Hidden Failures in Shipboard Electrical Integrated Propulsion Plant

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(ABSTRACT)

The differences between shipboard and land based power systems are explored to support the main focus of this work. A model was developed for simulating hidden failures on shipboard integrated propulsion plants, IPP. The model was then used to evaluate the segregation of the IPP high voltage, HV, buses in a similar fashion as a shipboard firemain. The HV buses were segregated when loss of propulsion power would put the ship as risk. This new treatment reduces the region of vulnerability by providing a high impedance boundary that limits the effects of a hidden failure of a current magnitude or differential based protective element, without the installation of any additional hardware or software. It is shown that this protection could be further improved through the use of a simple adaptive protection scheme that disarms unneeded protective elements in certain configurations.

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Chapter 1: Introduction and Review of Shipboard Systems and Hidden Failures

Orders for electric propulsion systems for ships around the world are increasing [1], [2]. These ships can be viewed as floating electrical generating plants, each with their own electrical load. While the basic principles are the same for ships and shore based electrical systems there are differences due to the small size of naval ships and it's risk of receiving battle damage. Therefore electrical systems are configured and operated differently than on land. This work applies the principles of hidden failures to a shipboard electrical system and evaluates a method of reducing the effect of these failures.

The idea of opening high voltage busties stems from naval publications on shipboard damage control. Electrical systems are often described in terms of piping systems to make them easier to understand for those who are not familiar with electrical principles. One of the most important principles of readying a shipboard system for possible damage is the principle of segregation. U.S. Navy manuals on shipboard damage control and stability state that “Segregation (subdivision) of essential systems, such as the fire main, limits the extent and effect of damage and isolates the damaged system”[3]. The Navy manual on shipboard firefighting [4] discusses the need to segregate the firemain system, or the shipboard fire fighting water system based on the expected or impending damage. This will ensure part of the firemain system will remain functional despite complete damage to another isolated section of the firemain.

This principle of segregation is well established for mechanical systems. However, the U.S. Navy's Naval Ship's Technical Manuals, NSTM, offer no such guidelines for electrical propulsion systems. These manuals discuss the need for military ships to have an electrical propulsion system that is biased towards security, meaning that the system will remain in service despite a fault. Reference [5] discusses the situations when all generators must be online; however, nothing is mentioned about the need to isolate, or segregate, the propulsion electrical system prior to expected damage. It also recommends that the ships service, non-propulsion, electrical system be operated in a split, or non-parallel configuration when the loss of electrical power would put the ship at risk. This work looks into the possibility of applying the same principles of opening bustie breakers to reduce the region of vulnerability for hidden failures.

This chapter describes the significant differences between shipboard power systems and land based industrial systems and explains the operation of an electrical system, typical of a Coast Guard icebreaker. While shipboard power systems share many similarities with land based industrial systems, they do have significant differences. This chapter also reviews the principles of hidden failures and region of vulnerability and relates them to shipboard power systems. Chapter 2 reviews the modeling process used to evaluate the effect of hidden failures on a shipboard power system, which involves the development of protective relay models that are capable of modeling hidden failures. Critical shipboard electrical loads have multiple sources of power; therefore, protection and control models were developed for these systems. To develop recommendations for a more secure configuration of shipboard power systems, simulations were run on the model developed and the results were analyzed in this Chapter 3. Chapter 4 explores the future work that can be done on this topic.

1-1 Shipboard Power Systems:

The goal of a shipboard power system is the same as a land based system: While the basic principles are the same to provide the required electrical power to meet the electrical load. Shipboard electrical systems have much more in common with land based industrial systems than with the electrical transmission system. Voltage levels, physical size, and equipment used on-board a ship are similar to those used at an industrial plant. However, unlike an industrial plant that draws power from a power grid with significant spinning reserves, shipboard power systems generate their own power and have relatively small spinning reserves. A brief overview of shipboard integrated electrical systems is provided below. References [5] and [6] provide a more in-depth review of the differences.

All shipboard electrical systems are ungrounded, delta systems. The main benefit of the ungrounded system is the reduction in the number of possible line faults from ten to just four, as there are only phase to phase and three phase faults, but no phase to ground faults [7]. This would be especially important in battle conditions as fewer faults are possible. Although, an individual phase may accidentally become grounded to the hull, it will not effect the electrical system until a second phase becomes grounded to the hull, resulting in a phase to phase fault. A more in-depth presentation on this topic can be found in reference [8]. In general, an ungrounded system reduces the complexity of the protection system as: 1) there is no need for relays and breakers on a ground wire, and 2) fewer current transformers, CT, are needed for differential protection as only two phases need to be monitored to provide protection for all three phases [7].

The physically small size of a ship precludes the use of more complicated protection schemes such as distance and pilot protection as they are not precise enough for use over such a short distance. The longest ship ever constructed, supertanker Knock Nevis, is 458.5m / 1,504 ft long, barely over a ¼ mile [9]. The Zone 1, Zone 2 and Zone 3 of transmission protection are not used aboard ships, or do ship systems use sectionalizers or reclosers for fault clearance as there are no trees or animals to create temporary, environmentally induced faults. Another benefit of the small physical size of ships means that communication between devices can be considered instantaneous. This fact allows for the implementation of very communication intensive protection and adaptive schemes without the complication of time delays.

1-1-1 Shipboard Configurations

Two main types of shipboard electrical systems exist. The first is a split plant where the propulsion system and the ship service electrical systems are separate. This system is typically used on mechanical propulsion ships, but, this could also be implemented on an either an AC or DC electric ship. A line diagram of a split plant configuration is shown in Figure 1.1. The second type is an integrated propulsion plant, IPP, system or integrated propulsion system, IPS, in which a common source provides power for both propulsion and for ship service systems. Power Electronics have allowed “fixed frequency” systems to power both motors and house loads [10]. The IPP systems are the focus of this work and are described in Figure 1.2.

