per generator to any load is established. The HV structure for *1PCM4* is shown in equation (4.7) where $Path_B$, $Path_C$, and $Path_D$ are similar in structure to $Path_A$ using the remaining generators one at a time. The remaining structure functions are shown in Appendix A, Section A.1 for each $PCM4$ and Appendix B, Section B.1 for each AIM .

$$HV_{1PCM4} = Path_A + Path_B + Path_C + Path_D \tag{4.7}$$

Equation (4.7) can also be written as equation (4.8) to compute the survivability of the HV structure.

$$HV_{1PCM4} = 1 - (1 - Path_A)(1 - Path_B)(1 - Path_C)(1 - Path_D) \tag{4.8}$$

4.2.2 Port/Starboard Split Bus Mode

The Port/Starboard Split Bus Mode introduces a configuration such that a bus is energized by two generators with one path from each generator as shown in Fig. 4.4. In this configuration, *MTG1* and *ATG1* energize buses $SWBD1S$, $SWBD1SA$, $SWBD3S$, and $SWBD3SA$ which are connected together, and *MTG2* and *ATG2* energize buses

$SWBD2S$, $SWBD2SA$, $SWBD4S$, and $SWBD4SA$ which are connected together. This configuration is different from the Common Bus Mode because the entire ring structure is not connected since there are no connections between buses $SWBD1S$ and $SWBD2SA$ and buses $SWBD3SA$ and $SWBD4S$. Bus tie lines $C1S2SA$ and $C3SA4S$ are not connected with circuit breakers $CB1S5$, $CB2SA2$, $CB3SA2$, and $CB4S2$ in open status as shown in Fig. 4.4. The structure to bus $SWBD4SA$ is derived below and only two paths will be shown.

The HV structure to each $PCM4$ and AIM consist of two series structures in parallel. In order to find all possible HV structures to *1PCM4* and $AIM2_{S2}$, one source is chosen. The first source that will be selected is *ATG2,* and an imaginary sink is placed at bus $SWBD4SA$. Next, the path to the sink is developed by placing each component that is encountered into a series structure. The first series set of components in this structure are components *ATG2*, *C2G*, *CB4S3*, and *CB4S1*. These set of components are labeled $Path_A$ as shown in equation (4.9).

$$Path_A = (ATG2)(C2G)(CB4S3)(CB4S1) \tag{4.9}$$

The second series structure begins with the second generator *MTG2*. The same procedure that was used to derive equation (4.9) is used to derive the series structure from *MTG2* to bus $SWBD4SA$. The set of components that are in the second structure are *MTG2*, *C4G*, *CB2S3*, *CB2S2*, *C2S4SA*, and *CB4SA2*. This set of components will be labeled $Path_B$ as a series structure shown in equation (4.10).

$$Path_B = (MTG2)(C4G)(CB2S3)(CB2S2)(C2S4SA)(CB4SA2) \tag{4.10}$$

$Path_A$ and $Path_B$ represent the two alternate paths in the HV structure to bus $SWBD4SA$ shown in equation (4.11). As stated above, the addition sign in equation (4.11) represents a parallel connection between $Path_A$ and $Path_B$, and can also be written as equation (4.12). The remaining HV structures for the Port/Starboard Split Bus Mode are shown in Appendix A, Section A.2 for each *PCM4* and Appendix B, Section B.2 for each AIM.

$$HV_{1PCM4} = Path_A + Path_B \tag{4.11}$$

$$HV_{1PCM4} = 1 - \left(1 - Path_A\right)\left(1 - Path_B\right) \tag{4.12}$$

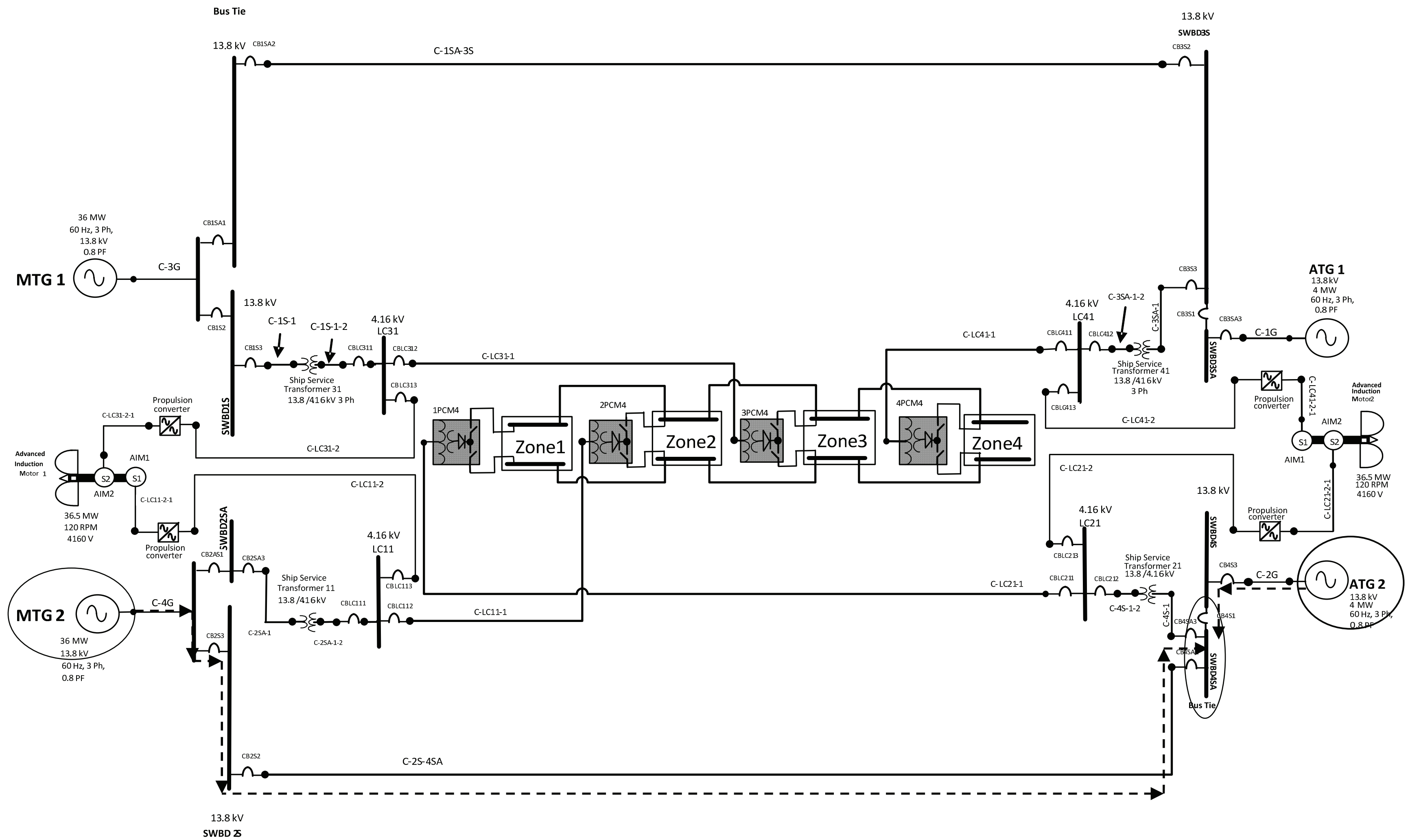

Fig. 4.4 HV Port/Starboard Split Bus Mode Schematic

4.2.3 Forward/Aft Split Bus Mode

The Forward/Aft Split Bus Mode is similar to the Port/Starboard Split Bus Mode because it too energizes a bus by two generators providing one path from each generator. In this configuration, *MTG1* and *MTG2* are connected together to energize buses $SWBD1S$, $SWBD1SA$, $SWBD2S$, and $SWBD2SA$, and *ATG1* and *ATG2* are connected together to energize $SWBD3S$, $SWBD3SA$, $SWBD4S$, and $SWBD4SA$ as shown in Fig. 4.5. This configuration is also different from the common bus mode because the entire ring structure is not used. The Forward/Aft Split Bus Mode, like the Port/Starboard Split Bus Mode, splits the ship's generators in half. In this configuration, the bus tie lines $C1SA3S$ and $C2S4SA$ are not connected with circuit breakers $CB1SA2$, $CB3S2$, $CB2S2$, and $CB4SA2$ in open status as shown in Fig. 4.5. The structure to bus $SWBD4SA$ is shown below and has only two paths from generators *ATG2* and *ATG1*.

The HV structure to each PCM4 and propulsion motor consists of two series structures in parallel. All HV structures to *1PCM4* and $AIM2_{S2}$, are determined to compute the load survivability to each load. The first source selected is *ATG2* and an imaginary sink is placed at bus $SWBD4SA$. Next, the components that are in the path from the source to sink are placed in a series structure. The first series set of components in this structure are components *ATG2*, *C2G*, *CB4S3*, and *CB4S1*. This set of components will be labeled $Path_A$ as shown in equation (0.56).

$$Path_A = (ATG2)(C2G)(CB4S3)(CB4S1) \tag{4.13}$$

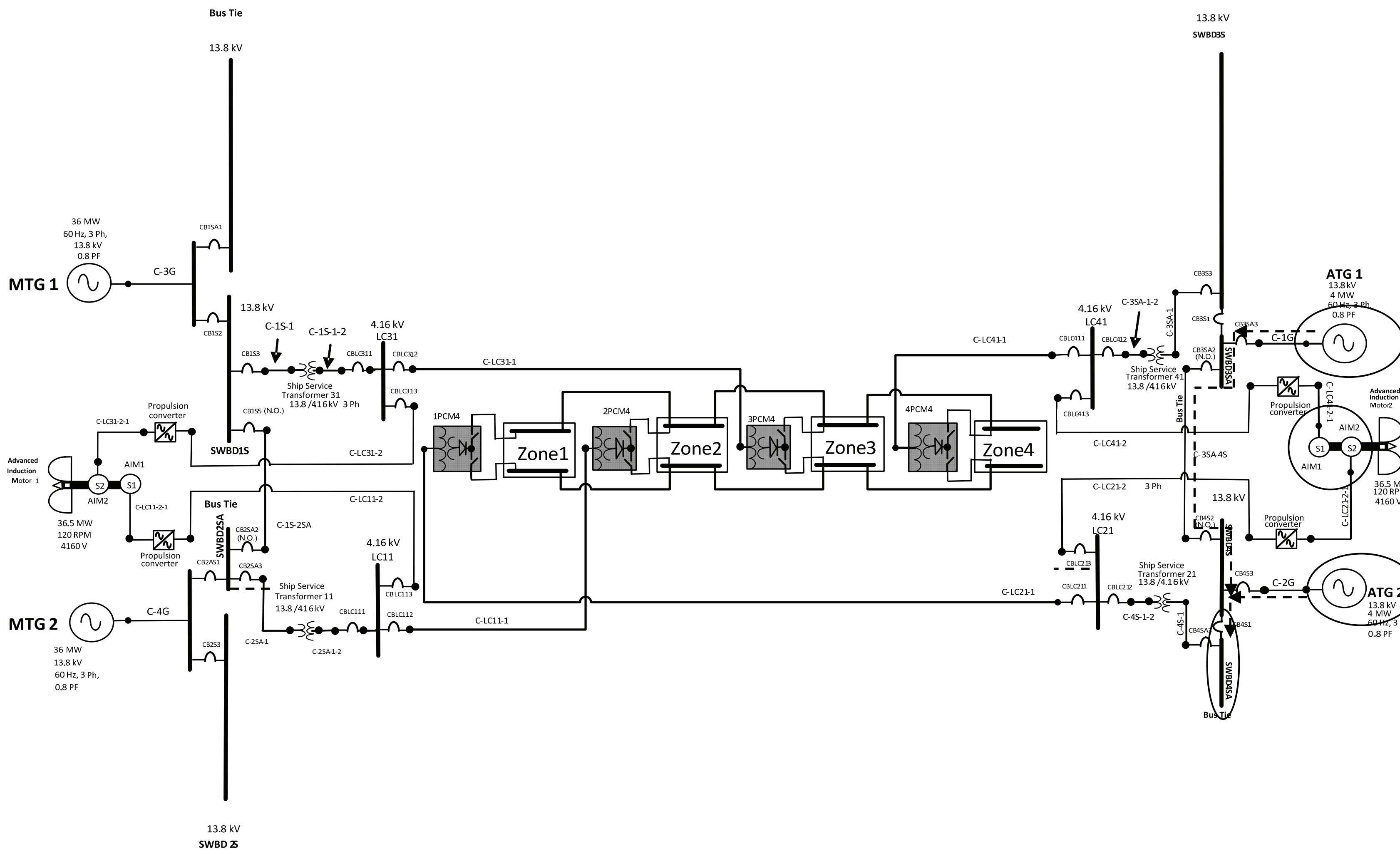

Fig. 4.5 HV Forward/Aft Split Bus Mode Schematic

The second series structure will begin with the second generator *ATG1*. The same procedure that was used to derive equation (4.13) is used to derive the series structure from *ATG1* to bus $SWBD4SA$. The set of components that are in the second structure are *ATG1*, *C1G*, *CB3SA3*, *CB3SA2*, *C3SA4S*, *CB4S2*, and *CB4S1*. This set of components will be labeled $Path_B$ as a series structure shown in equation (4.14)[1].

$$\begin{aligned} Path_B = &\left(ATG1\right)\left(C1G\right)\left(CB3SA3\right)\left(CB4S2\right)\ldots \\ &\left(C3SA4S\right)\left(CB3SA2\right)\left(CB4S1\right) \end{aligned} \tag{4.14}$$

$Path_A$ and $Path_B$ represent the two alternate paths in the HV structure to bus $SWBD4SA$ shown in equation (4.15). Since component *CB4S1* is common in both structures, it can be factored out and placed in series with the parallel combination of $Path_A$ and $Path_B$. $Path_A$ and $Path_B$ can also be written as equation (4.16). The remaining HV structures for the Forward/Aft Split Bus Mode are shown in Appendix A, Section A.3 for each *PCM4* and Appendix B, Section B.3 for each AIM.

$$HV_{1PCM4} = \left(CB4S1\right)\left(Path_A + Path_B\right) \tag{4.15}$$

$$HV_{1PCM4} = \left(CB4S1\right)\left(1-\left(1-Path_A\right)\left(1-Path_B\right)\right) \tag{4.16}$$

4.3 MV Structure Function

The MV system to each $PCM4$ and AIM will be the same independent of the configuration mode. The eight MV structures in this system consist of components that are grouped in a set labeled MV_n where n represents the path number from one to four to each $PCM4$ and from five to eight to each propulsion motor. The MV structures consist of cables, circuit breakers, and a transformer. The MV structures to the AIMs have an additional power electronic device, an AC/AC propulsion converter. As stated in section 2.2, the voltage level is stepped down from 13.8kVAC to 4.16kVAC through a transformer for components such as the AIM. In Fig. 4.6, the notional SPS configured in the Forward/Aft Split Bus Mode is used to show the MV paths from each switchboard to

[1] The three dots used in equations throughout this thesis implies to continue to the next line.

each $PCM4$ and AIM. The paths are shown with dotted lines and labeled MV_1 to MV_8. In the following two sections, the MV structures to each $PCM4$ and AIM will be presented.

4.3.1 PCM4 Structure Function

The MV structure to each $PCM4$ is a series structure from one of the buses as mentioned above in section 0 to one of the four *PCM4*s shown in Fig. 4.6. MV_1 structure function is determined by starting with the set of components structure to $1PCM4$ which consist of one transformer, three cables, and three circuit breakers. This MV structure starts with the first component behind bus $SWBD4SA$ and ends with the last component connected to $1PCM4$. The components in this MV structure are in a series structure and is given by equation (4.17). The remaining MV structures from buses $SWBD2SA$, $SWBD1S$, and $SWBD3SA$ to $2PCM4$, $3PCM4$, and $4PCM4$, respectively are given in Appendix A, Section A1. Note, the MV structure functions are the same for each configuration and are included in Appendix B, Section B1.

$$\begin{aligned} MV_1 = &(CB4SA3)(C4S1)(X21)(C4S12)\ldots \\ &(CBLC212)(CBLC211)(CLC211) \end{aligned} \tag{4.17}$$

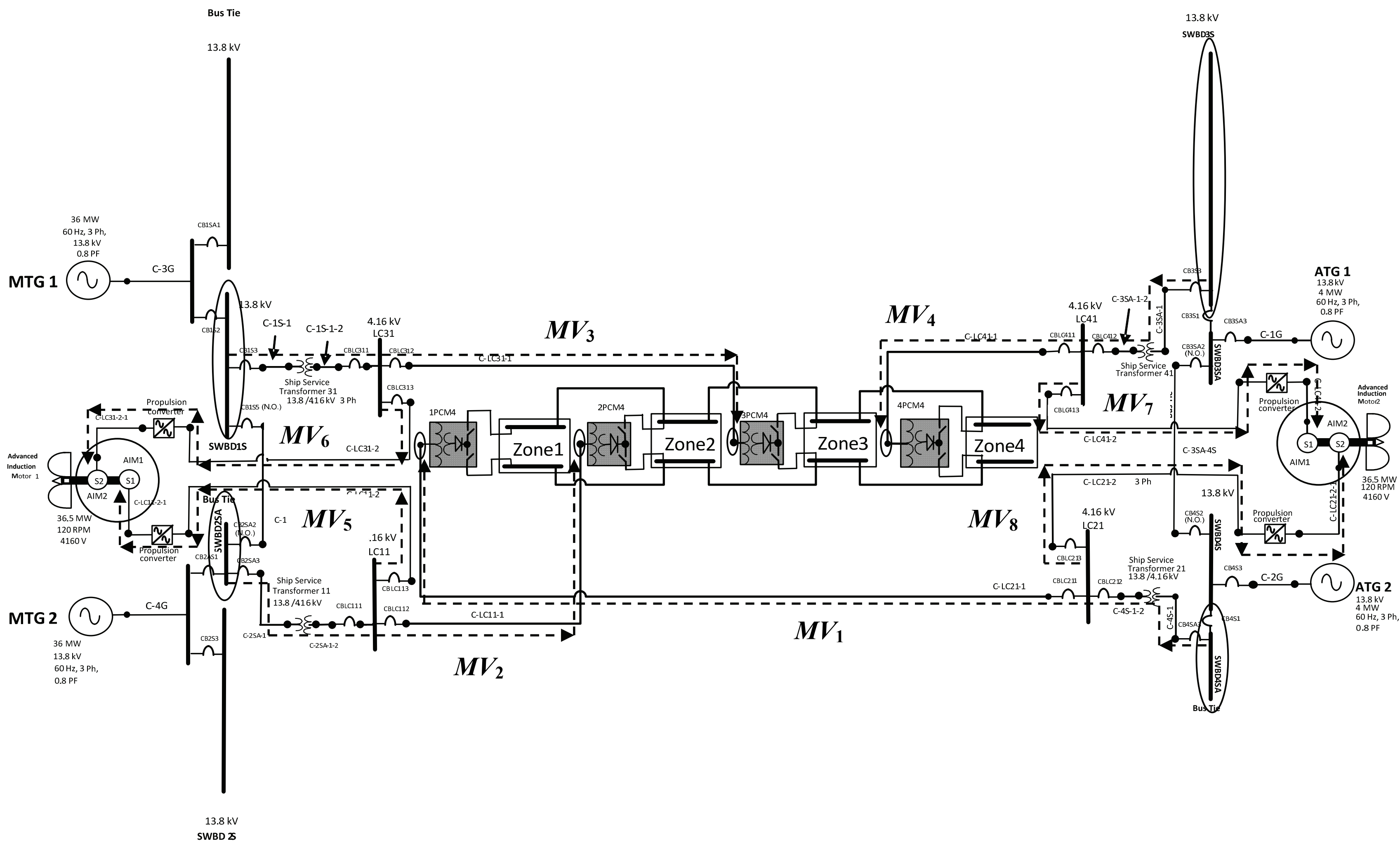

Fig. 4.6 MV Path Schematic

4.3.2 Propulsion Structure Function

The MV structures for each *AIM* are series structures from one of the buses as mentioned above to one of the four propulsion motors as shown in Fig. 4.6. MV_5 is determined by starting with the set of components structure to $AIM1_{S1}$ which consist of one transformer, four cables, one AC/AC propulsion converter, and three circuit breakers. The MV structure function is determined by the first component behind bus $SWBD2SA$, and ends with the last component connected to $AIM1_{S1}$. The components in this MV structure are in a series structure and given by equation (4.18). To distinguish the different propulsion converters connected to the induction motors, the propulsion converters are labeled $IM1PC_{S1}$, $IM1PC_{S2}$, $IM2PC_{S1}$, and $IM2PC_{S2}$. The remaining MV structures from buses $SWBD1S$, $SWBD3SA$, and $SWBD4SA$ to $AIM1_{S2}$, $AIM2_{S1}$, and $AIM2_{S2}$, respectively, are given in Appendix B, Section B1. The MV paths to each AIM are the same for each mode of configuration.

$$\begin{aligned} MV_5 = &(CB2SA3)(C2SA1)(X11)(C2SA12)(CBLC111)\ldots \\ &(CBLC113)(CLC112)(IM1PC_{S1})(CLC1121) \end{aligned} \tag{4.18}$$

4.4 HV/MV Structure Function

The subsystem structure for the each $PCM4$ and propulsion system consist of a HV structure in series with a MV structure as explained in sections 0 and 4.3. In this section, each structure function for the *PCM4*s and propulsion systems, defined as $\phi_k(\bar{X})$, will be presented using the HV and MV structures. The components that are used to derive the HV and MV structures are also used to determine each $PCM4$ and propulsion motor. The mode of operation is negligible because once the HV structure function is determined, the appropriate MV structure is also determined depending on the load that is being studied. The *PCM4* structure functions will be explained first, and then the propulsion motor structure functions will be explained.

4.4.1 PCM4 Structures

There are a total of four PCM4s; therefore there will be four general equations for each of the configuration modes. Equation (4.1) is used to determine the path/structures, beginning with $k=1$ or $k=1PCM4$. Equation (4.19) shows the HV structure derived in section 0 and the MV structure derived in section 4.3, which shows the path/structure to *1PCM4*. Equations (4.20) to (4.22) describe the remaining $PCM4$s for $k=2,\ 3,$ and 4 or $k=2PCM4,\ 3PCM4,$ and $4PCM4$. All HV and MV structure functions are shown in Appendix A, Sections A1-A3 for all modes of configuration.

$$\phi_{1PCM4}\left(\overline{X}\right)=\left(HV_{1PCM4}\right)\left(MV_{1}\right) \tag{4.19}$$

$$\phi_{2PCM4}\left(\overline{X}\right)=\left(HV_{2PCM4}\right)\left(MV_{2}\right) \tag{4.20}$$

$$\phi_{3PCM4}\left(\overline{X}\right)=\left(HV_{3PCM4}\right)\left(MV_{3}\right) \tag{4.21}$$

$$\phi_{4PCM4}\left(\overline{X}\right)=\left(HV_{4PCM4}\right)\left(MV_{4}\right) \tag{4.22}$$

4.4.2 Propulsion Structures

The propulsion structures are slightly different from the $PCM4$ structures because of the MV structure as stated earlier. There are also a total of four propulsion motors; therefore, there will be four general equations for each configuration mode. Equation (4.1) is used to determine the path structures, beginning with $k=5$ or $k=AIM1_{S1}$. Equation (4.23) shows how the HV structure function derived in section 0 and the MV structure function derived in section 4.3 is developed to $AIM1_{S1}$. Equations (4.24) to (4.26) are used to describe the remaining $PCM4$s for $k=6,\ 7,\ \text{and}\ 8$ or $k=AIM1_{S2},\ AIM2_{S1},\ \text{and}\ AIM2_{S2}$. HV_{2PCM4} to HV_{4PCM4} and MV_6 to MV_8 are shown in Appendix B, Sections B1-B3 for all configuration modes.

$$\phi_{AIM1S1}\left(\overline{X}\right)=\left(HV_{2PCM4}\right)\left(MV_{5}\right) \tag{4.23}$$

$$\phi_{AIM1S2}\left(\overline{X}\right)=\left(HV_{1PCM4}\right)\left(MV_{6}\right) \tag{4.24}$$

$$\phi_{AIM2S1}\left(\overline{X}\right)=\left(HV_{4PCM4}\right)\left(MV_{7}\right) \tag{4.25}$$

$$\phi_{AIM2S2}\left(\overline{X}\right)=\left(HV_{3PCM4}\right)\left(MV_{8}\right) \tag{4.26}$$

4.5 DC Zonal Structure Function

The low voltage system is a system at which the $PCM4$'s are energizing loads. These loads are located in each zone connected to the DC buses. As stated in section 2.2, these loads are connected to power converters in which the DC voltage is stepped down from 1kVDC to 375VDC, 650VDC, or 800VDC. Each AC load in each zone is fed by a PCM4 (DC/AC converter). The zones are interconnected by zone tie lines which consist of switches and cables. The components that are in a LV structure function are cables, bus transfers, switches, and converters. Bus transfers such as $Z1BT1$ is two individual switches labeled $pZ1BT1$ and $sZ1BT1$ for the port and starboard side of each zone. The power flows only through the normal or alternate path. Each zone is interconnected through zone ties connecting all four port DC buses and all four starboard DC buses as shown in

Fig. 4.7. Each zone tie consists of two switches and a cable. The zone tie structure functions are labeled $pTie_{1\_2}$ to connect zone one to zone two, $pTie_{2\_3}$ to connect zone two to zone three, and $pTie_{3\_4}$ to connect zone three to zone four on the port (upper) side of each zone. These three structures are shown in equation (4.27).

$$\begin{aligned} pTie_{1\_2} &= \left(Z1SW39\right)\left(C1Z21\right)\left(Z2SW41\right) \\ pTie_{2\_3} &= \left(Z2SW39\right)\left(C2Z31\right)\left(Z3SW41\right) \\ pTie_{3\_4} &= \left(Z3SW39\right)\left(C3Z41\right)\left(Z4SW41\right) \end{aligned} \tag{4.27}$$

The star (lower) side of each zone is labeled similarly except it will be labeled $sTie_{1\_2}$ to connect zone one and zone two, $sTie_{2\_3}$ to connect zone two and zone three, and $sTie_{3\_4}$ to connect zone three and zone four as shown in equation (4.28).

$$\begin{aligned} sTie_{1\_2} &= (Z1SW40)(C1Z22)(Z2SW42) \\ sTie_{2\_3} &= (Z2SW40)(C2Z32)(Z3SW42) \\ sTie_{3\_4} &= (Z3SW40)(C3Z42)(Z4SW42) \end{aligned} \tag{4.28}$$

4.5.1 Common Bus Mode and Port/Starboard Split Bus Mode

The loads in each zone are energized the same way in the Common Bus Mode and the Port/Starboard Split Bus Mode. This configuration includes closed switches *Z1SW20, Z2SW20, Z3SW19,* and *Z4SW19* and open switches *Z1SW19*, *Z2SW19*, *Z3SW20*, and *Z4SW20* on

Fig. 4.7 results in Fig. 4.8. The open switches are circled and labeled as shown in Fig. 4.8. The port side buses of each zone are energized by *3PCM4* and *4PCM4*, and the starboard side buses are energized by *1PCM4* and *2PCM4* as shown in Fig. 4.8. The vital loads are typically energized through the normal path and switched to their alternate path when bus transfers detect low voltage conditions.

4.5.2 Forward/Aft Split Bus Mode

The loads in the Forward/Aft Split Bus Mode are energized differently than the way described above for the Common Bus Mode and Port/Starboard Split Bus Mode. This configuration includes closed switches *Z1SW20*, *Z2SW19*, *Z3SW19*, and *Z4SW20* and opened switches *Z1SW19*, *Z2SW20*, *Z3SW20*, and *Z4SW19* on

Fig. 4.7 results in Fig. 4.9. The open switches are circled and labeled as shown in Fig. 4.9. The port side buses of each zone are energized by *2PCM4* and *3PCM4*, and the starboard side buses are energized by *1PCM4* and *4PCM4* as shown in Fig. 4.9. The general structure for vital and non-vital loads will be discussed in the next section.

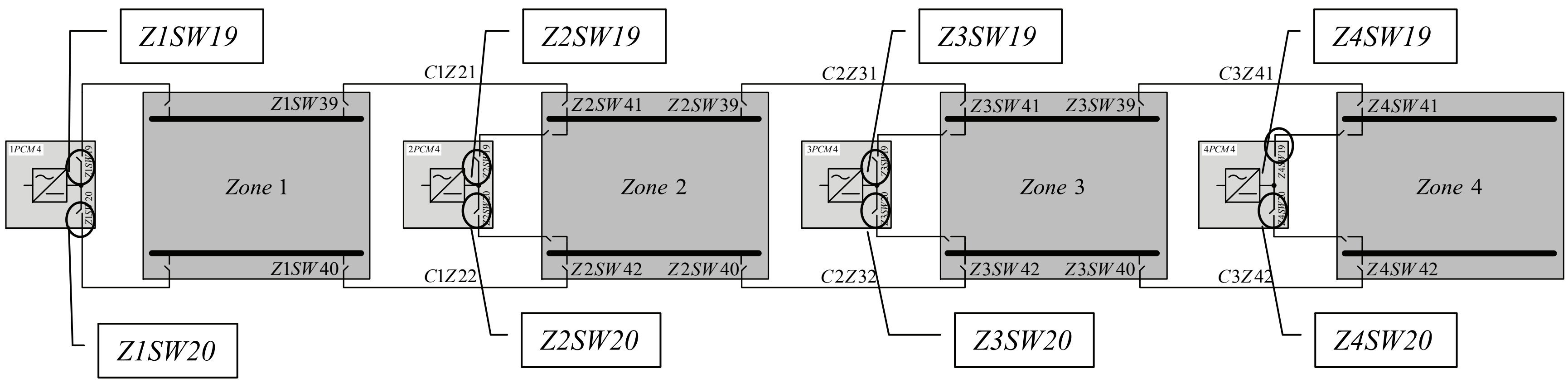

Fig. 4.7 DC Zonal System Schematic

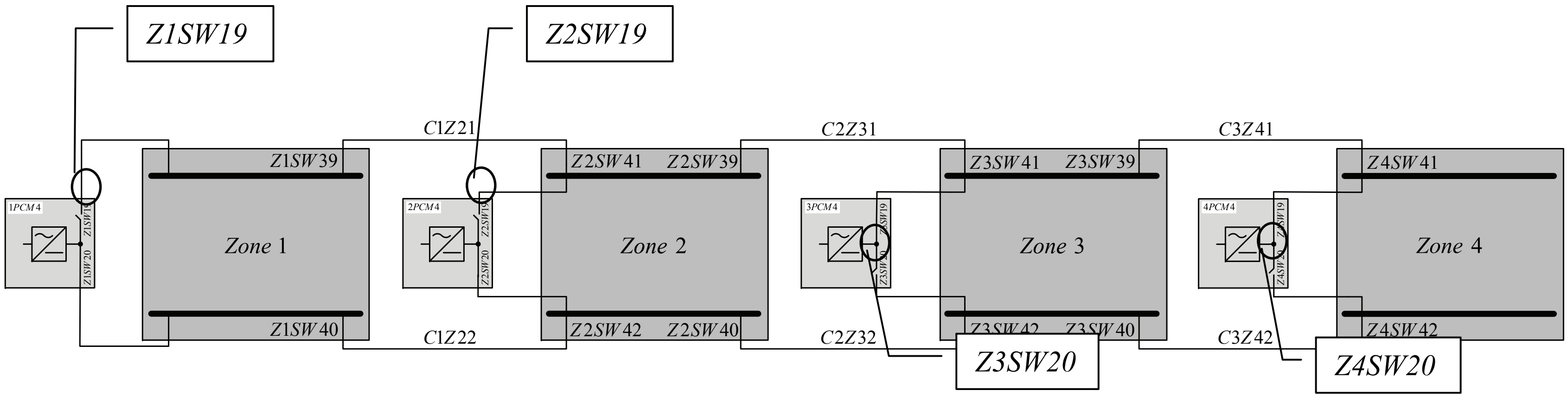

Fig. 4.8 Common Bus Mode and Port/Starboard Split Bus Mode Load Configuration

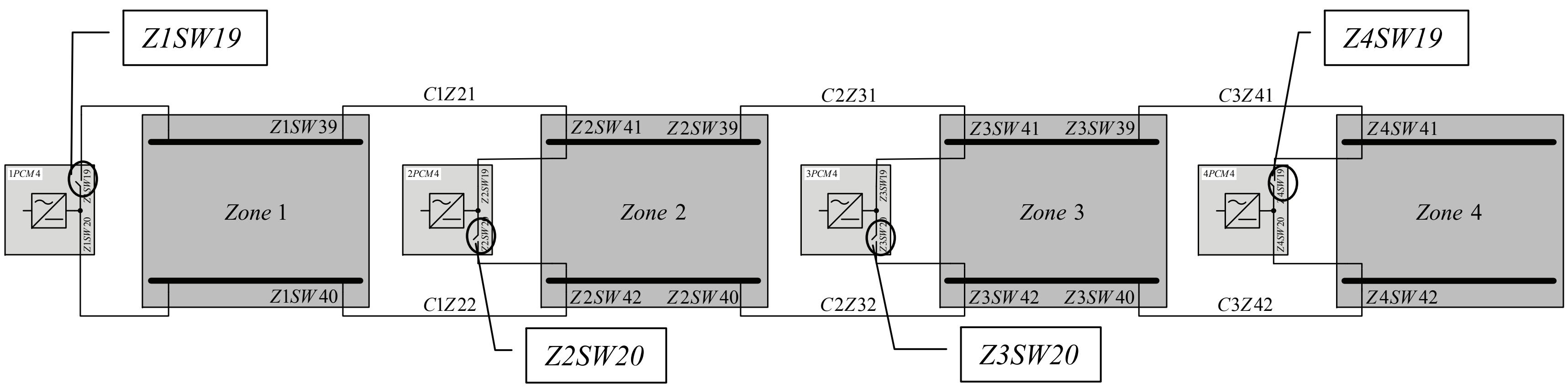

Fig. 4.9 Forward/Aft Split Bus Mode Load Configuration

4.5.3 Vital Load General Structure Functions

The vital loads in zone 1 shown in Fig. 4.10 are identified by the first letter in the load name beginning with the capital letter *V*. Zones two, three and four are mirror images of zone one. The loads in zone one are also labeled by the zone number *Z1*, load number *L1*, and if it is a DC or AC load by using *AC* or *DC*. For example*, VLZ1DCL1* represents the following: vital load, zone one, DC load one. Non-vital loads are identified in a similar manner except the letter *N* precedes the name of the load. A general structure function to each vital load is presented in this section. There are a total of eight paths to each vital load from each PCM4. The mode of operation will determine the structure for each vital load because of the bus transfers and the position of the switches from each PCM4.