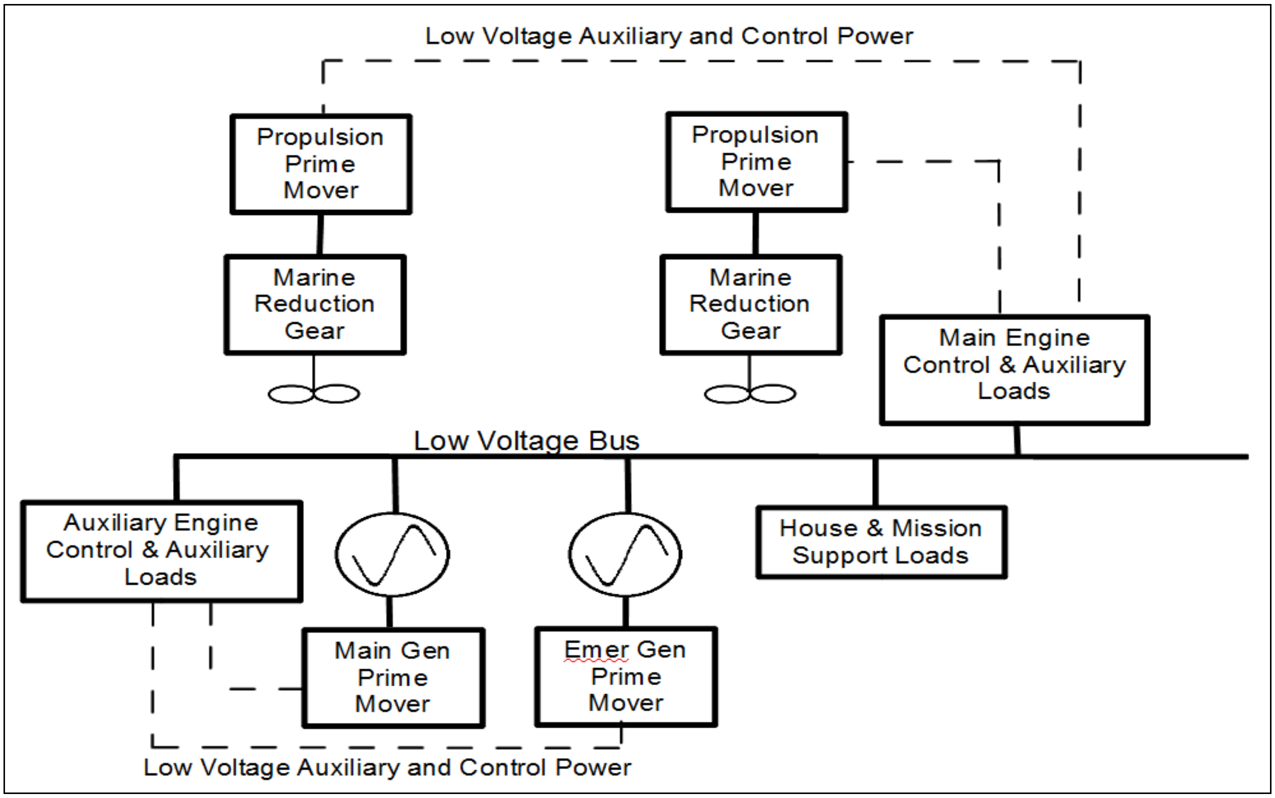

Figure 1.1: Shipboard Split Plant Diagram

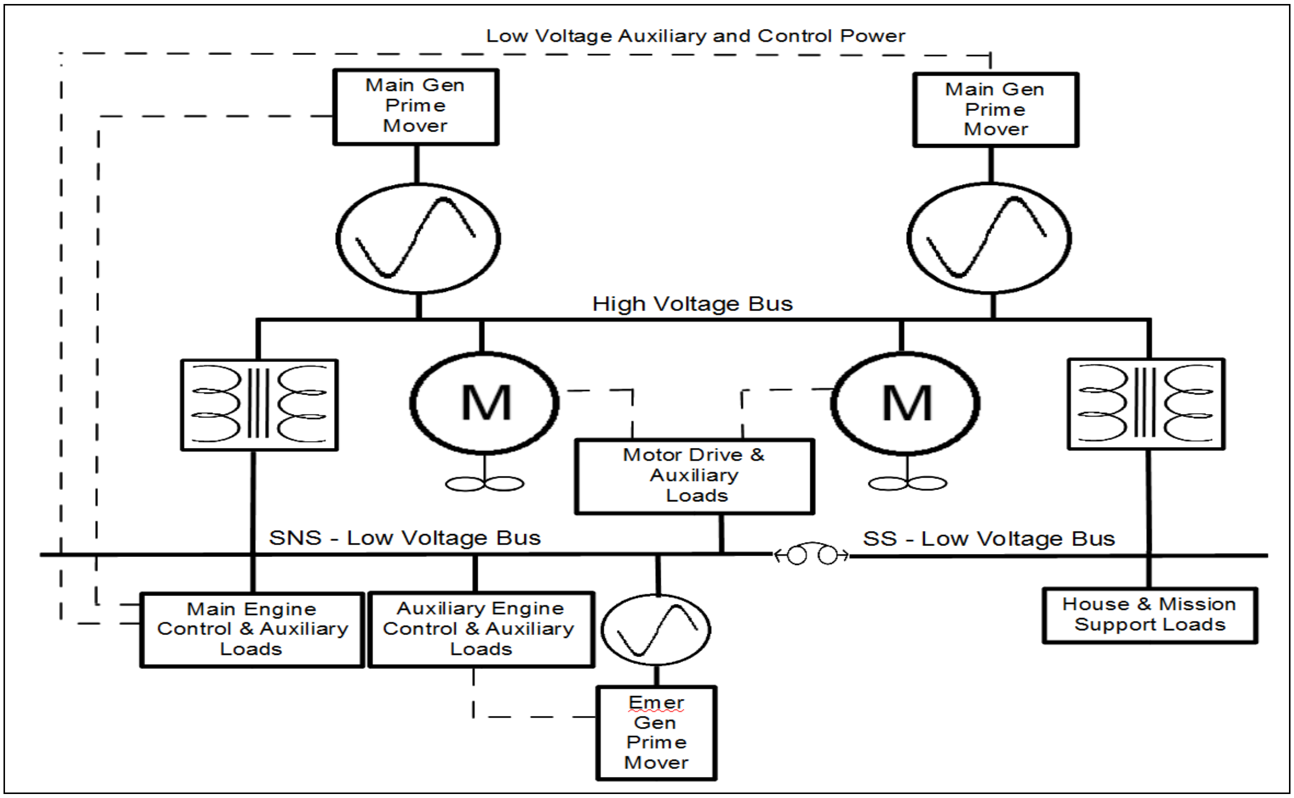

Figure 1.2: Integrated propulsion plant diagram

1-1-2 IPP Configuration:

Shipboard electrical plant configurations vary based on the ship's current mission and status. Three main configurations are possible: 1) shorepower, 2) anchor, and 3) underway. While a ship is moored, it will most likely be receiving electrical power from shore service and will not be running any onboard generators. However, an emergency generator, EG, may be in standby to power the ship in the event of a loss of shore power. When a ship is at anchor, it may be powered by either one of the main generators or the EG, or a combination of both. While underway, the ship will be powered by main generators and the EG will be in standby. The underway configuration is the subject of this thesis.

A shipboard electrical system is modeled in a typical underway configuration. In this mode all high voltage, propulsion generators are connected to the high voltage buses, thus allowing any one generator to power all loads. In normal service, transits, at anchor, or maintaining positions, a ship would not be running all of its generators. All generators would only be used when all propulsion motors may have to operate at full load. This may be during icebreaking operations, high speed transits, towing, or emergency situations as described in [5].

As shown in Figure 1.2, the 450 volt ship non-sensitive, SNS, bus is supplied by a Ship Service Transformer, SSTF, and the 450 volt ship sensitive, SS, bus is fed by a Ship Service Motor Generator, SSMG. An auxiliary or emergency generator, EG, would be in a standby mode. Under normal operation, the SS bus is closed to the ship's auxiliary, SA, bus. This allows for an alternative source of power for critical SNS loads connected to the SA bus via automatic bus transfer switches, ABTs. If power is lost to the SA bus the EG will energize and supply power to both the SS and SNS buses. Due to harmonics from the main motor frequency converters the SNS bus is not powered from the SS bus except in emergency situations.