The structure function to load *VLZ1DCL1* is determined by using $1PCM4$ as the source. From $1PCM4$, there are two paths to load *VLZ1DCL1*. The first set of components in the first path are *1PCM4*, *Z1SW19*, *CZ111*, *Z1SW25*, *Z1375VDC1*, *Z1SW1*, *CZ112*, *pZ1BT*, *CZ11*, and *Z1SW35*. These components are labeled as $Path_1$ as shown in equation (4.29).

$$\begin{aligned} Path_1 = &(1PCM4)(Z1SW19)(CZ111)(Z1SW25)(Z1375VDC1)(Z1SW1)\ldots \\ &(CZ112)(pZ1BT)(CZ11)(Z1SW35) \end{aligned} \tag{4.29}$$

The second path includes components *1PCM4*, *Z1SW20*, *CZ121*, *Z1SW26*, *Z1375VDC2*, *Z1SW10*, *CZ122*, *sZ1BT*, *CZ11*, and *Z1SW35*. These components are labeled as $Path_2$ as shown in equation (4.30).

$$\begin{aligned} Path_2 = &(1PCM4)(Z1SW20)(CZ121)(Z1SW26)(Z1375VDC2)(Z1SW10)\ldots \\ &(CZ122)(sZ1BT)(CZ11)(Z1SW35) \end{aligned} \tag{4.30}$$

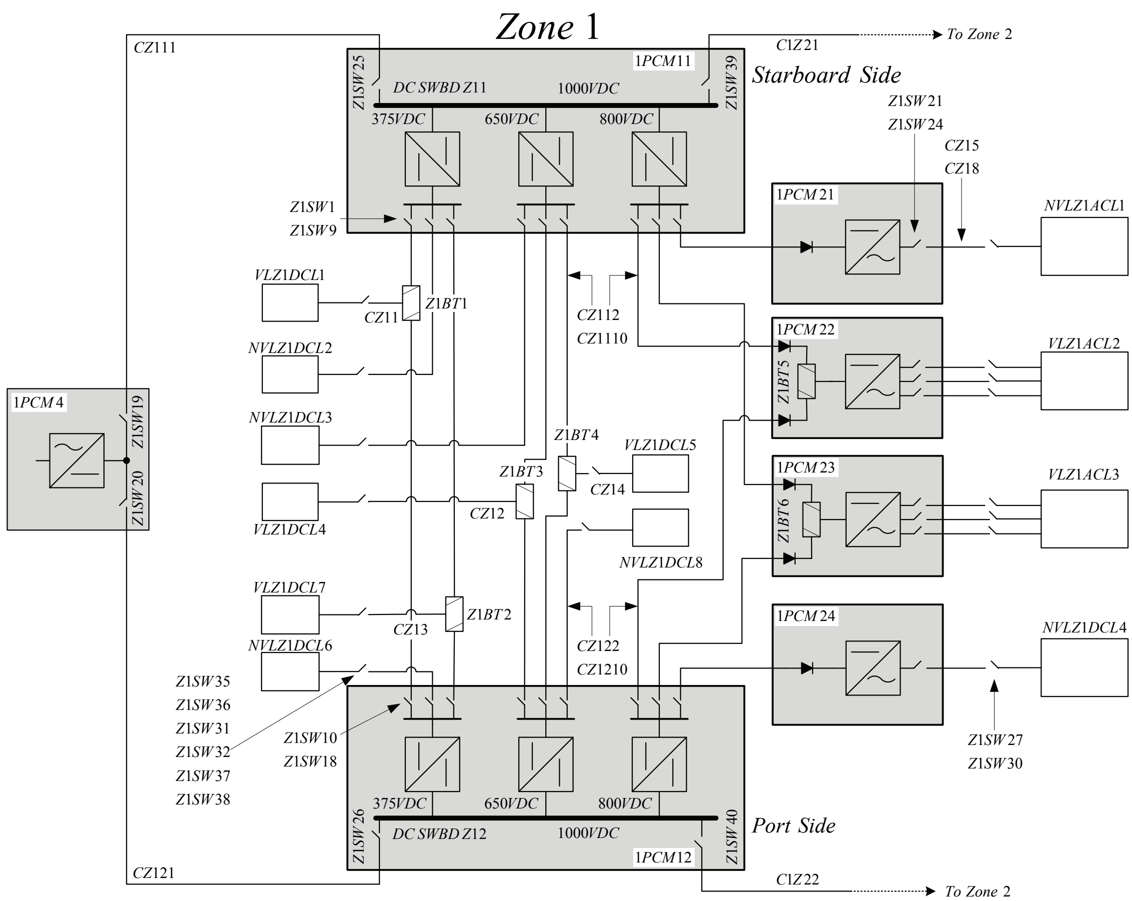

Fig. 4.10 Zone 1 Schematic

The next path begins from *2PCM4*. The same procedure is repeated one path at a time until the sink has been reached. As stated earlier, there are two paths from each *PCM4* to each vital load, and the zone tie that connects zone one to zone two is also included in the structure function to each vital load. For example, the Port (upper) side of schematic in Fig. 4.10 is used to determine the series structure from *2PCM4* to *VLZ1DCL1*. The components in this series structure function are *2PCM4*, *Z2SW19*, *CZ211*, $pTie_{1\_2}$, *Z1375VDC1*, *Z1SW1*, *CZ112*, *pZ1BT1*, *CZ11*, and *Z1SW35*. This set of components will be a series structure labeled $Path_3$ as shown in equation (4.31). In Appendix C, Section C1, the general structure functions for all loads are given.

$$\begin{aligned} Path_3 = &(2PCM4)(Z2SW19)(CZ211)(pTie_{1\_2})(Z1375VDC1)\ldots \\ &(Z1SW1)(CZ112)(pZ1BT1)(CZ11)(Z1SW35) \end{aligned} \tag{4.31}$$

When all eight structure functions are determined, the series structures will be placed in a parallel structure as shown in equation (4.32) which can also be written as equation (4.33). Not all paths will be active at a time because of the switches that are in each equation. The switches will be open or closed depending on the configuration mode.

$$\begin{aligned}\phi_{VLZ1DCL1}\left(\overline{X}\right) = {} & Path_1 + Path_2 + Path_3 + Path_4 + \ldots \\ & Path_5 + Path_6 + Path_7 + Path_8\end{aligned} \tag{4.32}$$

$$\begin{aligned}&\phi_{VLZ1DCL1}\left(\overline{X}\right) = 1 - \prod_{i=1}^{8}\left(1 - Path_i\right) \\ &\text{for } i = 1,\ 2,\ldots,8 \text{ number of paths to load } VLZ1DCL1\end{aligned} \tag{4.33}$$

All vital loads can be written in the form of equation (4.33), which represents the structure function for each of the vital loads in zones one through four. Each structure is unique because of the different components in each structure. In each mode of operation, four paths are not energized due to the configuration of the zones. For example, if the zones are configured such that the normal path of all vital loads in zones one and two are energized by *1PCM4* and *2PCM4*, six paths are not energized from the general structure function forming the normal path to load *VLZ1DCL1*. From equation (4.33), equation (4.34) is the structure function to load *VLZ1DCL1* in the Common Bus Mode and the Port/Starboard Split Bus Mode.

$$\phi_{VLZ1DCL1}\left(\overline{X}\right) = 1 - \prod_{i=1}^{2}\left(1 - Path_i\right) \tag{4.34}$$

where:

$$\begin{aligned}Path_1 = {} & \left(1PCM4\right)\left(Z1SW20\right)\left(CZ121\right)\left(Z1SW26\right)\left(Z1375VDC2\right)\ldots \\ & \left(Z1SW10\right)\left(CZ112\right)\left(sZ1BT1\right)\left(CZ11\right)\left(Z1SW35\right) \\ Path_2 = {} & \left(2PCM4\right)\left(Z2SW20\right)\left(sTie_{1\_2}\right)\left(Z1375VDC2\right)\ldots \\ & \left(Z1SW10\right)\left(CZ112\right)\left(sZ1BT1\right)\left(CZ11\right)\left(Z1SW35\right)\end{aligned}$$

Further, the alternate path of all vital loads in zones one and two are energized from the port side (*3PCM4* and *4PCM4*). In the previous example, the normal path structure function was given by the equation (4.33). The alternate path structure function is given by equation (4.43) in the Common Bus Mode or the Port/Starboard Split Bus Mode. The source is *3PCM4*, and the sink is *VLZ1DCL1*. The set of components in $Path_3$ are *3PCM4*, *Z3SW20*, *CZ321*, *Z3SW26*, $pTie_{1\_2}$, $pTie_{2\_3}$, *Z1375VDC1*, *Z1SW1*, *CZ112*, *CZ11*, *Z1SW35*, *pZ1BT1*, and are placed in a series structure shown in equation (4.35). $Path_4$ is given by the series structure from *4PCM4* to the sink shown in equation (4.36).

$$\begin{aligned} Path_3 = &\left(3PCM4\right)\left(Z3SW20\right)\left(CZ321\right)\left(Z3SW26\right)\left(pTie_{1\_2}\right)\left(pTie_{2\_3}\right)\ldots \\ &\left(Z1375VDC1\right)\left(Z1SW1\right)\left(CZ112\right)\left(pZ1BT1\right)\left(CZ11\right)\left(Z1SW35\right) \end{aligned} \tag{4.35}$$

$$\begin{aligned} Path_4 = &\left(4PCM4\right)\left(Z4SW20\right)\left(CZ421\right)\left(Z4SW26\right)\left(pTie_{1\_2}\right)\left(pTie_{2\_3}\right)\left(pTie_{3\_4}\right)\ldots \\ &\left(Z1375VDC1\right)\left(Z1SW1\right)\left(CZ112\right)\left(pZ1BT1\right)\left(CZ11\right)\left(Z1SW35\right) \end{aligned} \tag{4.36}$$

The bus transfer will never have the switch position connected to both the normal and alternate path. Therefore, two paths will exist to a vital load during a particular configuration.

4.5.4 Non-Vital Load General Structure Functions

The general structure function for non-vital loads are similar to vital loads because there are also multiple paths to each non-vital load from all PCM4s. The non-vital loads will never have more than two paths because there is only a normal path to these types of loads. The non-vital loads are supplied from the port side only or the starboard side only. In this section, all paths to *NVLZ1DCL2* are presented.

1PCM4 will serve as the source and the load *NVLZ1DCL2* will be the sink. Since there is only a normal path to these types of loads, then four paths are used to complete the general structure to the sink. The following components are used in the first series structure to the load: *1PCM4*, *Z1SW19*, *CZ111*, *Z1SW25*, *Z1375VDC1*, *Z1SW2*, *CZ113*, and *Z1SW36* shown in equation (437).

$$\begin{aligned} Path_1 = &\left(1PCM4\right)\left(Z1SW19\right)\left(CZ111\right)\left(Z1SW25\right)\ldots \\ &\left(Z1375VDC1\right)\left(Z1SW2\right)\left(CZ113\right)\left(Z1SW36\right) \end{aligned} \tag{4.37}$$

$Path_2$ shown in equation (4.38) will comprise of a zone tie from zone two. Starting from *2PCM4* the series path is established. These set of components are *2PCM4*, *Z2SW19*, *CZ211*, $pTie_{1\_2}$ from equation (4.27), *Z1375VDC1*, *Z1SW2*, *CZ113*, and *Z1SW36*.

$$\begin{aligned} Path_2 = &\left(2PCM4\right)\left(Z2SW19\right)\left(CZ211\right)\left(pTie_{1\_2}\right)\ldots \\ &\left(Z1375VDC1\right)\left(Z1SW2\right)\left(CZ113\right)\left(Z1SW36\right) \end{aligned} \tag{4.38}$$

After writing the remaining two series structures from *3PCM4* and *4PCM4*, the structure for *NVLZ1DCl2* can be written as shown in equation (4.39). Equation (4.39) can also be written as equation (4.40). The remaining structure functions for non-vital loads in each zone are given in Appendix C, Section C.1.1.

$$\phi_{NVLZ1DCL2}\left(\bar{X}\right) = Path_1 + Path_2 + Path_3 + Path_4 \tag{4.39}$$

$$\phi_{NVLZ1DCL2}\left(\bar{X}\right) = 1 - \prod_{i=1}^{4}\left(1 - Path_i\right) \tag{4.40}$$

For example, in the Port/Starboard Split Bus Mode, all non-vital loads connected to the port side of each zone are energized by *3PCM4* and *4PCM4*. In this configuration, two paths are eliminated from the general structure function forming the normal paths to load *NVLZ1DCL2*. From equation (4.40), equation (4.41) is the structure function to load *NVLZ1DCL2* in the Common Bus Mode and the Port/Starboard Split Bus Mode.

$$\phi_{NVLZ1DCL2}\left(\bar{X}\right) = 1 - \prod_{i=1}^{2}\left(1 - Path_i\right) \tag{4.41}$$

where:

$$\begin{aligned} Path_1 = &\left(3PCM4\right)\left(Z3SW19\right)\left(CZ311\right)\left(pTie_{1\_2}\right)\left(pTie_{2\_3}\right)\left(Z1375VDC1\right)\ldots \\ &\left(Z1SW1\right)\left(CZ113\right)\left(Z1SW36\right) \\ Path_2 = &\left(4PCM4\right)\left(Z4SW19\right)\left(CZ411\right)\left(pTie_{1\_2}\right)\left(pTie_{2\_3}\right)\left(pTie_{3\_4}\right)\left(Z1375VDC1\right)\ldots \\ &\left(Z1SW1\right)\left(CZ113\right)\left(Z1SW36\right) \end{aligned}$$

4.6 Reconfiguration

To this point, all structure functions to each load were formulated. Recall from section 0, all relevant components in a series structure must be operating for the system to operate. In the parallel structure, all components in one path must be operating for the system to be operational. The path to each $PCM4$ and AIM are considered to be a series structure, therefore the MV path and the HV path must be operating to energize the *PCM4*s and induction motors.

Overall reconfiguration is decided by comparing the normal and alternate path's conditional reliability for each of the loads in each zone. If the comparison of the normal and alternate paths to a load are close in survivability, then reconfiguration may not be needed. The loads in each zone are reconfigured by changing the topology. Since the non-vital loads do not have alternate paths, they can only be reconfigured by changing the topology. Also, each component must be checked to determine if any if the components have failed along the path to the load.

Reconfiguration is performed at the HV level of the IPS. Reconfiguration on the HV level is done by changing the topology. The current configuration must be known in order to know what configuration to change to. Similar to the loads in the zone, the path to each *PCM4* and induction motor are compared by mode of operation, and if the conditional survivability to each load is significantly higher in a different topology then reconfiguration may be needed.

The ranking of loads and paths are both based on priority. The sorting procedure is based on three parameters, the advanced induction motors, the paths to the *PCM4*s, and the vital and non-vital loads. Since the *PCM4*s and *AIM*s have no alternate path, the sorting for this type of load is very simple. The *AIM*s would be placed in order from most critical to least critical survivability value after comparing the two *AIM* values. The *PCM4*s are also ranked in a similar manner. Each *PCM4's* survivability value is compared to sort the *PCM4* in ascending order. For example, the *PCM4* survivability values in Table 4.1 will be sorted as shown in Table 4.2. From Table 4.2, component $2PCM4$ is the most critical component and $4PCM4$ is least critical.

Table 4.1 Unsorted Survivability Table

Component	Survivability
$1PCM4$	0.740529
$2PCM4$	0.703732
$3PCM4$	0.734103
$4PCM4$	0.742500

Table 4.2 Sorted Survivability

Component	Survivability
$2PCM4$	0.703732
$3PCM4$	0.734103
$1PCM4$	0.740529
$4PCM4$	0.742500

The vital and non-vital loads are sorted by the normal path to show which load is closest to failure. For both load types, the top five loads with most critical survivability are used to determine if reconfiguration is needed. The ranking of loads is discussed in chapter V of this thesis.

4.7 Summary

This chapter presented information about how to interpret a system using structures. The structures are determined by relevant components from the source to the sink. The IPS has three levels at which the structure was constructed, the HV level, the MV level, and the LV level. The loads are located in the MV and LV levels. The HV and MV levels are combined to formulate the structure to all MV loads. The power converters, PCM4s, are used as sources for the LV loads. The development of the procedure to compute the conditional survivability was shown in Fig. 4.1, which described the steps taken to compute load conditional survivability. Components are sorted from most critical to least critical to determine the need for reconfiguration.

This chapter provided information on structure function formulation for all LV loads, advanced induction motors, and the paths to each *PCM4*. The reconfiguration of loads was also addressed in this chapter to show how ranking is done with each type of load. The following chapter will discuss in detail the results from a few case studies. These case studies will emphasize reconfiguration and show how the failing of significant components affect load conditional survivability.

CHAPTER V

RESULTS

In this chapter, case studies are shown to illustrate scenarios where reconfiguration could be needed to improve the load survivability for a mission. These case studies show how failing components affect the survivability to loads over time. In the following sections, the middle of life is shown and how the failing components affect the survivability of a load during a horizon period. Since the system was separated between two load types, the $PCM4$ s and AIM s will be sorted from for each case study for these particular loads. The vital and non-vital loads in each zone are shown in its own case studies as well, and each load will be sorted from most critical to least critical. Only the top five most critical loads from each zone will be shown from each case study. The loads that are not above a desired threshold can easily be seen by sorting the loads from most critical to least critical. If five or more loads in the zone are below the threshold value, then reconfiguration is needed. If two or more HV/MV loads are below the threshold then reconfiguration is needed as well. The results will show the loads that are below the threshold value for a horizon period and if reconfiguration is needed.

5.1 Case Studies

The results are shown numerically and compared to similar components' paths to see the difference between a failing path and a non-failing path. To keep a good prospective, a Navy ship along with their components are considered to have at most a remaining/characteristic life (α) of thirty five years. The non-failing components will be chosen when present time x is selected. For example, if a present time $x=5$ then the non-failing components would have a remaining/characteristic life of $28 \leq \alpha \leq 30$. The horizon time is the sum of the present time and mission time $(t_h = x + t)$ where the mission time is the period over which the study will be performed. The failing components are set to fail within the mission time and before the horizon time. Therefore, the failing components remaining/characteristic life is less than the horizon time $(t_h - 2 \leq \alpha \leq t_h)$. The shape parameter β determines how fast a component will deteriorate. For example, if component A has a shape parameter $\beta = 2.3$ and component B has a shape parameter of $\beta = 3.5$, then component B will age faster after the characteristic life parameter has been reached.

In the next three sections, individual case studies are shown. Section 5.1.1 is a cable failure in zone one that will affect the conditional load survivability of vital and non-vital loads in two modes of configuration in the beginning, middle and end of life time periods. Section 5.1.2 is a zone tie failure that affects the conditional survivability to HV/MV loads. Section 5.1.3 is a transformer failure and it also affects the conditional survivability to HV/MV loads. All sections below will show the conditional survivability to loads in which the survivability is lowest in each time period and all modes of configuration.

5.1.1 Case Study 1: Cable Failure in Zone 1

The objective of this study is to show that reconfiguration is needed because on the normal path to the vital load (VLZ1DCL1) in zone 1; a critical component is failing or will fail during the mission time. The focus of this study is to show that the failing component listed in Table 5.1 affects the survivability to vital load VLZ1DCL1. The following data set in Table 5.1 shows the remaining life α in years and the shape parameter β for the failing cable and the remaining components. The other components' remaining life is between twenty four and twenty five years, and their shape parameter is between one and four. The present time x, horizon time tH, and the threshold values Thold for each period is also shown in Table 5.1.

.

Table 5.1 Case 1 Data Set

<table>
<tr><td colspan="2">Component</td><td colspan="2">α</td><td colspan="2">β</td></tr>
<tr><td colspan="2">CZ122</td><td colspan="2">11.025</td><td colspan="2">3.58</td></tr>
<tr><td colspan="2">Other</td><td colspan="2">$24 < \alpha < 25$</td><td colspan="2">$1 < \beta < 4$</td></tr>
<tr><td>Horizon Period</td><td colspan="2">x</td><td colspan="2">t_H (yrs)</td><td>T_{hold}</td></tr>
<tr><td>Early</td><td colspan="2">0</td><td colspan="2">6</td><td>0.3</td></tr>
<tr><td>Middle</td><td colspan="2">10</td><td colspan="2">13</td><td>0.2</td></tr>
<tr><td>End</td><td colspan="2">13</td><td colspan="2">17</td><td>0.1</td></tr>
</table>

The failing component is cable *CZ122* along the normal path to load *VLZ1DCL1*. From the cable will begin to fail faster than the other components over time because the remaining life is smaller than the other components. The results in Table 5.2 show the conditional survivability for each load in all modes of configuration. The beginning, middle, and end of life periods are shown in Table 5.2. The components in zones one and two are shown in this table because there are components below the threshold for each period. Loads in zones three and four are above the threshold value. Since the number of loads that are failing in the beginning and middle of life is lower than six, reconfiguration will not be needed for these two periods. The end of life period shows five components below the threshold for that period in the Forward/Aft Split Bus Mode (F/A SBM). If the mode of operation was in this configuration, reconfiguration would be needed. During the Common Bus Mode (CBM) and Port/Starboard Split Bus Mode (P/S SBM), all components except for load *VLZ1DCL1* are above the threshold, therefore reconfiguration would not be needed for this mode of operation. The failing component *CZ122* directly affects vital load *VLZ1DCL1* due to its low remaining life and the horizon period. The failing of other loads is due to the structure, remaining life and the horizon period as well.

Table 5.2 Case 1 Conditional Survivability Table

Beginning of Life			
CMB or P/S SBM		F/A SBM	
Zone 1			
VLZ1DCL1	0.2629	VLZ2DCL1	0.2681
VLZ1ACL2	0.3323	VLZ2ACL2	0.3389
NVLZ1ACL1	0.3828	NVLZ2ACL1	0.4112
NVLZ1ACL4	0.4046	NVLZ2ACL4	0.4126
VLZ1ACL3	0.5083	VLZ2ACL3	0.5184
Zone 2			
NVLZ2ACL1	0.3798	VLZ2ACL2	0.2306
VLZ2ACL2	0.3915	NVLZ2ACL1	0.4039
VLZ2DCL4	0.4549	VLZ2DCL4	0.4282
VLZ2ACL3	0.5170	VLZ2ACL3	0.4863
NVLZ2DCL8	0.5422	VLZ2DCL1	0.5005
Middle of Life			
CMB or P/S SBM		F/A SBM	
Zone 1			
VLZ1DCL1	0.1058	VLZ2DCL1	0.1041
VLZ1ACL2	0.2378	VLZ2ACL2	0.2340
NVLZ1ACL4	0.2705	NVLZ2ACL4	0.2661
VLZ1ACL3	0.2824	VLZ2ACL3	0.2778
NVLZ1ACL1	0.2852	NVLZ2ACL1	0.2806
End of Life			
CMB or P/S SBM		F/A SBM	
Zone 1			
VLZ1DCL1	0.0048	VLZ2DCL1	0.0044
NVLZ1ACL1	0.1156	VLZ2ACL2	0.1154
VLZ1ACL2	0.1266	NVLZ2ACL1	0.1459
VLZ1ACL3	0.1653	VLZ2ACL3	0.1507
NVLZ1ACL4	0.1756	NVLZ2ACL4	0.1601
Zone 2			
VLZ2ACL2	0.1262	VLZ2ACL2	0.0824
VLZ2ACL3	0.1394	VLZ2DCL1	0.0930
NVLZ2ACL1	0.1458	VLZ2ACL3	0.0941
VLZ2DCL4	0.1767	VLZ2DCL5	0.0974
NVLZ2ACL4	0.1857	NVLZ2ACL4	0.1558

5.1.2 Case Study 2: Port/Starboard Bus Tie Failure

The objective of this study is to show that reconfiguration may be needed because two critical cables in the Port/Starboard Split Bus Mode will fail during the mission. The results for Forward/Aft Split Bus Mode and Common Bus Mode will also be shown for comparison. The focus in this case is the path to each AIM and $PCM4$ in the Port/Starboard Split Bus Mode. The following data set in Table 5.3 shows the remaining life α in years and the shape parameter β for the failing cables and the remaining components. The *other* components' remaining life is between twenty eight and thirty years, and their shape parameter is between one and four. The present time x, horizon time t_H, and the threshold values T_{hold} for each period is also shown in Table 5.3.

Table 5.3 Case 3 Data Set

Component	A	β	
C2S4SA	7.099	2.83	
C1SA3S	6.267	1.53	
Other	$28 < \alpha < 30$	$1 < \beta < 4$	
Horizon Period	x	t_H (yrs)	T_{hold}
Early	0	5	0.75
Middle	5	8	0.65
End	11	18	0.1

The failing components are cables *C2S4SA* and *C1SA3S* which connects generators *MTG1* and *ATG1*, and *MTG2* and *ATG2* to supply all HV/MV loads. Table 5.3 shows that the cables will fail before the horizon time, and during the mission time. The results from Table 5.4 show conditional survivability for each $PCM4$ and AIM in all modes of operation. The survivability to each $PCM4$ and AIM are lower than the survivability of the Common Bus Mode (CBM) and Forward/Aft Split Bus Mode (F/A). In this case study, reconfiguration would be needed because one load is below the threshold in both the middle of life period and end of life period. The cables that are failing in this study affect the survivability to $2PCM4$ in the Port/Starboard Split Bus Mode (P/S) because half of the ring structure is used. If the cables were to actually fail, all loads in the

Port/Starboard Split Bus Mode would show a low survivability and reconfiguration would be needed.

Table 5.4 Case 3 Conditional Survivability Table

Component	Beginning of Life			Middle of Life			End of Life		
	CBM	P/S	F/A	CBM	P/S	F/A	CBM	P/S	F/A
1PCM4	0.8482	0.7943	0.8274	0.7494	0.6682	0.7405	0.1093	0.1089	0.1109
2PCM4	0.7804	0.6792	0.7523	0.7234	0.5725	0.7037	0.1073	0.1123	0.1111
3PCM4	0.8653	0.7953	0.8353	0.7545	0.6750	0.7341	0.1096	0.1107	0.1136
4PCM4	0.7864	0.7363	0.7803	0.7516	0.6650	0.7425	0.1130	0.1069	0.1144
AIM1	0.9813	0.9495	0.9718	0.9302	0.8580	0.9193	0.1483	0.1524	0.1534
AIM2	0.9297	0.9026	0.9228	0.8923	0.8374	0.8869	0.1354	0.1317	0.1372

5.1.3 Case Study 3: Transformer Failure

The objective of this study is to show how transformers X11 and X31 affect the conditional survivability to components AIM1S1, AIM1S2, 2PCM4, and 3PCM4. The focus in this case are the paths to $AIM1$ (AIM1S1 and AIM1S2), and PCM4s, 2PCM4, and 3PCM4 because the transformers are critical components to the loads and the HV configuration has no influence. The following data set in Table 5.5 shows the remaining life α in years and the shape parameter β for the failing cable and the remaining components. The other components' remaining life is between twenty seven and twenty five years, and their shape parameter is between one and four. The present time x, horizon time t_H, and the threshold values T_{hold} for each period is also shown in Table 5.5.

Table 5.5 Case 5 Data Set

Component	α	β
X_{11}	11.515	3.04
X_{31}	10.302	3.25
other	$25 < \alpha < 27$	$1 < \beta < 4$

Horizon Period	X	t_H	T_{hold}
Early	0	8	0.5
Middle	8	12	0.3
End	15	20	0.1

The failing components are transformers X_{11} and X_{31}. These transformers are very critical because they are needed for the HV/MV loads $AIM1_{S1}$, $AIM1_{S2}$, *2PCM4*, and *3PCM4* to function. From Table 5.5, the transformers are failing during the middle of life horizon period, and before the end of life horizon period. The results from Table 5.6 show that the survivability to load $1PCM4$ in the Port/Starboard Split Bus Mode and the Forward/Aft Split Bus Mode are below the threshold in the beginning of life period. Since only one load is below the threshold, reconfiguration will not be needed during this period. The middle and end of life periods show that the all loads are below the threshold and reconfiguration will be needed because 2 or more loads are below the threshold.

Table 5.6 Case 5 Conditional Survivability Table

Component	Beginning of Life			Middle of Life			End of Life		
	CBM	P/S	F/A	CBM	P/S	F/A	CBM	P/S	F/A
1PCM4	0.5193	0.4829	0.4847	0.0849	0.0776	0.0747	0.0065	0.0075	0.0072
2PCM4	0.7242	0.6815	0.6985	0.1145	0.1127	0.1090	0.0073	0.0083	0.0082
3PCM4	0.8053	0.7811	0.7714	0.0955	0.0636	0.0682	0.0013	0.0005	0.0018
4PCM4	0.6277	0.6123	0.6076	0.0933	0.0772	0.0859	0.0053	0.0062	0.0061
AIM1	0.8331	0.8117	0.8137	0.1320	0.1113	0.1119	0.0041	0.0042	0.0048
AIM2	0.8484	0.8243	0.8234	0.1268	0.1113	0.1143	0.0041	0.0048	0.0047

5.2 System Results for Case Studies

The system results from each case study are shown in two parts, the HV/MV summary table and the Zone summary table. Table 5.7 shows the data set for each analyzed study. The HV/MV loads as well as Zonal loads conditional survivability are shown in Tables 5.8 through 5.11. These loads are affected by components failing during a life period. In Case Study 1, transformers X_{11} and X_{31} are shown to be failing components, affecting the conditional survivability to HV/MV loads. In case Studies 2, 4, 5 and 6 are cables shown to be failing, affecting the conditional survivability to HV/MV loads. Case Study 3 shows AC/DC converter AIM_2CON_{S2} failing affecting the conditional survivability to Zonal loads. Case Study 7 and 8 shows cables failing, affecting the conditional survivability to HV/MV loads. Case Study 9 shows generator *MTG1* failing, affecting the conditional survivability to HV/MV loads.

The HV/MV summary table, Table 5.8, shows all loads in each horizon period. The Zone summary table shows the top five most critical load survivability values for each zone and horizon period. The Zone summary table, Tables 5.9 through 5.11, is also split into three tables, the early life table, the middle of life table, and the end of life table. Each table shows the beginning of life period, middle of life period, and the end of life period. The tables show a comparison of each configuration and how each load is sorted from one configuration to another. The *PCM4*s and *AIM*s are shown for only HV/MV studies and the low level loads (vital and non-vital loads) are shown for only LV studies. The remaining life (α) and shape parameter (β) are the same for each component through all three life periods or horizons. The present time and horizon time changes for each horizon in a case study.

In the data set summary table, α represents the remaining life in years and β is the shape parameter. The data set summary table, Table 5.7, also shows the horizon periods (early life, middle life, and end of life), the present time x in years, the horizon time t_H in years, and the threshold value T_{hold} for each period. In this section, the results for each load are shown sorted along with the corresponding data set.

Table 5.7 Data Set Summary Table

System Case Study 1		
Component	α	β
X_{11}	11.515	3.04
X_{31}	10.302	3.25
other	$25 < \alpha < 27$	$1 < \beta < 4$

Horizon Period	x	t_H	T_{hold}
Early	0	8	0.5
Middle	8	12	0.3
End	15	20	0.1

System Case Study 2		
Component	α	β
C2S4SA	7.099	2.83
C1SA3S	6.267	1.53
other	$28 < \alpha < 30$	$1 < \beta < 4$

Horizon Period	x	t_H	T_{hold}
Early	0	5	0.75
Middle	5	8	0.65
End	11	18	0.1

System Case Study 3		
Component	α	β
AIM_2CON_{S2}	7.099	2.83
other	$30 < \alpha < 32$	$1 < \beta < 4$

Horizon Period	x	t_H	T_{hold}
Early	0	3	0.85
Middle	3	6	0.80
End	9	12	0.4

Table 5.7 continued

System Case Study 4			
Component		α	β
C1SA3S		9.809	2.41
other		$26 < \alpha < 28$	$1 < \beta < 4$
Horizon Period	x	t_H	T_{hold}
Early	0	7	0.5
Middle	7	11	0.3
End	13	20	0.1
System Case Study 5			
Component		α	β
C1SA3S		8.602	3.79
C1S2SA		7.589	2.24
other		$28 < \alpha < 30$	$1 < \beta < 4$
Horizon Period	x	t_H	T_{hold}
Early	0	5	0.75
Middle	5	8	0.65
End	11	16	0.1
System Case Study 6			
Component		α	β
C1SA3S		15.168	3.75
C1S2SA		15.705	3.96
C3SA4S		16.449	1.72
other		$23 < \alpha < 25$	$1 < \beta < 4$
Horizon Period	x	T_H	T_{hold}
Early	0	6	0.5
Middle	6	10	0.4
End	10	14	0.1

Table 5.7 continued

System Case Study 7		
Component	α	β
C1Z21	8.848	3.51
C3Z42	9.053	2.08
other	$25 < \alpha < 30$	$1 < \beta < 4$

Horizon Period	x	t_H	T_{hold}
Early	0	5	0.7
Middle	5	10	0.4
End	15	19	0.15

System Case Study 8		
Component	α	β
CZ122	11.025	3.58
other	$24 < \alpha < 25$	$1 < \beta < 4$

Horizon Period	x	t_H	T_{hold}
Early	0	6	0.3
Middle	10	13	0.2
End	13	17	0.1

System Case Study 9		
Component	α	β
MTG1	15.135	3.14
other	$23 < \alpha < 25$	$1 < \beta < 4$

Horizon Period	x	*th*	*Thold*
Early	0	8	0.5
Middle	8	10	0.3
End	10	18	0.1

Table 5.8 HV/MV Load Survivability Summary Table

System Case Study	Component	Beginning of Life			Middle of Life			End of Life		
		CBM	P/S	F/A	CBM	P/S	F/A	CBM	P/S	F/A
1	1PCM4	0.6151	0.4671	0.3484	0.3940	0.3609	0.3061	0.0460	0.0503	0.0573
	2PCM4	0.5349	0.4992	0.5618	0.2574	0.2319	0.2494	0.0037	0.0042	0.0039
	3PCM4	0.2765	0.2241	0.2519	0.1239	0.1046	0.1190	0.0005	0.0005	0.0005
	4PCM4	0.7387	0.6260	0.5726	0.4642	0.4338	0.4007	0.0488	0.0592	0.0557
	AIM1	0.6748	0.5729	0.6291	0.3068	0.2732	0.2972	0.0025	0.0028	0.0027
	AIM2	0.7445	0.6680	0.5871	0.5729	0.5386	0.4890	0.0588	0.0678	0.0700
2	1PCM4	0.8482	0.7943	0.8274	0.7494	0.6682	0.7405	0.1093	0.1089	0.1109
	2PCM4	0.7804	0.6792	0.7523	0.7234	0.5725	0.7037	0.1073	0.1123	0.1111
	3PCM4	0.8653	0.7953	0.8353	0.7545	0.6750	0.7341	0.1096	0.1107	0.1136
	4PCM4	0.7864	0.7363	0.7803	0.7516	0.6650	0.7425	0.1130	0.1069	0.1144
	AIM1	0.9813	0.9495	0.9718	0.9302	0.8580	0.9193	0.1483	0.1524	0.1534
	AIM2	0.9297	0.9026	0.9228	0.8923	0.8374	0.8869	0.1354	0.1317	0.1372
3	1PCM4	0.9904	0.9877	0.9874	0.9507	0.9277	0.9253	0.6366	0.5139	0.5019
	2PCM4	0.8954	0.8927	0.8946	0.8530	0.8320	0.8440	0.4703	0.3833	0.4243
	3PCM4	0.9192	0.9188	0.9190	0.8543	0.8486	0.8513	0.4586	0.4214	0.4345
	4PCM4	0.8872	0.8859	0.8853	0.8029	0.7901	0.7867	0.3766	0.3257	0.3122
	AIM1	0.9930	0.9929	0.9930	0.9658	0.9619	0.9639	0.5856	0.5312	0.5539
	AIM2	0.9676	0.9670	0.9668	0.8423	0.8319	0.8295	0.3052	0.2639	0.2530

Table 5.8 continued

System Case Study	Component	Beginning of Life			Middle of Life			End of Life		
		CBM	P/S	F/A	CBM	P/S	F/A	CBM	P/S	F/A
4	1PCM4	0.7448	0.6957	0.6327	0.5398	0.5023	0.4560	0.0113	0.0110	0.0098
	2PCM4	0.4095	0.3868	0.3913	0.4199	0.3850	0.4056	0.0115	0.0105	0.0116
	3PCM4	0.6148	0.5349	0.5853	0.5164	0.4605	0.5070	0.0155	0.0151	0.0162
	4PCM4	0.4738	0.3914	0.4936	0.3721	0.2858	0.3363	0.0044	0.0040	0.0051
	AIM1	0.9043	0.8254	0.8941	0.7242	0.6692	0.7122	0.0149	0.0142	0.0154
	AIM2	0.8398	0.7844	0.7516	0.6444	0.5782	0.5772	0.0065	0.0062	0.0062
5	1PCM4	0.8229	0.8052	0.8091	0.7717	0.7292	0.7387	0.1186	0.1011	0.1050
	2PCM4	0.6655	0.6496	0.6415	0.6382	0.6080	0.5844	0.0638	0.0619	0.0580
	3PCM4	0.8624	0.8291	0.8302	0.7694	0.7131	0.7174	0.1083	0.1124	0.1132
	4PCM4	0.8483	0.8125	0.8245	0.7631	0.6502	0.7256	0.0952	0.0662	0.0919
	AIM1	0.9447	0.9309	0.9277	0.8979	0.8684	0.8626	0.1176	0.1189	0.1167
	AIM2	0.9110	0.8965	0.9026	0.8853	0.8354	0.8637	0.1052	0.0826	0.0973
6	1PCM4	0.7564	0.7171	0.7131	0.4398	0.4449	0.3430	0.1007	0.1084	0.0787
	2PCM4	0.6874	0.6563	0.6529	0.4493	0.4554	0.4101	0.1180	0.1267	0.1150
	3PCM4	0.7498	0.6897	0.6737	0.4404	0.4413	0.4430	0.1171	0.1325	0.1266
	4PCM4	0.5384	0.5014	0.4963	0.3311	0.3362	0.3380	0.0758	0.0846	0.0856
	AIM1	0.9081	0.8808	0.8857	0.6088	0.6129	0.5859	0.1413	0.1547	0.1440
	AIM2	0.7516	0.7211	0.7009	0.4992	0.5047	0.4512	0.0997	0.1088	0.0936