The generation systems of both the split plant and IPP ships must power the various auxiliary and control systems required to run the prime movers. These loads are generally powered from the 450 volt, low voltage buses. Examples of such auxiliaries would include fuel pumps, oil pumps, sea water and fresh water cooling pumps, engine control hardware, ect. A loss of any of these could result in the loss of propulsion due to a loss of the prime movers. The low voltage buses also power "house loads," or loads such as lighting and receptacles in work and living spaces. The loss of these systems is not an immediate concern for the ship and are not considered in this work.

The main advantage of the IPP is reduction of equipment required to meet electrical loads while maintaining one backup propulsion generator [11]. Ship service loads, which are orders of magnitudes smaller than propulsion loads, are powered by the same generators used for propulsion. This results in a minimum of one less installed generator on a ship. United States regulations [12] and good engineering practice require that sea going ships have more than one propulsion generator and that the ship's electrical service have a back up generator. An IPP configuration with two main generators and one auxiliary or emergency generators, fulfills this requirement with a total of three generating units. Where as a split plant configuration would require two propulsion generators, one ship's service generator and one EG for a total of four generation units. An IPP system results in a reduction of maintenance costs and manpower while increasing the payload of a ship, as is the current trend in both civilian and military shipping [11]. The benefit of the IPP power both the propulsion and house loads also presents a possible weakness as a disturbance in the ship's low voltage electrical system could negatively impact the propulsion system. This could result in the potentially dangerous situation of the ship being left with no power for propulsion or maneuvering.

Shipboard systems are partially reconfigurable, especially on the low voltage side using Automatic Bus Transfer, ABT, or Manual Bus Transfer, MBT, switches. Low voltage critical loads are connected to two sources of power via an ABT. In the event of the loss of power from the primary source, the ABT will switch the load to the alternate source. This alternative source could be either a different low voltage bus or the EG.

There are a wide range of IPP configurations in use depending on the mission of the specific ship. Military combatant ships that may have to contend with battle damage will have more robust systems, whereas cargo and passenger vessels would not need the same level of robustness. This work focus on a radial type system that is used onboard vessels such as U.S. Coast Guard icebreakers and New York City ferry vessels.

1-1-3 Shipboard Protection:

Shipboard systems use a limited number of protection schemes. Low voltage, end loads are generally protected by Molded Circuit Breakers, MCB's, that provide instantaneous short circuit, time delay, and overload protection. Low voltage buses and feeders are protected by power circuit breakers that are tripped by instantaneous, short time delay, long time delay relays. Transformers are protected by differential relays and instantaneous and time delay overcurrent relays. The trip time delays and current pick up levels of these relays must be coordinated with the downstream relays or breakers to prevent unneeded tripping resulting in more of the system being left without power. On the high voltage side, generators and motors are protected by differential current, over current, reverse power, over and under-voltage, and lock out relays. Operation of these relays is described in [7].

Shipboard power is distributed throughout the ship using bundled cables which are are constructed of insulated covered copper wires and have no separation between each cable. In contrast, the land based electrical transmission system, uses a combination of bare aluminum and steel conductor cable that are separated by many feet to provide the needed insulation. The per unit length DC resistance of shipboard cables is similar to those of transmission lines. However, the per unit length series reactance is about one order of magnitude less than those of transmission lines [13]. This lack of impedance leads to overcurrent coordination challenges as there are will be very little current difference between protective devices. This makes time delay coordination much more critical than on land and makes the system much more sensitive to hidden failures.

1-2 Hidden Failures:

Hidden failures are defined in reference [14] as “a permanent defect that will cause a relay or a relay system to incorrectly and inappropriately remove a circuit element(s) as a direct consequence of another switching event.” Two key terms are “permanent” and “another switching event.” [15] analyzes the hidden failures for a range of protective devices. Another switching event is defined as a switching caused by faults, overloads, reverse power flow or control actions from the engine or power control systems [14].

Hidden failures can further be broken into two categories [15]: hardware failures and relay settings, and human errors or negligence. A summary of hardware hidden failures on relays that are typically used on-board ships is provided below in Table 1.1:

Table 1.1: Protective Devices and associated hidden failures.

Relay Type	Hidden Failure(s)	Consequence
Overcurrent	None	Not Applicable
Time Delay Overcurrent	Shorted Timer	Unwanted trip due to lack of coordination.
Molded Circuit Breaker	Fail to Trip	Loss of power to bus due to upstream clearing of the fault
Differential	Shorted Restraint Coil	Unwanted trip will occur, depending on

		load
Frequency/UV/OV	None	Not Applicable
Reverse Power	Loss of Directionality O/C contact shorted	Unwanted trip at a low fault level
Reverse Power	Timer contact Shorted	Unwanted trip at instantaneous reverse power
Lock out	O/C contacts shorted	Device will not be placed online

The hidden failures in Table 2.1 describe the hardware failure of an electromechanical relay. While these relays are being replaced with digital relays in new ships, the failure method is still relevant as these same failures could present themselves in software in digital relays.

The second type of hidden failures are not hardware type failures, instead they represent an error in settings, connections or negligence; therefore they are harder to systematically track. Incorrect settings could result in a relay failing to operate when required or operating during high load conditions while no fault is present. A source of these hidden failures may be a result of not resetting, or replacing an MCB, when equipment is added to or removed from a bus. As shipboard power systems are considered special protection systems, these failures will be broadly review under the assumption that a relay does not operate. Methods of preventing these types of hidden failures extends beyond electrical engineering and into the realm of configuration management and the tracking of all changes to not only power system but the surrounding shipboard systems. Further analysis is beyond the scope of this work.

1-3 Region of Vulnerability:

The section of the power system that is affected by the loss of power due to a hidden failure is known as the "region of vulnerability." On land this is often based on the combination of relay settings and fault current magnitudes [14] and is measured in line length of distances on the order of miles or kilometers. Determining the region of vulnerability for land based distance relays is a simple algebra problem based on the length of the zone protected and the line impedences [14]. However, distance relays are not employed in shipboard systems.

Most protection elements on ships are based on current magnitude, either line current or differential current. Therefore the region of vulnerability extends out as far as where the overcurrent detector will detect a fault. For land based time-delay relays the most effective means of determining the region of vulnerability is to determine the maximum fault at each bus and determine if the fault current at the device in question is enough to trip the overcurrent detector [15]. This method is based on the fact that a reduction in fault current will be seen as one moves further from the fault.

The same theory can be applied to differential relays, which can suffer from a hidden failure of a shorted restraint coil. The coil need not be completely shorted, but rather shorted enough to present a different restraint then the non-shorted coil. In addition to the amount of coil shorted, the region of vulnerability depends on the difference between the CT rations on each side of the device protected. This leads to a wide range of distances that could be effected by a hidden failure making it nearly impossible to accurately determine the region of vulnerability.

Unlike on land based systems where the distance between buses is often measured in miles, distances on ships are measured in feet or meters. Thus, a distance based region of vulnerability would not be useful on shipboard systems as the entire electrical system is typically less than a quarter mile and the resulting line impedances will be negligible. Characteristics for polyethylene insulated cables, XPL, are shown in Table 1.2 [13]. As both lines and breakers have small impedances, the fault current will not change much from one bus to another bus when all breakers are closed.