Table 5.8 continued

System Case Study	Component	Beginning of Life			Middle of Life			End of Life		
		CBM	P/S	F/A	CBM	P/S	F/A	CBM	P/S	F/A
7	1PCM4	0.5193	0.4829	0.4847	0.0849	0.0776	0.0747	0.0065	0.0075	0.0072
	2PCM4	0.7242	0.6815	0.6985	0.1145	0.1127	0.1090	0.0073	0.0083	0.0082
	3PCM4	0.8053	0.7811	0.7714	0.0955	0.0636	0.0682	0.0013	0.0005	0.0018
	4PCM4	0.6277	0.6123	0.6076	0.0933	0.0772	0.0859	0.0053	0.0062	0.0061
	AIM1	0.8331	0.8117	0.8137	0.1320	0.1113	0.1119	0.0041	0.0042	0.0048
	AIM2	0.8484	0.8243	0.8234	0.1268	0.1113	0.1143	0.0041	0.0048	0.0047

Table 5.9 Zone Beginning of Life Summary Table

Case Study 1			
CMB or P/S SBM		F/A SBM	
Zone 1			
VLZ1ACL3	0.6997	VLZ1ACL3	0.6924
NVLZ1ACL4	0.7294	NVLZ1ACL4	0.7218
NVLZ1ACL1	0.8666	NVLZ1ACL1	0.8532
VLZ1DCL1	0.8701	VLZ1DCL1	0.8610
VLZ1DCL7	0.8759	VLZ1DCL7	0.8667
Zone 2			
VLZ2DCL1	0.7371	VLZ2DCL1	0.6926
NVLZ2ACL4	0.7713	NVLZ2ACL4	0.7632
VLZ2ACL3	0.8233	VLZ2ACL3	0.7652
VLZ2DCL4	0.8629	VLZ2DCL4	0.7842
VLZ2DCL7	0.8919	VLZ2DCL7	0.8776
Zone 3			
VLZ3ACL3	0.7552	VLZ3ACL3	0.7542
VLZ3DCL7	0.7786	VLZ3DCL7	0.7776
VLZ3DCL1	0.8044	VLZ3DCL1	0.8033
VLZ3DCL5	0.8293	VLZ3DCL5	0.8282
VLZ3ACL2	0.8484	VLZ3ACL2	0.8472
Zone 4			
NVLZ4ACL4	0.5127	VLZ4DCL5	0.7028
NVLZ4DCL6	0.5364	NVLZ4ACL1	0.7686
NVLZ4DCL8	0.5985	VLZ4ACL3	0.7809
VLZ4ACL2	0.7228	VLZ4ACL2	0.7924
NVLZ4ACL1	0.7688	NVLZ4ACL4	0.8118

Table 5.9 continued

Case Study 2			
CMB or P/S SBM		F/A SBM	
Zone 1			
VLZ1DCL1	0.2629	VLZ2DCL1	0.2681
VLZ1ACL2	0.3323	VLZ2ACL2	0.3389
NVLZ1ACL1	0.3828	NVLZ2ACL1	0.4112
NVLZ1ACL4	0.4046	NVLZ2ACL4	0.4126
VLZ1ACL3	0.5083	VLZ2ACL3	0.5184
Zone 2			
NVLZ2ACL1	0.3798	VLZ2ACL2	0.2306
VLZ2ACL2	0.3915	NVLZ2ACL1	0.4039
VLZ2DCL4	0.4549	VLZ2DCL4	0.4282
VLZ2ACL3	0.5170	VLZ2ACL3	0.4863
NVLZ2DCL8	0.5422	VLZ2DCL1	0.5005
Zone 3			
VLZ3DCL1	0.3601	VLZ2DCL1	0.3384
VLZ3ACL2	0.3702	VLZ2ACL2	0.3478
NVLZ3ACL4	0.3835	VLZ2ACL3	0.3673
VLZ3ACL3	0.3909	VLZ2DCL7	0.3770
VLZ3DCL7	0.4013	NVLZ2ACL4	0.4045
Zone 4			
NVLZ4ACL4	0.3108	VLZ2DCL1	0.3751
VLZ4DCL1	0.3650	NVLZ2ACL4	0.4001
NVLZ4DCL6	0.3739	VLZ2ACL2	0.4024
NVLZ4DCL8	0.4489	VLZ2DCL7	0.4732
VLZ4DCL4	0.5509	NVLZ2DCL6	0.4814

Table 5.10 Zone Middle of Life Summary Table

Case Study 1			
CMB or P/S SBM		F/A SBM	
Zone 1			
NVLZ1ACL1	0.2514	NVLZ1ACL1	0.2275
NVLZ1DCL3	0.3173	NVLZ1DCL3	0.2872
NVLZ1DCL2	0.3226	NVLZ1DCL2	0.2920
VLZ1ACL3	0.5264	VLZ1ACL3	0.4811
NVLZ1ACL4	0.5681	NVLZ1ACL4	0.5192
Zone 2			
VLZ2DCL1	0.5820	VLZ2ACL3	0.5472
NVLZ2ACL4	0.6064	NVLZ2ACL4	0.5500
VLZ2ACL3	0.6125	VLZ2DCL4	0.5829
VLZ2DCL4	0.6935	VLZ2DCL1	0.6033
VLZ2DCL7	0.7073	VLZ2DCL7	0.6753
Zone 3			
VLZ3ACL3	0.5533	VLZ3ACL3	0.5416
VLZ3DCL5	0.5969	VLZ3DCL5	0.5842
VLZ3ACL2	0.6175	VLZ3ACL2	0.6044
VLZ3DCL1	0.6316	NVLZ3ACL4	0.6135
VLZ3DCL7	0.6586	VLZ3DCL1	0.6182
Zone 4			
NVLZ4ACL4	0.2158	VLZ4DCL5	0.5599
NVLZ4DCL6	0.2199	VLZ4ACL2	0.5797
NVLZ4DCL8	0.2538	VLZ4ACL3	0.6158
VLZ4ACL2	0.5242	NVLZ4ACL1	0.6313
VLZ4DCL5	0.6262	VLZ4DCL7	0.6583

Table 5.10 continued

Case Study 2			
CMB or P/S SBM		F/A SBM	
Zone 1			
VLZ1DCL1	0.1058	VLZ2DCL1	0.1041
VLZ1ACL2	0.2378	VLZ2ACL2	0.2340
NVLZ1ACL4	0.2705	NVLZ2ACL4	0.2661
VLZ1ACL3	0.2824	VLZ2ACL3	0.2778
NVLZ1ACL1	0.2852	NVLZ2ACL1	0.2806
Zone 2			
VLZ2ACL2	0.2434	VLZ2ACL2	0.2042
NVLZ2ACL1	0.2582	VLZ2ACL3	0.2385
VLZ2ACL3	0.2629	VLZ2DCL1	0.2451
VLZ2DCL4	0.2740	VLZ2DCL5	0.2514
NVLZ2ACL4	0.2885	VLZ2DCL4	0.2646
Zone 3			
VLZ3ACL2	0.2431	VLZ2ACL2	0.2296
VLZ3DCL7	0.2451	VLZ2DCL7	0.2316
NVLZ3ACL4	0.2511	VLZ2DCL5	0.2418
VLZ3DCL5	0.2559	VLZ2ACL3	0.2474
VLZ3ACL3	0.2619	NVLZ2ACL4	0.2604
Zone 4			
NVLZ4ACL4	0.2497	VLZ2ACL2	0.2737
NVLZ4ACL1	0.2521	VLZ2ACL3	0.2836
VLZ4ACL3	0.2720	VLZ2DCL1	0.2844
NVLZ4DCL6	0.2815	VLZ2DCL7	0.2918
VLZ4DCL1	0.2849	NVLZ2ACL4	0.2947

Table 5.11 Zone End of Life Summary Table

Case Study 1			
CMB or P/S SBM		F/A SBM	
Zone 1			
NVLZ1ACL1	0.1437	NVLZ1ACL1	0.1766
VLZ1ACL2	0.1979	VLZ1ACL2	0.1865
VLZ1ACL3	0.2084	VLZ1ACL3	0.1964
NVLZ1DCL3	0.2466	NVLZ1ACL4	0.2417
NVLZ1DCL2	0.2487	VLZ1DCL1	0.2507
Zone 2			
NVLZ2ACL1	0.1999	VLZ2ACL2	0.1422
VLZ2ACL3	0.2037	VLZ2DCL7	0.1654
VLZ2ACL2	0.2110	VLZ2ACL3	0.1693
NVLZ2ACL4	0.2267	VLZ2DCL5	0.1806
VLZ2DCL7	0.2658	NVLZ2ACL4	0.1809
Zone 3			
VLZ3DCL4	0.1463	VLZ3DCL4	0.1413
VLZ3ACL3	0.1545	VLZ3ACL3	0.1493
VLZ3DCL5	0.1665	VLZ3DCL5	0.1609
VLZ3ACL2	0.1751	VLZ3ACL2	0.1692
NVLZ3ACL4	0.1844	VLZ3DCL1	0.1829
Zone 4			
VLZ4ACL3	0.1010	NVLZ4ACL1	0.2202
VLZ4DCL1	0.1703	VLZ4DCL5	0.2662
VLZ4DCL4	0.1961	VLZ4ACL2	0.2707
NVLZ4ACL4	0.1993	VLZ4ACL3	0.2711
VLZ4ACL2	0.2050	VLZ4DCL7	0.2734

Table 5.11 continued

Case Study 2			
CMB or P/S SBM		F/A SBM	
Zone 1			
VLZ1DCL1	0.0048	VLZ2DCL1	0.0044
NVLZ1ACL1	0.1156	VLZ2ACL2	0.1154
VLZ1ACL2	0.1266	NVLZ2ACL1	0.1459
VLZ1ACL3	0.1653	VLZ2ACL3	0.1507
NVLZ1ACL4	0.1756	NVLZ2ACL4	0.1601
Zone 2			
VLZ2ACL2	0.1262	VLZ2ACL2	0.0824
VLZ2ACL3	0.1394	VLZ2DCL1	0.0930
NVLZ2ACL1	0.1458	VLZ2ACL3	0.0941
VLZ2DCL4	0.1767	VLZ2DCL5	0.0974
NVLZ2ACL4	0.1857	NVLZ2ACL4	0.1558
Zone 3			
VLZ3ACL2	0.1154	VLZ2ACL2	0.1036
VLZ3DCL7	0.1191	VLZ2DCL7	0.1070
VLZ3DCL5	0.1244	VLZ2DCL5	0.1117
VLZ3ACL3	0.1317	VLZ2ACL3	0.1182
NVLZ3ACL4	0.1382	VLZ2DCL4	0.1353
Zone 4			
VLZ4ACL3	0.1214	VLZ2ACL2	0.1595
NVLZ4ACL4	0.1236	VLZ2ACL3	0.1630
VLZ4ACL2	0.1442	NVLZ2ACL1	0.1794
VLZ4DCL7	0.1602	VLZ2DCL1	0.1948
VLZ4DCL4	0.1760	VLZ2DCL7	0.1997

In case study 1, of Table 5.8, the threshold for load conditional survivabilities are 0.5, 0.3, and 0.1 for the beginning, middle, and end of life periods respectively. In the beginning of life period, load *3PCM4*’s conditional survivability is below the threshold in all three modes of configuration. In the Forward/Aft and Port/Starboard Split Bus Mode configurations, loads *1PCM4, 2PCM4,* and *3PCM4* are below the threshold value. The Common Bus Mode configuration shows that one load, *3PCM4*, is affected by failing components in the beginning of life period. The middle of life period shows loads *2PCM4,* and *3PCM4* are below the threshold of 0.3, and *AIM1* is also below the threshold in the Port/Starboard and Forward/Aft Split Bus Modes. The end of life period shows that all loads will not survive in this time period. This is due to the remaining life of the failing component as well as the other components remaining life over a period of time.

In case study 2, of Table 5.8, the threshold for load conditional survivabilities are 0.75, 0.65, and 0.1 for the beginning, middle, and end of life periods respectively. In the beginning of life period, load *2PCM4*'s conditional survivability is below the threshold in the Port/Starboard Split Bus Mode in the beginning and middle of life periods. The end of life period shows that all loads will survive in this time period.

In case study 3, of Table 5.8, the threshold for load conditional survivabilities are 0.85, 0.8, and 0.4 for the beginning, middle, and end of life periods respectively. In the beginning of life period, no loads are below the threshold in all three modes of configuration. The middle of life period shows that load *4PCM4* is below the threshold of 0.8 in the Port/Starboard and Forward/Aft Split Bus Modes. The end of life period shows that loads *4PCM4* and *AIM2* in the Common Bus Mode and Forward/Aft Split Bus Mode are below the threshold of 0.4. Loads *2PCM4*, *AIM2*, and *4PCM4* in the Port/Starboard Split Bus Mode are also below the threshold of 0.4 in the end of life period.

In case study 4, of Table 5.8, the threshold for load conditional survivabilities are 0.5, 0.3, and 0.1 for the beginning, middle, and end of life periods respectively. In the beginning of life period, load *2PCM4*'s conditional survivability is below the threshold in all three modes of configuration. In the Port/Starboard Split Bus Mode configuration, load *4PCM4*'s conditional survivability is also below the threshold value in the beginning of life period. The middle of life period shows that load *4PCM4* is below the threshold of 0.3 in the Port/Starboard Split Bus Mode. The end of life period shows that all loads will not survive in this time period. This is due to the remaining life of the failing component as well as the other components remaining life over a period of time.

In case study 5, of Table 5.8, the threshold for load conditional survivabilities are 0.75, 0.65, and 0.1 for the beginning, middle, and end of life periods respectively. In the beginning of life period, load *2PCM4*'s conditional survivability is below the threshold in the Forward/Aft and Port/Starboard Split Bus Modes and will not survive during this period. The middle of life period shows load *2PCM4* is below the threshold of 0.65 in all modes of configuration and will not survive during this period. The end of life period shows that loads *2PCM4* and *4PCM4* in all three modes of configuration will not survive in this time period because they are not above the threshold of 0.1. Furthermore in the end of life period, AIM2 is also below the threshold and will not survive in the Forward/Aft and Port/Starboard Split Bus Modes.

In case study 6, of Table 5.8, the threshold for load conditional survivabilities are 0.5, 0.4, and 0.1 for the beginning, middle, and end of life periods respectively. In the beginning of life period, load *4PCM4*'s conditional survivability is below the threshold in the Forward/Aft Split Bus Mode. The middle of life period shows that load *4PCM4* is below the threshold in all modes of configuration. Load *1PCM4* in the Forward/Aft Split Bus Mode is also below the threshold in middle of life period. The end of life period shows that load *4PCM4* will not survive in this time period for all modes of configuration. Load *1PCM4* is below the threshold in the Forward/Aft Split Bus Mode, and load AIM2 will not survive because it is below the threshold in the Common Bus Mode as well as the Forward/Aft Split Bus Mode. The loads will not survive during the end of life period.

In case study 7, of Table 5.8, the threshold for load conditional survivabilities are 0.5, 0.3, and 0.1 for the beginning, middle, and end of life periods respectively. In the beginning of life period, load *1PCM4*'s conditional survivability is below the threshold in the Port/Starboard and Forward/Aft Split Bus Modes. The middle and end of life periods shows that loads will not survive during these time periods.

In case study 1, of Table 5.9 through 5.11, the threshold for load conditional survivabilities are 0.7, 0.4, and 0.15 for the beginning, middle, and end of life periods respectively. Each zone shows loads that are affected by a component or components that are failing in each of the time periods. In the beginning of life period, shown in Table 5.9, load *VLZ1ACL3* conditional survivability in Zone 1 is below the threshold in all three modes of configuration. Load *VLZ2DCL1* conditional survivability in Zone 2 is below the threshold in the Forward/Aft Split Bus Mode. Loads *NVLZ4ACL4*, *NVLZ4ACL6*, and

NVLZ4ACL8 conditional survivability in Zone 4 is below the threshold in the Common Bus Mode or Port/Starboard Split Bus Mode. The middle of life period, shown in Table 5.10, shows loads *NVLZ1ACL1*, *NVLZ1DCL3*, and *NVLZ1DCL2* are below the threshold of 0.4 in Zone 1, in all modes of configuration. Loads *NVLZ4ACL4*, *NVLZ4ACL6*, and *NVLZ4ACL8* conditional survivability in Zone 4 is below the threshold in the Common Bus Mode. The end of life period, shown in Table 5.11, shows that load *NVLZ4ACL1* conditional survivability in Zone 1 is below the threshold in the Common Bus Mode. In Zone 2, load *VLZ2ACL1* conditional survivability is also below the threshold in the Forward/Aft Split Bus Mode. Also in the Forward/Aft Split Bus Mode in Zone 3, loads *VLZ3DCL4* and *VLZ3ACL3* are below the threshold value of 0.15. The Common Bus Mode in Zones 3 and 4, loads *VLZ3DCL4* and *VLZ4ACL3* respectively are also below the threshold value and these noted loads will not survive during the beginning, middle, and end of life periods.

In case study 2, of Table 5.9 through 5.11, the threshold for load conditional survivabilities are 0.3, 0.2, and 0.1 for the beginning, middle, and end of life periods respectively. Each zone shows loads that are affected by a component or components that are failing in each of the time periods. In the beginning of life period, shown in Table 5.9, load *VLZ1DCL1* conditional survivability in Zone 1 is below the threshold in all three modes of configuration. Load *VLZ2ACL2* conditional survivability in Zone 2 is below the threshold in the Forward/Aft Split Bus Mode. The middle of life period, shown in Table 5.10, shows load *VLZ1DCL1* is below the threshold of 0.2 in Zone 1, in all modes of configuration. The end of life period, shown in Table 5.11, shows that load *VLZ1DCL1* conditional survivability in Zone 1 is below the threshold in all configuration modes. In Zone 2, loads *VLZ2ACL2*, *VLZ2DCL1*, *VLZ2ACL3*, and *VLZ2DCL5* conditional survivability are also below the threshold in the Forward/Aft Split Bus Mode and these noted loads will not survive during the beginning, middle, and end of life periods.