Table 1.2: Characteristics of XPL Cable

	Conductor Size (mm^2)		
	25	240	630
Series Resistance R (Ω/km)	0.927	0.098	0.042
Series Reactance X (Ω/km)	0.097	0.073	0.09
Susceptance ωC (mS/km)	0.059	0.146	0.202

The method of measuring the region of vulnerability based on line length is not the most effective method for use onboard ships, rather the region of vulnerability should be measured as the loads that will be lost as a result of a hidden failure. The methodology for determining the effected buses can be similar to those used on land, however, the only large impedance that will be seen on a ship would be an open circuit breaker.

By assuming the region of vulnerability extends to the nearest open breaker makes determining the region of vulnerability much simpler as no calculations are required, but rather an analysis of the power system to locate the open breakers.

This also allows for a much more accurate determination of the region for vulnerability for hidden failures on differential relays as open breakers serve as a firm boundary for region of vulnerability.

Chapter 2: Modeling

The majority of ships, in use today, utilize a mechanical propulsion plant with the electrical plant providing power for auxiliary equipment such as pumps, lighting, controls and miscellaneous equipment. In 2007 and 2008 the percentage of electric propulsion ships orders were 4.9%, 550 units, and 8.2%, 998 units [1,2]. This limits the pool of facilities that can generate reports of failures that will be of interest for this study. Unlike the U.S power grid, is unlikely for ship to have electrical failures that effect a large population, therefore there are no requirements to report shipboard power failures to a regulating body unless there was significant damage resulting from the power failure.

A generic model of a shipboard IPP system, described in Chapter 1 was created to test validity of the hidden failure analysis. Modeling of the power system components is based on reference [16]. The purpose of this model was to examine the system response to hidden failures. Protective relay models were constructed to accurately portray the relay's functionality and to allow the easy insertion of hidden failures as defined in reference [15]. As the focus of this work is the response of the protection system, loads were modeled as parallel resistive and inductive circuits with approximately a .8 (lagging) power factor. The effect of noise from variable speed drives and impulse loads were neglected.

For performance modeling of the protection system "Manitoba HVDC Research Center's Power System Computer Aided Design / Electromagnetic Transient including DC (PSCAD/EMTDC)", hereon referred to as PSCAD, software was selected. Unlike load flow programs, PSCAD is widely used to model electrical and control system transient responses. PSCAD was selected for its component libraries, its ability to simulator transients conditions such as faults, and its easy to user control interfaces. As the goal of this study is to examine the system response to hidden failures, load flow analysis was not needed.

2-1 Model Base:

The model in this work is based largely off the U.S. Coast Guard Great Lakes icebreaker, MACKINAW. Coast Guard drawings for MACKINAW were used to determine the system architecture of this model [17]. The electrical layout of MACKINAW was chosen for its similarly to the layout of other electrical propulsion ships, such as the new Molinari class ferries in the New York City Ferry system [18]. Equipment information was used from the Coast Guard icebreaker HEALY [19-21]. Where knowledge of system operation was required, the author made assumptions based on personal experience aboard ships. Specific settings for protective elements was determined based on recommended shipboard or industrial practices and was never taken from any shipboard technical literature.

This combination of sources for the model helped to provide a functional, yet genetic model for this work. Additionally, no critical information about either ship is exposed.

2-2 Modeling Philosophy:

Time delay over current , TDOC, protection was not installed on low voltage, end loads, as a timer failure, will only effect the load. While this would still be considered a hidden failure, the effects will only be on the end load and are not of significant impact in this study. Timer failures were modeled for transformer, motor generator, bustie, and generator protective relays.

Reference [15] states that frequency relays do not have any hidden failure modes. As over and under voltage relays operate in much the same mode as frequency relays, it can be assumed that neither of them have hidden failure modes. Therefore, they are not modeled in this work.

2-3 Protection Devices:

2-3-1 Instantaneous Overcurrent Relay

The most basic types of relays is the instantaneous overcurrent relay, a Type 50, or simply an overcurrent relay, OC. The OC relay compares the level of input current to a preset value and initiates a trip command if the current is above the trip level. Overcurrent relays can suffer from the hidden failure: failing to operate. The output of the OC element and a switch, to simulate failure to operate, are connected to an AND gate. The breaker will only trip if the output of both the OC element and the switch are high. The seal-in circuit, ensures the relay will trip once trip current has been present, even if the current were to quickly decrease. This was simulated by using a counter that has an initial value of 0. If a fault current is detected, the counter increments and stays at 1. As there is no automatic fault clearing on ship,the counter can not be automatically reset. The model of OC relay is shown in Figure 2.1

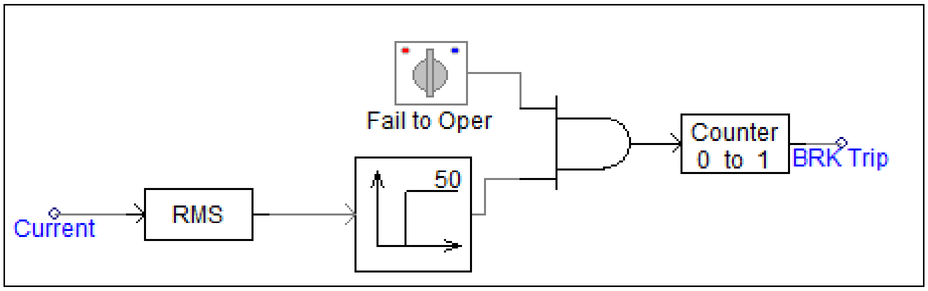

Figure 2.1: Instantaneous Overcurrent Relay Model

2-3-2 Time Delay Overcurrent Relay

A time delay overcurrent relay,Type 51 relay is used for bus and generator protection. The TDOC relay will open a breaker after a time delay that is based on the fault current magnitude. This allows for coordination with downstream protective devices. A TDOC can have two hardware hidden failures; 1) a timer failure and 2) failure to operate, as this has been considered a special protection system.

The TDOC relay model provided in PSCAD could not be used for this work as there was no way to bypass the delay timer. Therefore, a relay with equivalent characteristics was designed using math and control elements in the PSCAD libraries. This allowed for the insertion of a timer failure, and the use of variables for trip and time dial setting. To simulate a timer failure, the time delay output signal is connected to the timer override switch. If the switch is set to a logic 1, a trip signal will be issued without a time delay. The failure to operate is simulated the same way as with the OC relay. Binary time delays are used in the timer circuit. These delay timers accept a variable for their setting and will only go high if the input remains high for the length of a time delay. The complete 50/51 relay is presented in Figure 2.2.