5.2.1 HV/MV System Failures

The HV/MV loads are very critical components because they provide the IPS with mobility and the supply to vital and non-vital loads. The HV/MV loads can be affected locally, and the system as a whole can be affected by components in the ring structure, the MV structure, and generators. The cables in the ring structure impact HV/MV loads depending on the mode of configuration. The Common Bus Mode uses all components in the ring structure, but the survivability may not standout because of multiple paths to the loads. The Port/Starboard and Forward/Aft Split Bus Modes show the survivability significance depending on the cable that is failing. Results of case studies two, four, five, and six show how the failing cables affect conditional survivability to loads. The remaining life of the failing cables also has an impact on the system. The system as a whole may need to be reconfigured if two or more loads are below the desired threshold value.

Components in the MV structure also present problems for HV/MV loads because these components are in series with the load. If any MV component fails, the survivability to the load will be close to the failing component value. Transformers to the $PCM4$s will directly show a small survivability value to a specific $PCM4$ but not necessarily to the AIM. If two transformers are failing to a particular AIM the survivability will be reflected. This is shown in case study 1. The system would need to be reconfigured if two or more transformers were to fail in a horizon period.

Generators directly affect all HV/MV loads. If any generator fails during the horizon period, the supply path to a load is lost. Case study 9 shows an example of how a generator affects the survivability to a load. The system will show a low survivability if a generator is lost. The generator is the most critical component in this system because the generators are the source of energy. If there is no source of energy, then there is no supply path for a load.

5.2.2 Zonal System Failures

The normal path to vital loads is very critical. If any component along this path fails, the load will not be supplied. The loads in all zones are combined and treated as one system. This system will need to be reconfigured if five or more components' survivability is lower than the threshold value. Cables are the most essential components in each zone. If a cable fails along the normal path, the survivability will be low as shown in case studies seven and eight. The cable in series with a load will show a low survivability to a load. The remaining life of the components and the horizon period affect the zone system because of the components in series to the loads.

5.3 Summary

This chapter presented results of various case studies. These studies showed load survivability on two levels. Components failing during the horizon time lowered a component's conditional survivability significantly. Components failing along a series path affect the survivability to a load significantly. The MV path is an example of this situation. The more components that are in series with one another, the lower the survivability becomes. To avoid this series situation, most reliability engineers use redundancy as much as possible to avoid situations as such. The more redundancy, the more expensive the project becomes, because of the cost of components. The following chapter will discuss in detail the conclusions drawn from this work and the future work.

CHAPTER VI

CONCLUSIONS AND FUTURE WORK

The research study presented in this thesis is a part of a research project being conducted by Power System Automation Laboratory (PSAL) at Texas A&M University, College Station. The goal of the research study is to develop a predictive control reconfiguration technique using remaining life of each electrical component on an all-electric shipboard power system. This technique should use the remaining life of each component and compute the conditional survivability to each load on the all electric ship. The objective of this research work presented in this thesis was to develop a framework for computing conditional survivability of loads and an approach for assessing the need for reconfiguration based on these values. The research work addressed the following:

1) Aging equipment and how it fails with time and remaining life.
2) How the remaining life of equipment affects a load and sub-system's survivability.
3) Structure functions and how they are used in computing conditional survivability

In the following sections, the conclusions from each chapter and future work are discussed.

The thesis work done as part of an ongoing research being conducted in the PSAL of Texas A&M University to show when to do reconfiguration on shipboard power systems. All power electrical equipment can fail due to heat stresses causing insulation breakdowns. By using the *Arrhenius Model*, the remaining life of a component can be determined. The Weibull Reliability function shows how a component performs over time given the shape parameter β and scale parameter α. In this work, the scale parameter, α, represents remaining life of each component.

Chapter III presented the mathematical model of each component by using a form of the *Arrhenius Model* and other parameters that affected the failure of each component. These models were shown to understand what happens mathematically to a component if it was over stressed thermally. The relationship between the *Arrhenius Model* and Weibull Reliability Model was established through the scale parameter α. Since the scale parameter represents characteristic/remaining life, and the *Arrhenius Model*, $L = Ae^{\left(\frac{\Delta H}{kT}\right)}$, shows the lifetime of a component, then $\alpha = L$. By using the remaining life of a component and substituting L into the Weibull Distribution, the *Arrhenius-Weibull* Reliability equations can be used to calculate the survivability of a component.

The series structure function and the parallel structure function are introduced to understand the symbolic and mathematical representations. The series structure is a system at which components are connected end to end and the survivability is a product of the components. The parallel structure is a connection at which the components' inputs were connected together and the output ends are connected together. The mathematical representation of the parallel structure is by the *OR* logic or an addition sign of all the components in parallel.

The integrated shipboard power system has series, parallel, and series-parallel structures to describe how each component is connected to one another. The reliability of each component and the structure are used together to show the probability of a system surviving $P(T > x)$. The probability that a component survives another t time units $P(T > t + x)$, is calculated the same way, using the same components and structures. The conditional survivability $P(T > x + t \mid T > x)$ is the condition that a system or component has already survived for an amount of time. The probability is also equal to the reliability of a component, therefore, $P(T > x) = R(x)$, $P(T > t + x) = R(t + x)$, and $P(T > x + t \mid T > x) = \dfrac{R(x+t)}{R(x)}$.

Chapter IV describes the solution methodology that was used to perform the studies and produce the results. The entire ship was isolated into three sections to derive structure functions to each load. These structure functions consisted of the HV level, MV level, and the LV level. The HV and MV levels were used in series for each MV level load such as the induction motors and the PCM4s for all three configurations. The LV level loads used the PCM4s as a source, and two structures (normal path and alternate path) are derived for each vital load for the Common Bus Mode or Port/Starboard Split Bus Mode and the Forward/Aft Split Bus Mode.

Chapter V presented case studies. These case studies show that reconfiguration is needed to improve the reliability to the loads. It also shows how the failure of a critical component affects the reliability to loads. Reconfiguration can only be done on the HV and LV levels. At the HV level, the system can be switched between three configurations (Common Bus Mode, Port/Starboard Split Mode, and Forward/Aft Split Bus Mode). At the LV level, loads can be reconfigured using the Common Bus Mode or Port/Starboard Split Bus Mode and the Forward/Aft Split Bus Mode. Since vital loads are essential, there are two paths for each of the loads that allow for reconfiguration from the normal path to the alternate path.

6.1 Conclusions

With this proposed methodology, the conditional survivability can be shown to make a decision to reconfigure. Since the actual shape parameter β and scale parameter α for each components is not available, then random generation was used in this work used to produce results. This method will work when the shape parameter β is given by the manufacturer, and the parameters from each component are measured to find the characteristic life α. A major disadvantage with MV structure is that it is a series structure with no redundancies. The more components in a series structure, the lower the survivability. If one component fails in the MV structure, then the MV structure fails and the MV loads cannot be served. The major advantage of HV and LV systems is that there are redundancies making the path to the load more reliable. In the LV system, reconfiguration can take place in more than one way. The vital loads can be reconfigured due to bus transfers and the mode of configuration. Non-vital load's survivability can only be improved by the mode of operation.

6.2 Future Work

The main work would include using the conditional survivability structures to determining if reconfiguration is possible based on a recommended topology. This work covered all loads in two separate parts, the HV/MV level and the Zonal level. The shipboard power system should be studied using both the HV/MV and LV structures together to show overall system conditional survivability to each load. The IPS also should be studied using the 4-Way Split Bus Mode when the topology of this configuration is known. Since remaining life of power electronic devices were not determined, an approach to determine the remaining life of power electronic devices should be explored to modify HV/MV as well as LV structures to get an more accurate system conditional survivability to loads. The addition of breakers between the alternate and main bus on the HV/MV levels should also be taken into consideration because the alternate provides an additional path to each load in the HV/MV level. A reconfiguration subroutine should be implemented to determine if reconfiguration is possible based on results from the conditional survivability to each load.

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APPENDIX A

PCM4 STRUCTURE FUNCTIONS

A.1 Common Bus Structure from Generators to 1PCM4-4PCM4

$$Ring = \left(Ring_A\right)\left(Ring_B\right) \tag{A.1}$$

where :

$$\left(Ring_A\right) = \left(CB4S1\right)\left(CB4S2\right)\left(C3SA4S\right)\left(CB3SA2\right)\left(CB3S1\right)\left(CB3S2\right)\left(C1SA3S\right)\left(CB1SA2\right)\left(CB1SA1\right)$$
$$\left(Ring_B\right) = \left(CB1S2\right)\left(CB1S5\right)\left(C1S2SA\right)\left(CB2SA2\right)\left(CB2SA1\right)\left(CB2S3\right)\left(CB2S2\right)\left(C2S4SA\right)\left(CB4SA2\right)$$

$$1PCM\,4 = \left(HV_{1PCM\,4}\right)\left(MV_1\right) \tag{A.2}$$

where :

$$\left(HV_{1PCM\,4}\right) = Path_A + Path_B + Path_C + Path_D$$

$$Path_A = \left(ATG2\right)\left(C2G\right)\left(CB4S3\right)\left[\left(CB4S1\right) + \left(\frac{\left(Ring\right)}{\left(CB4S1\right)}\right)\right]$$

$$Path_B = \left(ATG1\right)\left(C1G\right)\left(CB3SA3\right)\left[\left(CB3SA2\right)\left(C3SA4S\right)\left(CB4S2\right)\left(CB4S1\right) + \left(\frac{\left(Ring\right)}{\left(CB3SA2\right)\left(C3SA4S\right)\left(CB4S2\right)\left(CB4S1\right)}\right)\right]$$

$$Path_C = \left(MTG2\right)\left(C4G\right)\left[\left(CB2S3\right)\left(CB2S2\right)\left(C2S4SA\right)\left(CB4SA2\right) + \left(\frac{\left(Ring\right)}{\left(CB2S3\right)\left(CB2S2\right)\left(C2S4SA\right)\left(CB4SA2\right)}\right)\right]$$

$$Path_D = \left(MTG1\right)\left(C3G\right)\left[Path_{d1} + Path_{d2}\right]$$

where:

$$Path_{d1} = \left(CB1SA1\right)\left(CB1SA2\right)\left(C1SA3S\right)\left(CB3S2\right)\left(CB3S1\right)\left(CB3SA2\right)\left(C3SA4S\right)\left(CB4S2\right)\left(CB4S1\right)$$
$$Path_{d2} = \left(CB1S2\right)\left(CB1S5\right)\left(C1S2SA\right)\left(CB2SA2\right)\left(CB2AS1\right)\left(CB2S3\right)\left(CB2S2\right)\left(C2S4SA\right)\left(CB4SA2\right)$$
$$MV_1 = \left(CB4SA3\right)\left(C4S1\right)\left(X21\right)\left(C4S12\right)\left(CBLC212\right)\left(CBLC211\right)\left(CLC211\right)$$

$$2PCM4 = \left(HV_{Z2}\right)\left(MV_{2}\right) \tag{A.3}$$

where:

$$\left(HV_{2PCM4}\right) = Path_{A} + Path_{B} + Path_{C} + Path_{D}$$

$$Path_{A} = \left(MTG2\right)\left(C4G\right)\left[\left(CB2AS1\right) + \left(\frac{\left(Ring\right)}{\left(CB2AS1\right)}\right)\right]$$

$$Path_{B} = \left(MTG1\right)\left(C3G\right)\left[\left(CB1S2\right)\left(CB1S5\right)\left(C1S2SA\right)\left(CB2SA2\right) + \left(\frac{\left(Ring\right)}{\left(CB1S2\right)\left(CB1S5\right)\left(C1S2SA\right)\left(CB2SA2\right)}\right)\right]$$

$$Path_{C} = \left(ATG2\right)\left(C2G\right)\left(CB4S3\right)\left[\left(Path_{c1}\right) + \left(\frac{\left(Ring\right)}{\left(Path_{c1}\right)}\right)\right]$$

where:

$$Path_{c1} = \left(CB4S1\right)\left(CB4SA2\right)\left(C2S4SA\right)\left(CB2S2\right)\left(CB2S3\right)\left(CB2AS1\right)$$

$$Path_{D} = \left(ATG1\right)\left(C1G\right)\left(CB3SA3\right)\left[Path_{d1} + Path_{d2}\right]$$

where:

$$Path_{d1} = \left(CB3S1\right)\left(CB3S2\right)\left(C1SA3S\right)\left(CB1SA2\right)\left(CB1SA1\right)\left(CB1S2\right)\left(CB1S5\right)\left(C1S2SA\right)\left(CB2SA2\right)$$

$$Path_{d2} = \left(CB2AS1\right)\left(CB2S3\right)\left(CB2S2\right)\left(C2S4SA\right)\left(CB4SA2\right)\left(CB4S1\right)\left(CB4S2\right)\left(C3SA4S\right)\left(CB3SA2\right)$$

$$MV_{2} = \left(CB2SA3\right)\left(C2SA1\right)\left(X11\right)\left(C2SA12\right)\left(CBLC111\right)\left(CBLC112\right)\left(CLC111\right)$$

$$3PCM4 = \left(HV_{3PCM4}\right)\left(MV_{3}\right) \tag{A.4}$$

where :

$$\left(HV_{3PCM4}\right) = Path_A + Path_B + Path_C + Path_D$$

$$Path_A = (MTG1)(C3G)\left[(CB1S2) + \left(\frac{(Ring)}{(CB1S2)}\right)\right]$$

$$Path_B = (MTG2)(C4G)\left[(CB2AS1)(CB2SA2)(C1S2SA)(CB1S5) + \left(\frac{(Ring)}{(CB2AS1)(CB2SA2)(C1S2SA)(CB1S5)}\right)\right]$$

$$Path_C = (ATG1)(C1G)(CB3SA3)\left[(Path_{c1}) + \left(\frac{(Ring)}{(Path_{c1})}\right)\right]$$

where :

$$Path_{c1} = (CB3S1)(CB3S2)(C1SA3S)(CB1SA2)(CB1SA1)(CB1S2)$$

$$Path_D = (ATG2)(C2G)(CB4S3)\left[Path_{d1} + Path_{d2}\right]$$

where :

$$Path_{d1} = (CB4S1)(CB4SA2)(C2S4SA)(CB2S2)(CB2S3)(CB2AS1)(CB2SA2)(C1S2SA)(CB1S5)$$

$$Path_{d2} = (CB1S2)(CB1SA1)(CB1SA2)(C1SA3S)(CB3S2)(CB3SA3)(CB3SA2)(C3SA4S)(CB3SA2)$$

$$MV_3 = (CB1S3)(C1S1)(X31)(CBLC311)(CBLC312)(CLC311)$$

$$4PCM4 = \left(HV_{4PCM4}\right)\left(MV_{4}\right) \tag{A.5}$$

where:

$$\left(HV_{4PCM4}\right) = Path_{A} + Path_{B} + Path_{C} + Path_{D}$$

$$Path_{A} = (ATG1)(C1G)(CB3SA3)\left[(CB3S1) + \left(\frac{(Ring)}{(CB3S1)}\right)\right]$$

$$Path_{B} = (ATG2)(C2G)(CB4S3)\left[(CB4S2)(C3SA4S)(CB3SA2)(CB3S1) + \left(\frac{(Ring)}{(CB4S2)(C3SA4S)(CB3SA2)(CB3S1)}\right)\right]$$

$$Path_{C} = (MTG1)(C3G)\left[(CB1SA1)(CB1SA2)(C1SA3S)(CB3S2) + \left(\frac{(Ring)}{(CB1SA1)(CB1SA2)(C1SA3S)(CB3S2)}\right)\right]$$

$$Path_{D} = (MTG2)(C4G)\left[Path_{d1} + Path_{d2}\right]$$

where:

$$Path_{d1} = (CB2S3)(CB2S2)(C2S4SA)(CB4SA2)(CB4S1)(CB4S2)(C3SA4S)(CB3SA2)(CB3S1)$$

$$Path_{d2} = (CB3S2)(C1SA3S)(CB1SA2)(CB1SA1)(CB1S2)(CB1S5)(C1S2SA)(CB2SA2)(CB2AS1)$$

$$MV_{4} = (CB3S3)(C3SA1)(X41)(C3SA12)(CBLC411)(CBLC412)(CLC411)$$

A.2 Port/Starboard Split Structure from Generators to 1PCM4-4PCM4

$$1PCM4 = \left(HV_{1PCM4}\right)\left(MV_{1}\right) \tag{A.6}$$

where :

$$HV_{1PCM4} = Path_A + Path_B$$

$$Path_A = (ATG2)(C2G)(CB4S3)(CB4S1)$$

$$Path_B = (MTG2)(C4G)(CB2S3)(CB2S2)(C2S4SA)(CB4SA2)$$

$$MV_1 = (CB4SA3)(C4S1)(X21)(C4S12)(CBLC212)(CBLC211)(CLC211)$$

$$2PCM4 = (HV_{2PCM4})(MV_2) \tag{A.7}$$

where :

$$HV_{2PCM4} = Path_C + Path_D$$

$$Path_C = (MTG2)(C4G)(CB2AS1)$$

$$Path_D = (ATG2)(C2G)(CB4S3)(CB4S1)(CB4SA2)(C2S4SA)(CB2S2)(CB2S3)(CB2AS1)$$

$$MV_2 = (CB2SA3)(C2SA1)(X11)(C2SA12)(CBLC111)(CBLC112)(CLC111)$$

$$3PCM4 = (HV_{3PCM4})(MV_3) \tag{A.8}$$

where :

$$HV_{3PCM4} = Path_A + Path_B$$

$$Path_A = (MTG1)(C3G)(CB1S2)$$

$$Path_B = (ATG1)(C1G)(CB3SA3)(CB3S1)(CB3S2)(C1SA3S)(CB1SA2)(CB1SA1)(CB1S2)$$

$$MV_3 = (CB1S3)(C1S1)(X31)(CBLC311)(CBLC312)(CLC311)$$

$$4PCM4 = (HV_{4PCM4})(MV_4) \tag{A.9}$$

where :

$$HV_{4PCM4} = Path_C + Path_C$$

$$Path_C = (ATG1)(C1G)(CB3SA3)(CB3S1)$$

$$Path_D = (MTG1)(C3G)(CB1SA2)(C1SA3S)(CB3S2)$$

$$MV_4 = (CB3S3)(C3SA1)(X41)(C3SA12)(CBLC411)(CBLC412)(CLC411)$$

A.3 Forward/Aft Split Structure from Generators to 1PCM4-4PCM4

$$1PCM4 = (HV_{1PCM4})(MV_1) \tag{A.10}$$

where :

$$HV_{Z1} = (CB4S1)(Path_A + Path_B)$$

$$Path_A = (ATG2)(C2G)(CB4S3)$$

$$Path_B = (ATG1)(C1G)(CB3SA3)(CB4S2)(C3SA4S)(CB3SA2)$$

$$MV_1 = (CB4SA3)(C4S1)(X21)(C4S12)(CBLC212)(CBLC211)(CLC211)$$

$$2PCM4 = (HV_{Z2})(MV_2) \tag{A.11}$$

where :

$$HV_{2PCM4} = Path_C + Path_D$$

$$Path_C = (MTG2)(C4G)(CB2AS1)$$

$$Path_D = (MTG1)(C3G)(CB1S2)(CB1S5)(C1S2SA)(CB2SA2)$$

$$MV_2 = (CB2SA3)(C2SA1)(X11)(C2SA12)(CBLC111)(CBLC112)(CLC111)$$

$$3PCM4 = \left(HV_{3PCM4}\right)\left(MV_{3}\right) \tag{A.12}$$

where:

$$HV_{3PCM4} = Path_{A} + Path_{B}$$
$$Path_{A} = \left(MTG1\right)\left(C3G\right)\left(CB1S2\right)$$
$$Path_{B} = \left(MTG2\right)\left(C4G\right)\left(CB2AS1\right)\left(CB2SA2\right)\left(C1S2SA\right)\left(CB1S5\right)$$
$$MV_{3} = \left(CB1S3\right)\left(C1S1\right)\left(X31\right)\left(C1S12\right)\left(CBLC311\right)\left(CBLC312\right)\left(CLC311\right)$$

$$4PCM4 = \left(HV_{4PCM4}\right)\left(MV_{4}\right) \tag{A.13}$$

where:

$$HV_{4PCM4} = \left(CB3S1\right)\left(Path_{C} + Path_{D}\right)$$
$$Path_{C} = \left(ATG1\right)\left(C1G\right)\left(CB3SA3\right)$$
$$Path_{D} = \left(ATG2\right)\left(C2G\right)\left(CB4S3\right)\left(CB4S2\right)\left(C3SA4S\right)\left(CB3SA2\right)$$
$$MV_{4} = \left(CB3S3\right)\left(C3SA1\right)\left(X41\right)\left(C3SA12\right)\left(CBLC411\right)\left(CBLC412\right)\left(CLC411\right)$$