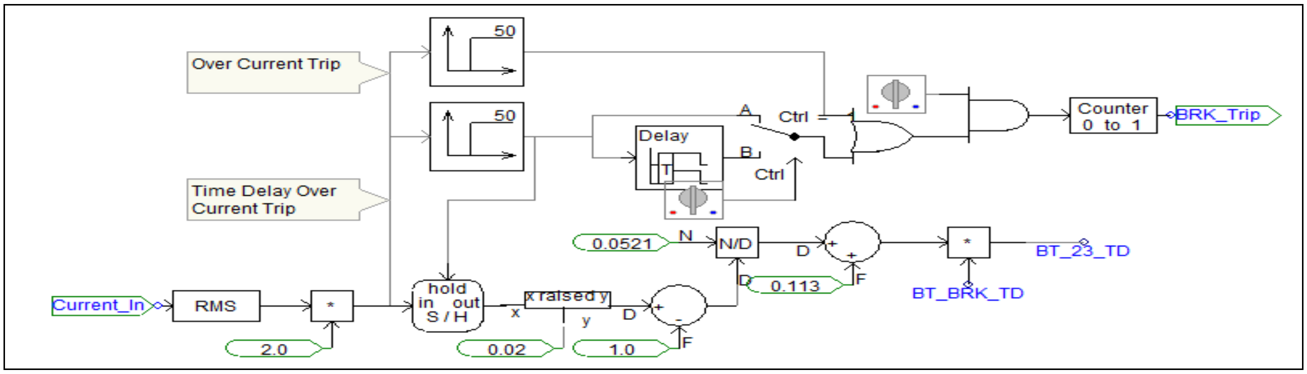

Figure 2.2: 50/51 Relay Model

2-3-3 Direction Power Relay

Directional power relays, Type 32, or reverse power relays, protect the generator prime mover from being driven by the power system, or “motoring”. Diesel engines and gas turbines will experience damage if they are subject to reverse power conditions of 5-25% and 10-50% of rated power, respectively. Reverse power relays are typically set at 50% of this value [13] and have a time delay of about 30s [22]. Reverse power relays can suffer from two hidden failures: 1) timer failure or 2) permanent closure of the directional element [15]. Each of these hidden failures will cause a trip given enough time. The loss of the timer could cause a trip when another generators is being brought online and there is a short reverse power condition while the units are synchronizing. The loss of the directionality element would result in a trip once the current exceeds the trip setting and the time delay has passed.

In this work, a hidden failure in a reverse power relay is modeled as the loss of both the directionality and the timer. The loss of the directionality is the true hidden failure, and the loss of the timer is used to speed the simulations by not having to wait the full 30 seconds before seeing a trip. The model used is shown below in Figure 2.3.

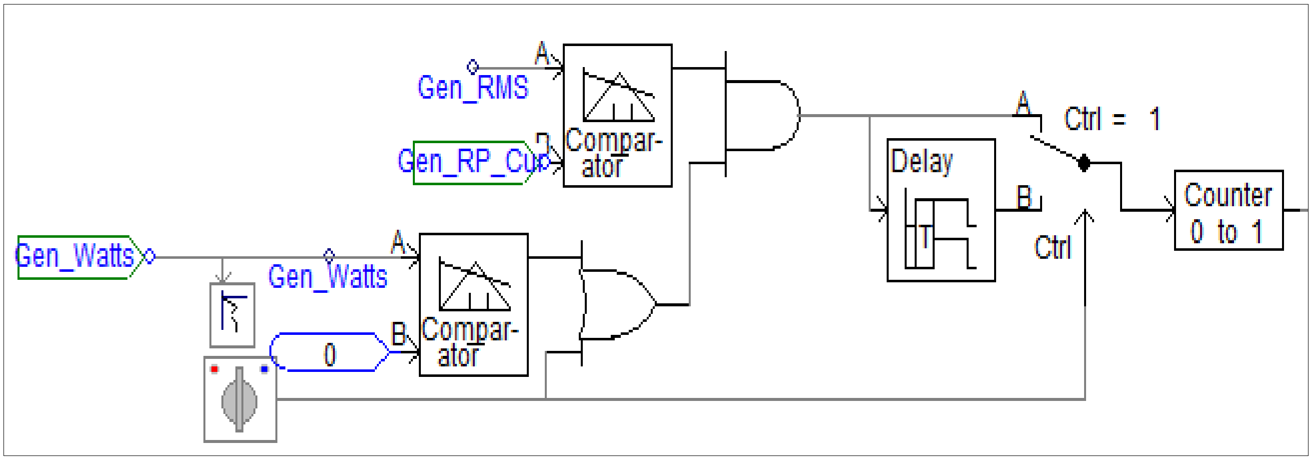

Figure 2.3: Directional Power/Reverse Power Relay

2-3-4 Lock Out Relay

Type 86, lock out relays are used to ensure offline generator or motors are not accidentally energized. Reference [15] states that a hidden failure on a lock out relay will simply prevent the unit from coming online. While this will have little consequence on a land based systems, this could result in the overload of online generators and/or unneeded load shedding in a ship. The lock out relay is armed as soon as the frequency and voltage drop below a set value that is well below any emergency situation. The frequency and voltage relays will close, in the event that they lose control power and will remain armed until both the frequency and voltage have risen above their respective set points for a predetermined amount of time. If, before this time limit is up, current exceeds the overcurrent element set point the unit will trip. Therefore, a permanently closed overcurrent element will remain hidden during normal operation and shut down, but will not allow the unit to be placed online. A lock out relay is modeled as a switch controlling the breaker. The hidden failure is simulated by setting the switch high, thus opening the breaker. The lock out relay model is shown in Figure 2.4.

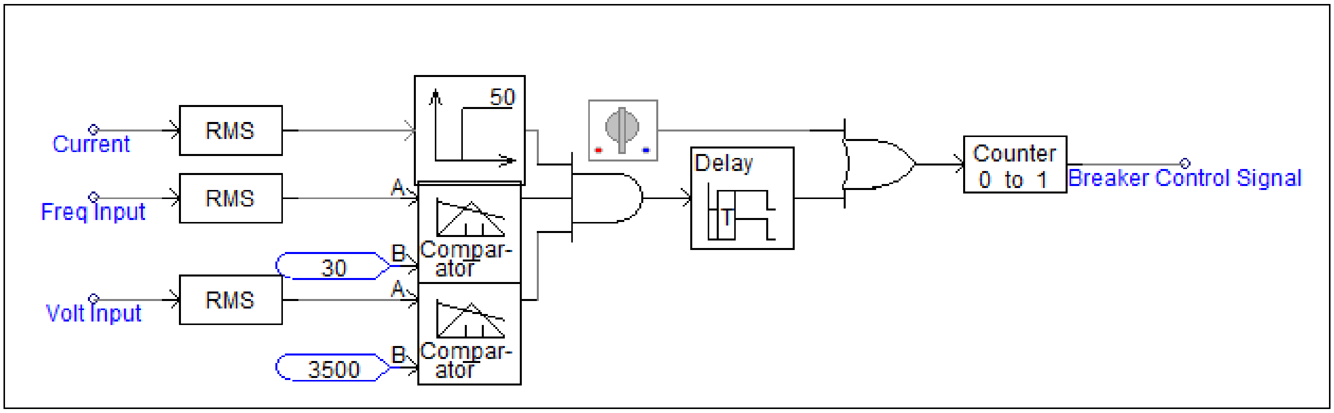

Figure 2.4: Lock Out Relay Model

2-3-5 Differential Relay

Transformers, motors, and generators are typically protected by percentage differential relays. Differential relaying is accomplished by comparing the incoming and outgoing currents of the protected device. One of the currents is scaled by the ratio of the transformer and if the difference between the two currents is greater than a pre-set percentage of the load, then the relay will trip. As a result, the relay is not affected by changing loads. Thus, a well set percentage differential relay will not require updating throughout its life. Differential protection also protects the lines between each of the measurement points. In this model, it is assumed that the CT's for differential protection are located in the switchgear on the primary and secondary sides of a transformer. Thus, a differential protection scheme will protect both the transformers and the cables. For motors and generators, the one set of CT's is in the closest switchgear and the second set is in the motor or generator, thus providing protection for both the equipment and the feeder cable. As ships are relatively small, communication between both sets of CT's is not an issue.

Percentage differential relays can suffer from a hidden failure resulting from a shorted restraint coil. In electromechanical relays the restraint coil generated torque to oppose the tripping coil's attempt to operate the relay. If the restraint coil is the the shorted, ie current is not flowing through all the windings, the restraint coil will not produce the restraining torque needed to prevent relay operation. In digital relay, this is accomplished using mathematical functions and digital logic.

To model a shorted restraint coil, one of the CT inputs to the restraint current circuit was multiplied by one of normal operation, or zero to simulate a hidden failure. In practice, differential transformers have a phase correction input to allow for the protection of delta-wye or wye-delta connected transformers. The PSCAD library has a percentage differential model. However, there was no option to change in the internal calculations of the bias, or restraint current. Therefore, a percentage differential relay was constructed and is shown in Figure 2.5. There are no hidden failures associated with the phase inputs, thus they have not been included in this model.

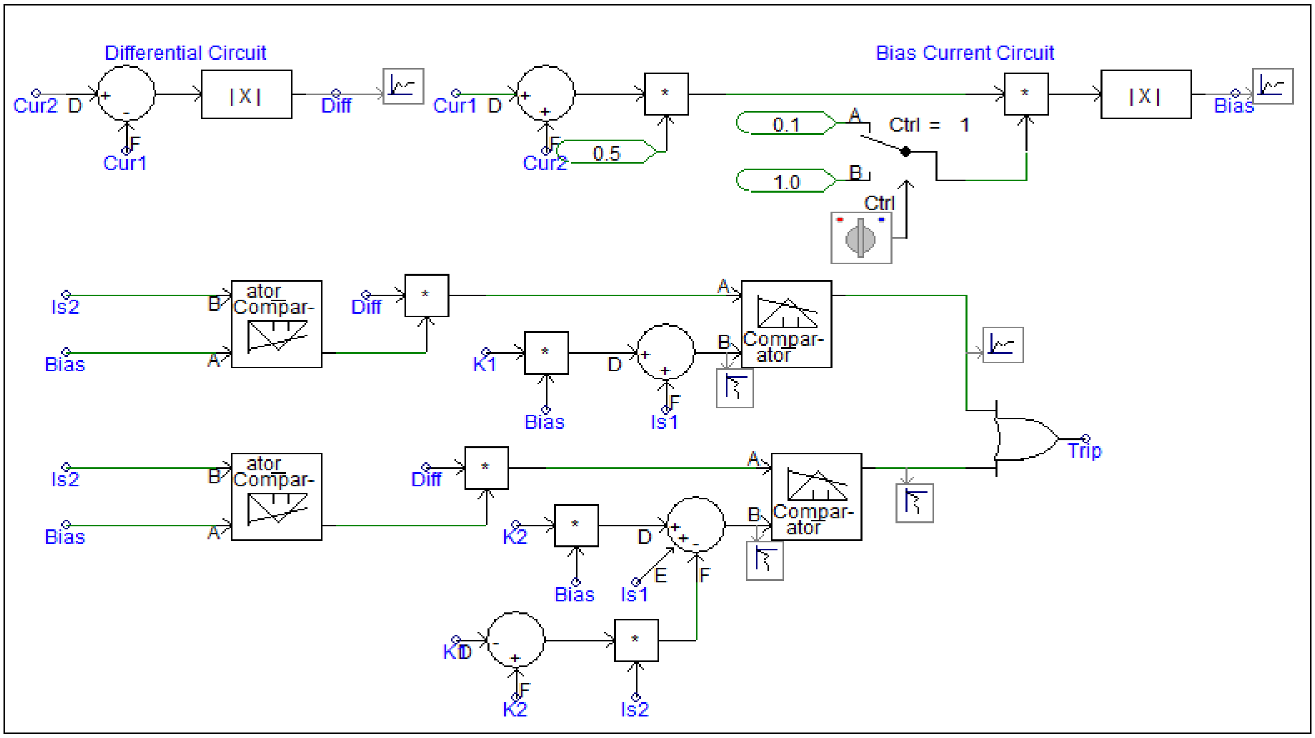

Figure 2.5: Percentage Differential Relay.

Some of the protective elements on ships do not have hidden failure modes. These are of no interest in this work, therefore, they are not modeled. However, if they were the only device protecting a piece of equipment, they were still used. In no case was an element left unprotected.

The following devices were not modeled:

Overvoltage
Load TDOC
Power Factor/ Loss of Field Relays
Overload

2-3-6 Breakers:

The provided PSCAD model for breakers was used. The breakers were set to an interrupt of up to 5 kA [23].

2-3-7 Faults:

The PSCAD library has a fault model that allows any fault resistance value to be used. For this work two fault levels, resulting in two different levels of fault current, were used. The bolted fault was set at .01 ohms and the non-bolted fault was .1 ohms. Faults were controlled using the switch interface thru a timer set at .1 seconds. This time delayed allowed the model to reach steady state before the faults occurred. Once a fault was present, it remained present for the remainder of the simulation.

2-4 Electrical Components:

A simple, one-line diagram of the high voltage system is shown in Figure 2.6.