APPENDIX B

PROPULSION STRUCTURE FUNCTIONS

B.1 Common Bus Structure from Generators to AIM_{S1}-AIM_{S2}

$$AIM1_{S1} = \left(HV_{2PCM4}\right)\left(MV_{5}\right) \tag{B.1}$$

where:

$$\left(HV_{2PCM4}\right) = Path_A + Path_B + Path_C + Path_D$$

$$Path_A = \left(MTG2\right)\left(C4G\right)\left[\left(CB2AS1\right) + \left(\frac{\left(Ring\right)}{\left(CB2AS1\right)}\right)\right]$$

$$Path_B = \left(MTG1\right)\left(C3G\right)\left[\left(CB1S2\right)\left(CB1S5\right)\left(C1S2SA\right)\left(CB2SA2\right) + \left(\frac{\left(Ring\right)}{\left(CB1S2\right)\left(CB1S5\right)\left(C1S2SA\right)\left(CB2SA2\right)}\right)\right]$$

$$Path_C = \left(ATG2\right)\left(C2G\right)\left(CB4S3\right)\left[\left(Path_{c1}\right) + \left(\frac{\left(Ring\right)}{\left(Path_{c1}\right)}\right)\right]$$

where:

$$Path_{c1} = \left(CB4S1\right)\left(CB4SA2\right)\left(C2S4SA\right)\left(CB2S2\right)\left(CB2S3\right)\left(CB2AS1\right)$$

$$Path_D = \left(ATG1\right)\left(C1G\right)\left(CB3SA3\right)\left[Path_{d1} + Path_{d2}\right]$$

where:

$$Path_{d1} = \left(CB3S1\right)\left(CB3S2\right)\left(C1SA3S\right)\left(CB1SA2\right)\left(CB1SA1\right)\left(CB1S2\right)\left(CB1S5\right)\left(C1S2SA\right)\left(CB2SA2\right)$$

$$Path_{d2} = \left(CB2AS1\right)\left(CB2S3\right)\left(CB2S2\right)\left(C2S4SA\right)\left(CB4SA2\right)\left(CB4S1\right)\left(CB4S2\right)\left(C3SA4S\right)\left(CB3SA2\right)$$

$$MV_{5} = \left(CB2SA3\right)\left(C2SA1\right)\left(X11\right)\left(C2SA12\right)\left(CBLC111\right)\left(CBLC113\right)\left(CLC112\right)\left(IM1CONS1\right)\left(CLC1121\right)$$

$$AIM1_{S2} = \left(HV_{3PCM4}\right)\left(MV_{6}\right) \tag{B.2}$$

where:

$$\left(HV_{3PCM4}\right) = Path_A + Path_B + Path_C + Path_D$$

$$Path_A = (MTG1)(C3G)\left[(CB1S2) + \left(\frac{(Ring)}{(CB1S2)}\right)\right]$$

$$Path_B = (MTG2)(C4G)\left[(CB2AS1)(CB2SA2)(C1S2SA)(CB1S5) + \left(\frac{(Ring)}{(CB2AS1)(CB2SA2)(C1S2SA)(CB1S5)}\right)\right]$$

$$Path_C = (ATG1)(C1G)(CB3SA3)\left[(Path_{c1}) + \left(\frac{(Ring)}{(Path_{c1})}\right)\right]$$

where:

$$Path_{c1} = (CB3S1)(CB3S2)(C1SA3S)(CB1SA2)(CB1SA1)(CB1S2)$$

$$Path_D = (ATG2)(C2G)(CB4S3)\left[Path_{d1} + Path_{d2}\right]$$

where:

$$Path_{d1} = (CB4S1)(CB4SA2)(C2S4SA)(CB2S2)(CB2S3)(CB2AS1)(CB2SA2)(C1S2SA)(CB1S5)$$

$$Path_{d2} = (CB1S2)(CB1SA1)(CB1SA2)(C1SA3S)(CB3S2)(CB3SA3)(CB3SA2)(C3SA4S)(CB3SA2)$$

$$MV_6 = (CB1S3)(C1S1)(X31)(C1S12)(CBLC311)(CBLC313)(CLC312)(IM1CONS2)(CLC3121)$$

$$AIM2_{S1} = \left(HV_{4PCM4}\right)\left(MV_7\right) \qquad \text{(B.3)}$$

where :

$$\left(HV_{4PCM4}\right) = Path_A + Path_B + Path_C + Path_D$$

$$Path_A = (ATG1)(C1G)(CB3SA3)\left[(CB3S1) + \left(\frac{(Ring)}{(CB3S1)}\right)\right]$$

$$Path_B = (ATG2)(C2G)(CB4S3)\left[(CB4S2)(C3SA4S)(CB3SA2)(CB3S1) + \left(\frac{(Ring)}{(CB4S2)(C3SA4S)(CB3SA2)(CB3S1)}\right)\right]$$

$$Path_C = (MTG1)(C3G)\left[(CB1SA1)(CB1SA2)(C1SA3S)(CB3S2) + \left(\frac{(Ring)}{(CB1SA1)(CB1SA2)(C1SA3S)(CB3S2)}\right)\right]$$

$$Path_D = (MTG2)(C4G)\left[Path_{d1} + Path_{d2}\right]$$

where :

$$Path_{d1} = (CB2S3)(CB2S2)(C2S4SA)(CB4SA2)(CB4S1)(CB4S2)(C3SA4S)(CB3SA2)(CB3S1)$$

$$Path_{d2} = (CB3S2)(C1SA3S)(CB1SA2)(CB1SA1)(CB1S2)(CB1S5)(C1S2SA)(CB2SA2)(CB2AS1)$$

$$MV_7 = (CB3S3)(C3SA1)(X41)(C3SA12)(CBLC412)(CBLC413)(CLC412)(IM2CONS1)(CLC4121)$$

$$AIM2_{S2} = \left(HV_{1PCM4}\right)\left(MV_8\right) \tag{B.4}$$

where :

$$\left(HV_{1PCM4}\right) = Path_A + Path_B + Path_C + Path_D$$

$$Path_A = \left(ATG2\right)\left(C2G\right)\left(CB4S3\right)\left[\left(CB4S1\right) + \left(\frac{\left(Ring\right)}{\left(CB4S1\right)}\right)\right]$$

$$Path_B = \left(ATG1\right)\left(C1G\right)\left(CB3SA3\right)\left[\left(CB3SA2\right)\left(C3SA4S\right)\left(CB4S2\right)\left(CB4S1\right) + \left(\frac{\left(Ring\right)}{\left(CB3SA2\right)\left(C3SA4S\right)\left(CB4S2\right)\left(CB4S1\right)}\right)\right]$$

$$Path_C = \left(MTG2\right)\left(C4G\right)\left[\left(CB2S3\right)\left(CB2S2\right)\left(C2S4SA\right)\left(CB4SA2\right) + \left(\frac{\left(Ring\right)}{\left(CB2S3\right)\left(CB2S2\right)\left(C2S4SA\right)\left(CB4SA2\right)}\right)\right]$$

$$Path_D = \left(MTG1\right)\left(C3G\right)\left[Path_{d1} + Path_{d2}\right]$$

where :

$$Path_{d1} = \left(CB1SA1\right)\left(CB1SA2\right)\left(C1SA3S\right)\left(CB3S2\right)\left(CB3S1\right)\left(CB3SA2\right)\left(C3SA4S\right)\left(CB4S2\right)\left(CB4S1\right)$$

$$Path_{d2} = \left(CB1S2\right)\left(CB1S5\right)\left(C1S2SA\right)\left(CB2SA2\right)\left(CB2AS1\right)\left(CB2S3\right)\left(CB2S2\right)\left(C2S4SA\right)\left(CB4SA2\right)$$

$$MV_8 = \left(CB4SA3\right)\left(C4S1\right)\left(X21\right)\left(C4S12\right)\left(CBLC212\right)\left(CBLC213\right)\left(CLC212\right)\left(IM2CONS2\right)\left(CLC2121\right)$$

B.2 Port/Starboard Structure from Generators to AIM_{S1}-AIM_{S2}

$$AIM1_{S1} = \left(HV_{2PCM4}\right)\left(MV_5\right) \tag{B.5}$$

where :

$$HV_{2PCM4} = Path_A + Path_B$$

$$Path_A = (MTG2)(C4G)(CB2AS1)$$

$$Path_B = (ATG2)(C2G)(CB4S3)(CB4S1)(CB4SA2)(C2S4SA)(CB2S2)(CB2S3)(CB2AS1)$$

$$MV_5 = (CB2SA3)(C2SA1)(X11)(C2SA12)(CBLC111)(CBLC113)(CLC112)(IM1CONS1)(CLC1121)$$

$$AIM1_{S2} = (HV_{3PCM4})(MV_6) \tag{B.6}$$

where :

$$HV_{3PCM4} = Path_A + Path_B$$

$$Path_A = (MTG1)(C3G)(CB1S2)$$

$$Path_B = (ATG1)(C1G)(CB3SA3)(CB3S1)(CB3S2)(C1SA3S)(CB1SA2)(CB1SA1)(CB1S2)$$

$$MV_6 = (CB1S3)(C1S1)(X31)(C1S12)(CBLC311)(CBLC313)(CLC312)(IM1CONS2)(CLC3121)$$

$$AIM2_{S1} = (HV_{4PCM4})(MV_7) \tag{B.7}$$

where :

$$HV_{4PCM4} = Path_A + Path_B$$

$$Path_A = (MTG1)(C3G)(CB3S2)(C1SA3S)(CB1SA2)(CB1SA1)$$

$$Path_B = (ATG1)(C1G)(CB3SA3)(CB3S1)$$

$$MV_7 = (CB3S3)(C3SA1)(X41)(C3SA12)(CBLC412)(CBLC413)(CLC412)(IM2CONS1)(CLC4121)$$

$$AIM2_{S2} = (HV_{1PCM4})(MV_8) \tag{B.8}$$

where:

$$HV_{1PCM4} = Path_A + Path_B$$
$$Path_A = (MTG2)(C4G)(CB2S3)(CB2S2)(C2S4SA)(CB4SA2)$$
$$Path_B = (ATG2)(C2G)(CB4S3)(CB4S1)$$
$$MV_8 = (CB4SA3)(C4S1)(X21)(C4S12)(CBLC212)(CBLC213)(CLC212)(IM2CONS2)(CLC2121)$$

B.3 Forward/Aft Structure from Generators to AIM_{S1}-AIM_{S2}

$$AIM1_{S1} = (HV_{2PCM4})(MV_5) \tag{B.9}$$

where:

$$HV_{2PCM4} = Path_C + Path_D$$
$$Path_C = (MTG2)(C4G)(CB2AS1)$$
$$Path_D = (MTG1)(C3G)(CB1S2)(CB1S5)(C1S2SA)(CB2SA2)$$
$$MV_5 = (CB2SA3)(C2SA1)(X11)(C2SA12)(CBLC111)(CBLC113)(CLC112)(IM1CONS1)(CLC1121)$$

$$AIM1_{S2} = (HV_{3PCM4})(MV_6) \tag{B.10}$$

where:

$$HV_{3PCM4} = Path_A + Path_B$$
$$Path_A = (MTG1)(C3G)(CB1S2)$$
$$Path_B = (MTG2)(C4G)(CB2AS1)(CB2SA2)(C1S2SA)(CB1S5)$$
$$MV_6 = (CB1S3)(C1S1)(X31)(C1S12)(CBLC311)(CBLC313)(CLC312)(IM1CONS2)(CLC3121)$$

$$AIM2_{S1} = \left(HV_{4PCM4}\right)\left(MV_{7}\right) \qquad (0.104)$$

where:

$$HV_{Z4PCM4} = \left(CB3S1\right)\left(Path_{C} + Path_{D}\right)$$

$$Path_{C} = \left(ATG1\right)\left(C1G\right)\left(CB3SA3\right)\left(CB3S1\right)$$

$$Path_{D} = \left(ATG2\right)\left(C2G\right)\left(CB4S3\right)\left(CB4S2\right)\left(C3SA4S\right)\left(CB3SA2\right)\left(CB3S1\right)$$

$$MV_{7} = \left(CB3S3\right)\left(C3SA1\right)\left(X41\right)\left(C3SA12\right)\left(CBLC412\right)\left(CBLC413\right)\left(CLC412\right)\left(IM2CONS1\right)\left(CLC4121\right)$$

$$AIM2_{S2} = \left(HV_{1PCM4}\right)\left(MV_{8}\right) \qquad (B.12)$$

where:

$$HV_{1PCM4} = \left(CB3S1\right)\left(Path_{A} + Path_{B}\right)$$

$$Path_{A} = \left(ATG2\right)\left(C2G\right)\left(CB4S3\right)\left(CB4S1\right)$$

$$Path_{B} = \left(ATG1\right)\left(C1G\right)\left(CB3SA3\right)\left(CB4S2\right)\left(C3SA4S\right)\left(CB3SA2\right)\left(CB4S1\right)$$

$$MV_{8} = \left(CB4SA3\right)\left(C4S1\right)\left(X21\right)\left(C4S12\right)\left(CBLC212\right)\left(CBLC213\right)\left(CLC212\right)\left(IM2CONS2\right)\left(CLC2121\right)$$

APPENDIX C

LOAD STRUCTURE FUNCTIONS

C.1 PCM4 Path to Zone 1

$$Path_1 = (1PCM4)(Z1SW20)(CZ121)(Z1SW26)$$
$$Path_2 = (1PCM4)(Z1SW19)(CZ111)(Z1SW25)$$
$$Path_3 = (2PCM4)(Z2SW20)(CZ221)(Z2SW26)(s\_Tie_{1\_2})$$
$$Path_4 = (2PCM4)(Z2SW19)(CZ211)(Z2SW25)(p\_Tie_{1\_2})$$
$$Path_5 = (3PCM4)(Z3SW20)(CZ321)(Z3SW26)(s\_Tie_{1\_2})(s\_Tie_{2\_3})$$
$$Path_6 = (3PCM4)(Z3SW19)(CZ311)(Z3SW25)(p\_Tie_{1\_2})(p\_Tie_{2\_3})$$
$$Path_7 = (4PCM4)(Z4SW20)(CZ421)(Z4SW26)(s\_Tie_{1\_2})(s\_Tie_{2\_3})(s\_Tie_{3\_4})$$
$$Path_8 = (4PCM4)(Z4SW19)(CZ411)(Z4SW25)(p\_Tie_{1\_2})(p\_Tie_{2\_3})(p\_Tie_{3\_4})$$

C.1.1 375VDC

$$VLZ1DCL1 = (CZ11)(Z1SW35)\left[(pZ1BT1)(Port) + (sZ1BT1)(Star)\right] \tag{C.1}$$

where:

$$Star = (Z1375VDC2)(Z1SW10)(CZ122)(Path_1 + Path_3 + Path_5 + Path_7)$$
$$Port = (Z1375VDC1)(Z1SW1)(CZ112)(Path_2 + Path_4 + Path_6 + Path_8)$$

$$NVLZ1DCL2 = (Z1375VDC1)(Z1SW2)(CZ113)(Z1SW36)\left[Path_2 + Path_4 + Path_6 + Path_8\right] \tag{C.2}$$

$$VLZ1DCL7 = (CZ13)(Z1SW37)\left[(pZ1BT2)(Port) + (sZ1BT2)(Star)\right] \tag{C.3}$$

where :

$$Star = (Z1375VDC2)(Z1SW12)(CZ124)(Path_1 + Path_3 + Path_5 + Path_7)$$

$$Port = (Z1375VDC1)(Z1SW3)(CZ114)(Path_5 + Path_6 + Path_7 + Path_8)$$

$$NVLZ1DCL6 = (Z1375VDC2)(Z1SW11)(CZ123)(Z1SW38)[Path_1 + Path_3 + Path_5 + Path_7] \tag{C.4}$$