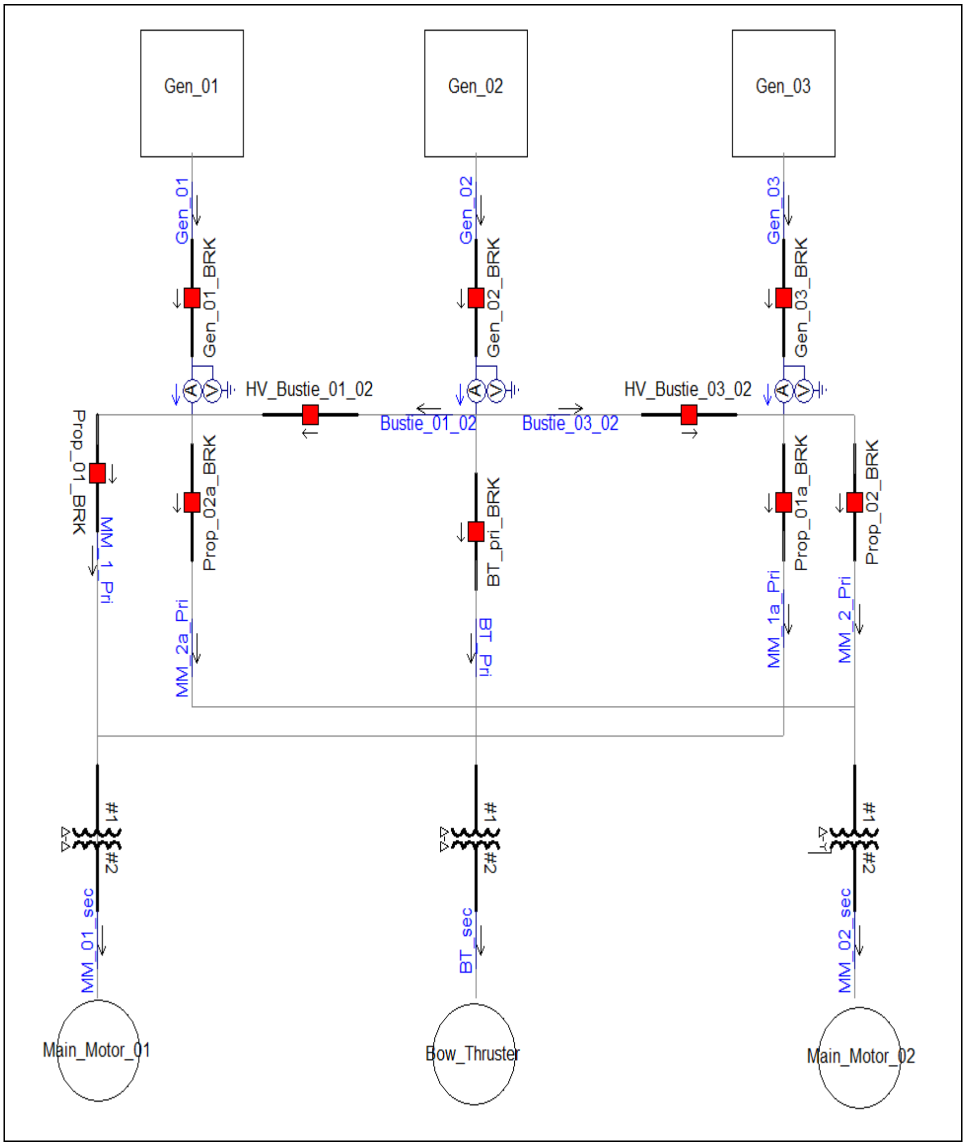

Figure 2.6: One-line diagram of High Voltage model

2-4-1 High Voltage Busties:

Busties connect the two buses together. These circuit breakers are used to separate the buses during fault conditions and for routine operations. During a fault on the high voltage bus, the nearest bustie should open to separate the unaffected buses from the faulted bus; this will result in the minimum load loss. A fault on HV bus #1 or #3 will not result in any loss of load due to the automatic alternative power sources; however, it will result in a loss of generation of the amount of generator #1 or #3. If a fault occurs on HV bus #2, the bow thruster, which does not have an an alternative source of power would therefore be unusable. The protection scheme for the HV busties is shown in Figure 2.7.

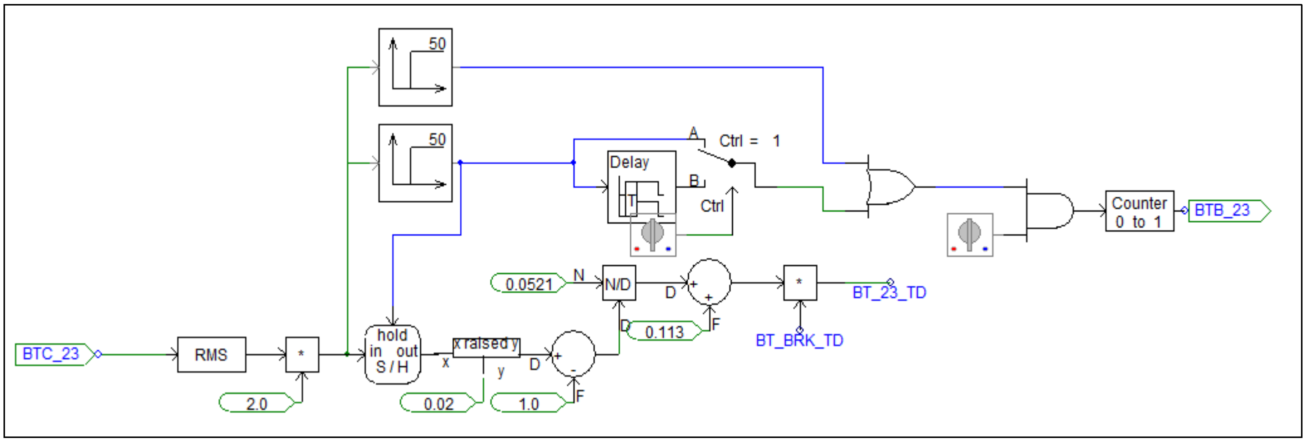

Figure 2.7: HV Bustie Protection

2-4-2 Main Motors and frequency converters:

The main motors and bow thruster were modeled using constant load single-phase resistive and reactive components connected in either an ungrounded delta or wye connection, as needed. As both the resistive and reactive loads stayed constant, these devices behaved much the same as a motor and motor controller combination would, but without the complications of a motor controller or frequency converter; therefore, frequency converters were not modeled for this study. The master library in PSCAD provides only three phase constant loads, not the single phase loads need, thus the three phase loads had to modified for the use at hand.

The provided loads could be used as variable loads if the “allow signal names” box was checked. The load signal could be connected to a control source and the loads could be varied throughout the simulation. The fixed load takes voltage measurements across the load to ground and determines the resistance or inductance as follows:

$R = V^2_{LG}/P$

$L = V^2_{LG}*pi*f/S$

One main motor was modeled as a delta connected motor and the other as a wye connected motor to allow extra flexibility in being adapted to different uses. Motors are dual wound motors. Which helps to reduce the 6th harmonic, provide for more torque in a smaller package, and some measure of redundancy, in the case of a failure in the frequency converter. However, they do not provide any redundancy in the power distribution systems, as they are both powered from the same feeder, thus they are modeled as in the same fashion as a single wound motor, the same as the bow thruster motor [24].

2-4-2-1 Main Motor Protection and Control:

The main motors are protected with OC, TDOC and differential protective devices. Additionally, an undervoltage switches the main motor power supply to an alternate power source, after a time delay, if the primary source drops below a preset value. To prevent the alternate source from closing to a fault, the alternate power source breakers will open if the primary source breakers opened due to an overcurrent trip.

2-4-3 Low Voltage Section:

A simple one-line diagram of the modeled power systems is shown in Figure 2.8 on the next page.