C.1.2 650VDC

$$VLZ1DCL4 = (CZ12)(Z1SW32)[(pZ1BT3)(Port) + (sZ1BT3)(Star)] \tag{C.5}$$

where :

$$Star = (Z1650VDC2)(Z1SW13)(CZ125)(Path_1 + Path_3 + Path_5 + Path_7)$$

$$Port = (Z1650VDC1)(Z1SW5)(CZ116)(Path_2 + Path_4 + Path_6 + Path_8)$$

$$NVLZ1DCL3 = (Z1650VDC1)(Z1SW4)(CZ115)(Z1SW31)[Path_2 + Path_4 + Path_6 + Path_8] \tag{C.6}$$

$$VLZ1DCL5 = (CZ14)(Z1SW34)[(pZ1BT4)(Port) + (sZ1BT4)(Star)] \tag{C.7}$$

where :

$$Star = (Z1650VDC2)(Z1SW14)(CZ126)(Path_1 + Path_3 + Path_5 + Path_7)$$

$$Port = (Z1650VDC1)(Z1SW6)(CZ117)(Path_2 + Path_4 + Path_6 + Path_8)$$

$$NVLZ1DCL8 = (Z1650DC2)(Z1SW15)(CZ127)(Z1SW35)[Path_1 + Path_3 + Path_5 + Path_7] \tag{C.8}$$

C.1.3 800VDC

$$NVLZ1ACL1 = (Z1800VDC1)(Z1SW9)(CZ1110)(1PCM21)(Z1SW21)(CZ15)(Z1SW27)(Path_2 + Path_4 + Path_6 + Path_8) \tag{C.9}$$

$$VLZ1ACL3 = (1PCM23)(Z1SW22)(CZ16)(Z1SW28)(Port + Star) \tag{C.10}$$

where:

$$Star = (CZ129)(Z1SW17)(Z1800DC2)(Path_1 + Path_3 + Path_5 + Path_7)$$

$$Port = (CZ119)(Z1SW8)(Z1800DC1)(Path_2 + Path_4 + Path_6 + Path_8)$$

$$VLZ1ACL2 = (Z1SW29)(CZ17)(Z1SW23)(1PCM22)(Port + Star) \tag{C.11}$$

where:

$$Star = (CZ128)(Z1SW16)(Z1800DC2)(Path_1 + Path_3 + Path_5 + Path_7)$$

$$Port = (CZ118)(Z1SW7)(Z1800DC1)(Path_2 + Path_4 + Path_6 + Path_8)$$

$$NVLZ1ACL4 = (Z1800VDC2)(Z1SW18)(CZ1210)(1PCM24)(Z1SW24)(CZ18)(Z1SW30)(Path_1 + Path_3 + Path_5 + Path_7) \tag{C.12}$$

C.2 PCM4 Path to Zone 2

$$Path_1 = (1PCM4)(Z1SW20)(CZ121)(Z1SW26)(s\_Tie_{1\_2})$$
$$Path_2 = (1PCM4)(Z1SW19)(CZ111)(Z1SW25)(p\_Tie_{1\_2})$$
$$Path_3 = (2PCM4)(Z2SW20)(CZ221)(Z2SW26)$$
$$Path_4 = (2PCM4)(Z2SW19)(CZ211)(Z2SW25)$$
$$Path_5 = (3PCM4)(Z3SW20)(CZ321)(Z3SW26)(s\_Tie_{2\_3})$$
$$Path_6 = (3PCM4)(Z3SW19)(CZ311)(Z3SW25)(p\_Tie_{2\_3})$$
$$Path_7 = (4PCM4)(Z4SW20)(CZ421)(Z4SW26)(s\_Tie_{2\_3})(s\_Tie_{3\_4})$$
$$Path_8 = (4PCM4)(Z4SW19)(CZ411)(Z4SW25)(p\_Tie_{2\_3})(p\_Tie_{3\_4})$$

C.2.1 375VDC

$$VLZ2DCL1 = (Z2SW35)(CZ21)\left[(pZ2BT1)(Port) + (sZ2BT1)(Star)\right] \quad (C.13)$$

where:

$$Star = (Z2375VDC2)(Z2SW10)(CZ222)(Path_1 + Path_3 + Path_5 + Path_7)$$
$$Port = (Z2375VDC1)(Z2SW1)(CZ212)(Path_2 + Path_4 + Path_6 + Path_8)$$

$$NVLZ2DCL2 = (Z2375VDC1)(Z2SW2)(CZ213)(Z2SW36)\left[Path_2 + Path_4 + Path_6 + Path_8\right] \quad (C.14)$$

$$NVLZ2DCL6 = (Z2SW38)(CZ223)(Z2SW11)(Z2375VDC2)\left[Path_1 + Path_3 + Path_5 + Path_7\right] \quad (C.15)$$

$$VLZ2DCL7 = (Z2SW37)(CZ23)\left[(pZ2BT2)(Port) + (sZ2BT2)(Star)\right] \quad (C.16)$$

where :

$$Star = (Z2375VDC2)(Z2SW12)(CZ224)(Path_1 + Path_3 + Path_5 + Path_7)$$

$$Port = (Z2375VDC1)(Z2SW3)(CZ214)(Path_2 + Path_4 + Path_6 + Path_8)$$

C.2.2 650VDC

$$NVLZ2DCL3 = (Z2SW31)(CZ215)(Z2SW4)(Z2650VDC1)[Path_2 + Path_4 + Path_6 + Path_8] \tag{C.17}$$

$$VLZ2DCL4 = (Z2SW32)(CZ22)[(pZ2BT3)(Port) + (sZ2BT3)(Star)] \tag{C.18}$$

where :

$$Star = (CZ225)(Z2SW13)(Z2650VDC2)(Path_1 + Path_3 + Path_5 + Path_7)$$

$$Port = (CZ216)(Z2SW5)(Z2650VDC1)(Path_2 + Path_4 + Path_6 + Path_8)$$

$$VLZ2DCL5 = (Z2SW34)(CZ24)[(pZ2BT4)(Port) + (sZ2BT4)(Star)] \tag{C.19}$$

where :

$$Star = (CZ226)(Z2SW14)(Z2650VDC2)(Path_1 + Path_3 + Path_5 + Path_7)$$

$$Port = (CZ217)(Z2SW6)(Z2650VDC1)(Path_2 + Path_4 + Path_6 + Path_8)$$

$$NVLZ2DCL8 = (Z2SW35)(CZ227)(Z2SW15)(Z2650VDC2)[Path_1 + Path_3 + Path_5 + Path_7] \tag{C.20}$$

C.2.3 800VDC

$$NVLZ2ACL1 = (Z2SW27)(CZ25)(Z2SW21)(2PCM21)(CZ2110)(Z2SW9)(Z2800VDC1)(Path_2 + Path_4 + Path_6 + Path_8) \tag{C.21}$$

$$VLZ2ACL3 = (Z2SW28)(CZ26)(Z2SW22)(2PCM23)(Port + Star) \tag{C.22}$$

where :

$$Star = (CZ229)(Z2SW17)(Z2800DC2)(Path_1 + Path_3 + Path_5 + Path_7)$$

$$Port = (CZ219)(Z2SW8)(Z2800DC1)(Path_2 + Path_4 + Path_6 + Path_8)$$

$$VLZ2ACL2 = (Z2SW29)(CZ27)(Z2SW23)(2PCM22)(Port + Star) \tag{C.23}$$

where :

$$Star = (CZ228)(Z2SW16)(Z2800DC2)(Path_1 + Path_3 + Path_5 + Path_7)$$

$$Port = (CZ218)(Z2SW7)(Z2800DC1)(Path_2 + Path_4 + Path_6 + Path_8)$$

$$NVLZ2ACL4 = (Z2SW30)(CZ28)(Z2SW24)(2PCM21)(CZ2210)(Z2SW18)(Z2800VDC2)(Path_1 + Path_3 + Path_5 + Path_7) \tag{C.24}$$

C.3 PCM4 Path to Zone 3

$$Path_1 = (1PCM4)(Z1SW20)(CZ121)(Z1SW26)(s\_Tie_{1\_2})(s\_Tie_{2\_3})$$
$$Path_2 = (1PCM4)(Z1SW19)(CZ111)(Z1SW25)(p\_Tie_{1\_2})(p\_Tie_{2\_3})$$
$$Path_3 = (2PCM4)(Z2SW20)(CZ221)(Z2SW26)(s\_Tie_{2\_3})$$
$$Path_4 = (2PCM4)(Z2SW19)(CZ211)(Z2SW25)(p\_Tie_{2\_3})$$
$$Path_5 = (3PCM4)(Z3SW20)(CZ321)(Z3SW26)$$
$$Path_6 = (3PCM4)(Z3SW19)(CZ311)(Z3SW25)$$
$$Path_7 = (4PCM4)(Z4SW20)(CZ421)(Z4SW26)(s\_Tie_{2\_3})(s\_Tie_{3\_4})$$
$$Path_8 = (4PCM4)(Z4SW19)(CZ411)(Z4SW25)(p\_Tie_{2\_3})(p\_Tie_{3\_4})$$

C.3.1 375VDC

$$VLZ3DCL1 = (Z3SW35)(CZ31)\left[(pZ3BT1)(Port) + (sZ3BT1)(Star)\right] \tag{C.25}$$

where:

$$Star = (CZ322)(Z3SW10)(Z3375VDC2)(Path_1 + Path_3 + Path_5 + Path_7)$$
$$Port = (CZ312)(Z3SW1)(Z3375VDC1)(Path_2 + Path_4 + Path_6 + Path_8)$$

$$NVLZ3DCL2 = (Z3SW36)(CZ313)(Z3SW2)(Z3375VDC1)\left[Path_2 + Path_4 + Path_6 + Path_8\right] \tag{C.26}$$

$$NVLZ3DCL6 = (Z3SW38)(CZ323)(Z3SW11)(Z3375VDC2)\left[Path_1 + Path_3 + Path_5 + Path_7\right] \tag{C.27}$$

$$VLZ3DCL7 = (Z3SW37)(CZ33)\left[(pZ3BT2)(Port) + (sZ3BT2)(Star)\right] \tag{C.28}$$

where :

$$Star = (CZ324)(Z3SW12)(Z3375VDC2)(Path_1 + Path_3 + Path_5 + Path_7)$$

$$Port = (CZ314)(Z3SW3)(Z3375VDC1)(Path_2 + Path_4 + Path_6 + Path_8)$$

C.3.2 650VDC

$$NVLZ3DCL3 = (Z3SW31)(CZ315)(Z3SW4)(Z3650VDC1)[Path_2 + Path_4 + Path_6 + Path_8] \tag{C.29}$$

$$VLZ3DCL4 = (Z3SW32)(CZ32)(Z3BT3)[(pZ3BT3)(Port) + (sZ3BT3)(Star)] \tag{C.30}$$

where :

$$Star = (CZ325)(Z3SW13)(Z3650VDC2)(Path_1 + Path_3 + Path_5 + Path_7)$$

$$Port = (CZ316)(Z3SW5)(Z3650VDC1)(Path_2 + Path_4 + Path_6 + Path_8)$$

$$VLZ3DCL5 = (Z3SW34)(CZ34)(Z3BT4)[(pZ3BT4)(Port) + (sZ3BT4)(Star)] \tag{C.31}$$

where :

$$Star = (CZ326)(Z3SW14)(Z3650VDC2)(Path_1 + Path_3 + Path_5 + Path_7)$$

$$Port = (CZ317)(Z3SW6)(Z3650VDC1)(Path_2 + Path_4 + Path_6 + Path_8)$$

$$NVLZ3DCL8 = (Z3SW35)(CZ327)(Z3SW15)(Z3650VDC2)[Path_1 + Path_3 + Path_5 + Path_7] \tag{C.32}$$

C.3.3 800VDC

$$NVLZ2ACL1 = (Z3SW27)(CZ35)(Z3SW21)(3PCM21)(CZ3110)(Z3SW9)(Z3800VDC1)[Path_2 + Path_4 + Path_6 + Path_8] \tag{C.33}$$

$$VLZ3ACL3 = (Z3SW28)(CZ36)(Z3SW22)(3PCM23)(Port + Star) \tag{C.34}$$

where:

$$Star = (CZ329)(Z3SW17)(Z3800VDC2)(Path_1 + Path_3 + Path_5 + Path_7)$$

$$Port = (CZ319)(Z3SW8)(Z3800DC1)(Path_2 + Path_4 + Path_6 + Path_8)$$

$$VLZ3ACL2 = (Z3SW29)(CZ37)(Z3SW23)(3PCM22)(Port + Star) \tag{C.35}$$

where:

$$Star = (CZ328)(Z3SW16)(Z3800VDC2)(Path_1 + Path_3 + Path_5 + Path_7)$$

$$Port = (CZ318)(Z3SW7)(Z3800DC1)(Path_2 + Path_4 + Path_6 + Path_8)$$

$$NVLZ3ACL4 = (Z3SW30)(CZ38)(Z3SW24)(3PCM21)(CZ3210)(Z3SW18)(Z3800VDC2)[Path_1 + Path_3 + Path_5 + Path_8] \tag{C.36}$$

C.4 PCM4 Path to Zone 4

$$Path_1 = (1PCM4)(Z1SW20)(CZ121)(Z1SW26)(s\_Tie_{1\_2})(s\_Tie_{2\_3})(s\_Tie_{3\_4})$$
$$Path_2 = (1PCM4)(Z1SW19)(CZ111)(Z1SW25)(p\_Tie_{1\_2})(p\_Tie_{2\_3})(p\_Tie_{3\_4})$$
$$Path_3 = (2PCM4)(Z2SW20)(CZ221)(Z2SW26)(s\_Tie_{1\_2})(s\_Tie_{2\_3})$$
$$Path_4 = (2PCM4)(Z2SW19)(CZ211)(Z2SW25)(p\_Tie_{1\_2})(p\_Tie_{2\_3})$$
$$Path_5 = (3PCM4)(Z3SW20)(CZ321)(Z3SW26)(s\_Tie_{3\_4})$$
$$Path_6 = (3PCM4)(Z3SW19)(CZ311)(Z3SW25)(p\_Tie_{3\_4})$$
$$Path_7 = (4PCM4)(Z4SW20)(CZ421)(Z4SW26)$$
$$Path_8 = (4PCM4)(Z4SW19)(CZ411)(Z4SW25)$$

C.4.1 375VDC

$$VLZ4DCL1 = (Z4SW35)(CZ41)\left[(pZ4BT1)(Port) + (sZ4BT1)(Star)\right] \tag{C.37}$$

where :

$$Star = (CZ422)(Z4SW10)(Z3800VDC2)(Path_1 + Path_3 + Path_5 + Path_7)$$
$$Port = (CZ412)(Z4SW1)(Z4375VDC1)(Path_2 + Path_4 + Path_6 + Path_8)$$

$$NVLZ4DCL2 = (Z4SW36)(CZ413)(Z4SW2)(Z4375VDC1)\left[Path_2 + Path_4 + Path_6 + Path_8\right] \tag{C.38}$$

$$NVLZ4DCL6 = (Z4SW38)(CZ423)(Z4SW11)(Z4375VDC2)\left[Path_1 + Path_3 + Path_5 + Path_7\right] \tag{C.39}$$

$$VLZ3DCL7 = (Z4SW37)(CZ43)\left[(pZ4BT2)(Port) + (sZ4BT2)(Star)\right] \tag{C.40}$$

where :

$$Star = (CZ424)(Z4SW12)(Z3800VDC2)(Path_1 + Path_3 + Path_5 + Path_7)$$

$$Port = (CZ414)(Z4SW3)(Z4375VDC1)(Path_2 + Path_4 + Path_6 + Path_8)$$

C.4.2 650VDC

$$NVLZ4DCL3 = (Z4SW31)(CZ415)(Z4SW4)(Z4650VDC1)[Path_2 + Path_4 + Path_6 + Path_8] \quad (C.41)$$

$$VLZ4DCL4 = (Z4SW32)(CZ42)[(pZ4BT3)(Port) + (sZ4BT3)(Star)] \quad (C.42)$$

where :

$$Star = (CZ425)(Z4SW13)(Z3800VDC2)(Path_1 + Path_3 + Path_5 + Path_7)$$

$$Port = (CZ416)(Z4SW6)(Z4650VDC1)(Path_2 + Path_4 + Path_6 + Path_8)$$

$$VLZ4DCL5 = (Z4SW34)(CZ44)(Z3BT4)[(pZ4BT4)(Port) + (sZ4BT4)(Star)]$$

(C.43)

where :

$$Star = (CZ426)(Z4SW14)(Z3800VDC2)(Path_1 + Path_3 + Path_5 + Path_7)$$

$$Port = (CZ417)(Z4SW7)(Z4650VDC1)(Path_2 + Path_4 + Path_6 + Path_8)$$

$$NVLZ4DCL8 = (Z4SW35)(CZ427)(Z4SW15)(Z4650VDC2)[Path_1 + Path_3 + Path_5 + Path_7] \quad (C.44)$$

C.4.3 800VDC

$$NVLZ4ACL1=(Z4SW27)(CZ45)(Z4SW21)(4PCM21)(CZ4110)(Z4SW9)(Z4800VDC1)[Path_2+Path_4+Path_6+Path_8] \quad (C.45)$$

$$VLZ4ACL3=(Z4SW28)(CZ46)(Z4SW22)(4PCM23)(Port+Star) \quad (C.46)$$

where :

$$Star=(CZ429)(Z4SW17)(Z3800VDC2)(Path_1+Path_3+Path_5+Path_7)$$

$$Port=(CZ419)(Z4SW8)(Z4800DC1)(Path_2+Path_4+Path_6+Path_8)$$

$$VLZ4ACL2=(Z4SW29)(CZ47)(Z4SW23)(4PCM22)(Port+Star) \quad (C.47)$$

where :

$$Star=(CZ428)(Z4SW16)(Z3800VDC2)(Path_1+Path_3+Path_5+Path_7)$$

$$Port=(CZ418)(Z4SW7)(Z4800DC1)(Path_2+Path_4+Path_6+Path_8)$$

$$NVLZ4ACL4=(Z4SW30)(CZ48)(Z4SW24)(4PCM21)(CZ4210)(Z4SW18)(Z4800VDC2)(Path_1+Path_3+Path_5+Path_7) \quad (C.48)$$

VITA

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