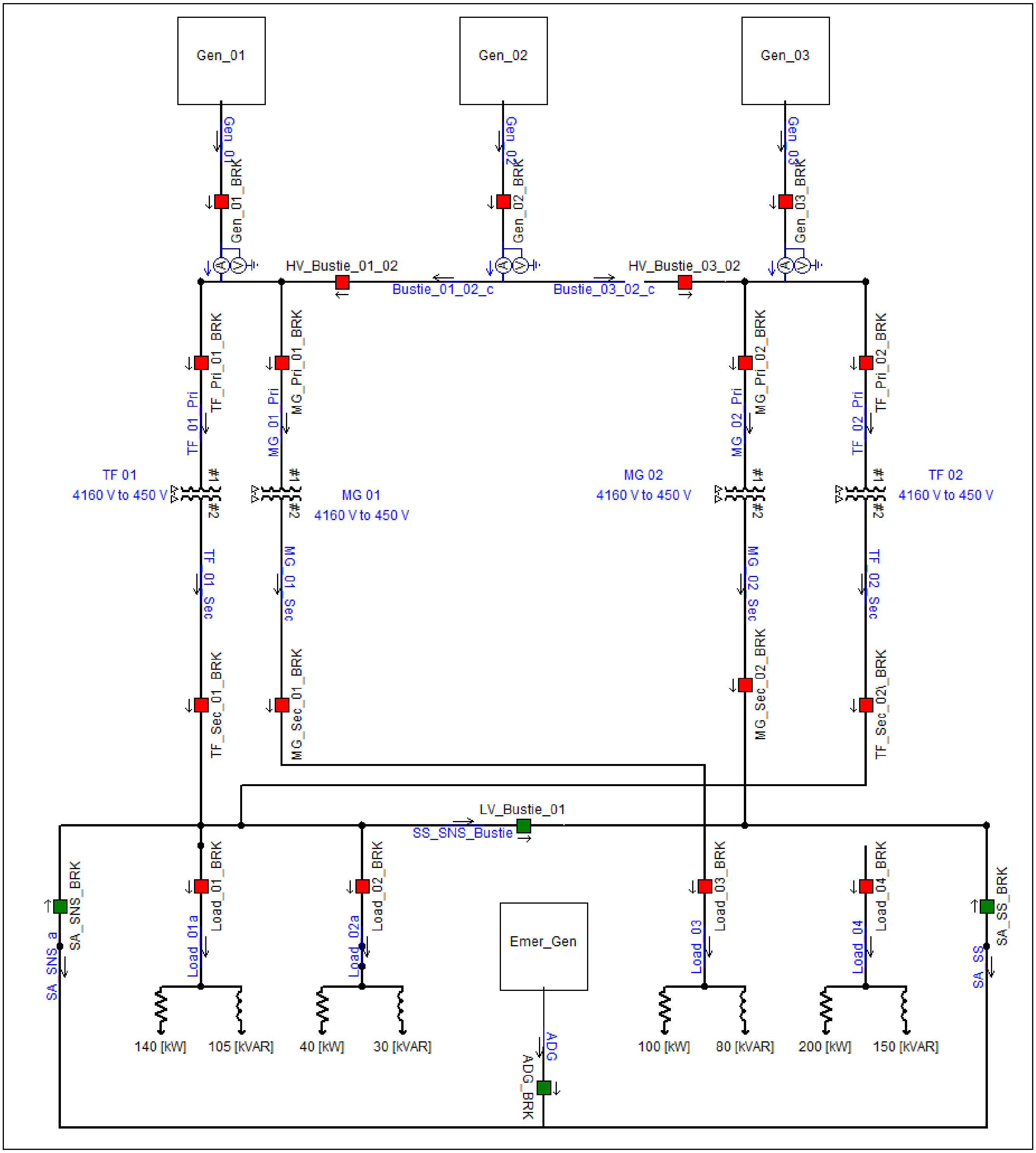

Figure 2.8 One Line Diagram for Low Voltage System

2-4-3-1 Transformers:

In addition to the protection relays, transformer breakers are also controlled by logic to ensure a continuous power supply to the low voltage buses. Either of the transformers can supply power, but only one can be online at a time. Transformer #1 is controlled only by the protection equipment; however, transformer #2 is set to be in the opposite state of the transformer #1, unless the protection elements detect a fault. Additionally, the voltage sensing of transformer #2 is only active when the breaker for transformer #2 is closed. The required control logic is shown below in Figure 2.9.

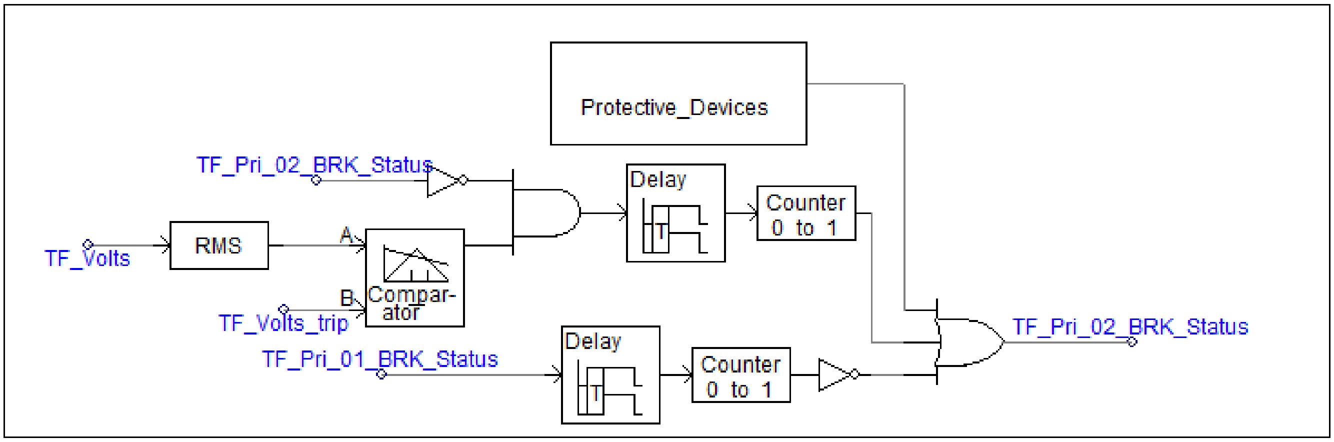

Figure 2.9. Transformer and Motor Generator Control

2-4-3-2 Motor Generator Sets:

Motor generator, MG, sets provide clean power to sensitive electronics such as control systems, computers, radars, etc. Two main setups are possible: 1) the MG filters and changes voltage levels or 2) the MG set only filters and a transformer changes the voltage level. MG sets were modeled as a single transformer as there are no motor drivers to contribute to harmonic noise in the electrical system. Transformers and MG sets are both protected by OC, TDOC, and differential protection. MG sets were modeled as transformers as accurate motor drives would not significantly improve the functionality of this model. This allowed control for MG sets to be implemented the same way as for transformers.

2-4-3-3 Emergency Generator and Low Voltage Busties:

The model has three low voltage buses: non-sensitive, SNS, sensitive, SS, and ships auxiliary, SA. In the event that the transformers, or MG sets, both fail the emergency generator, EG, will come online and supply the low voltage loads. The EG and the low voltage busties are controlled by voltage sensing. If the SNS and SS buses lose power, the EG will come online after a preset time delay. The EG breaker will close and then the appropriate SA or SNS breaker will close.

This sequence will be attempted for any loss of voltage on either the SNS or

SA buses. If the EG closes into a fault, the protective elements will open the appropriate breakers.

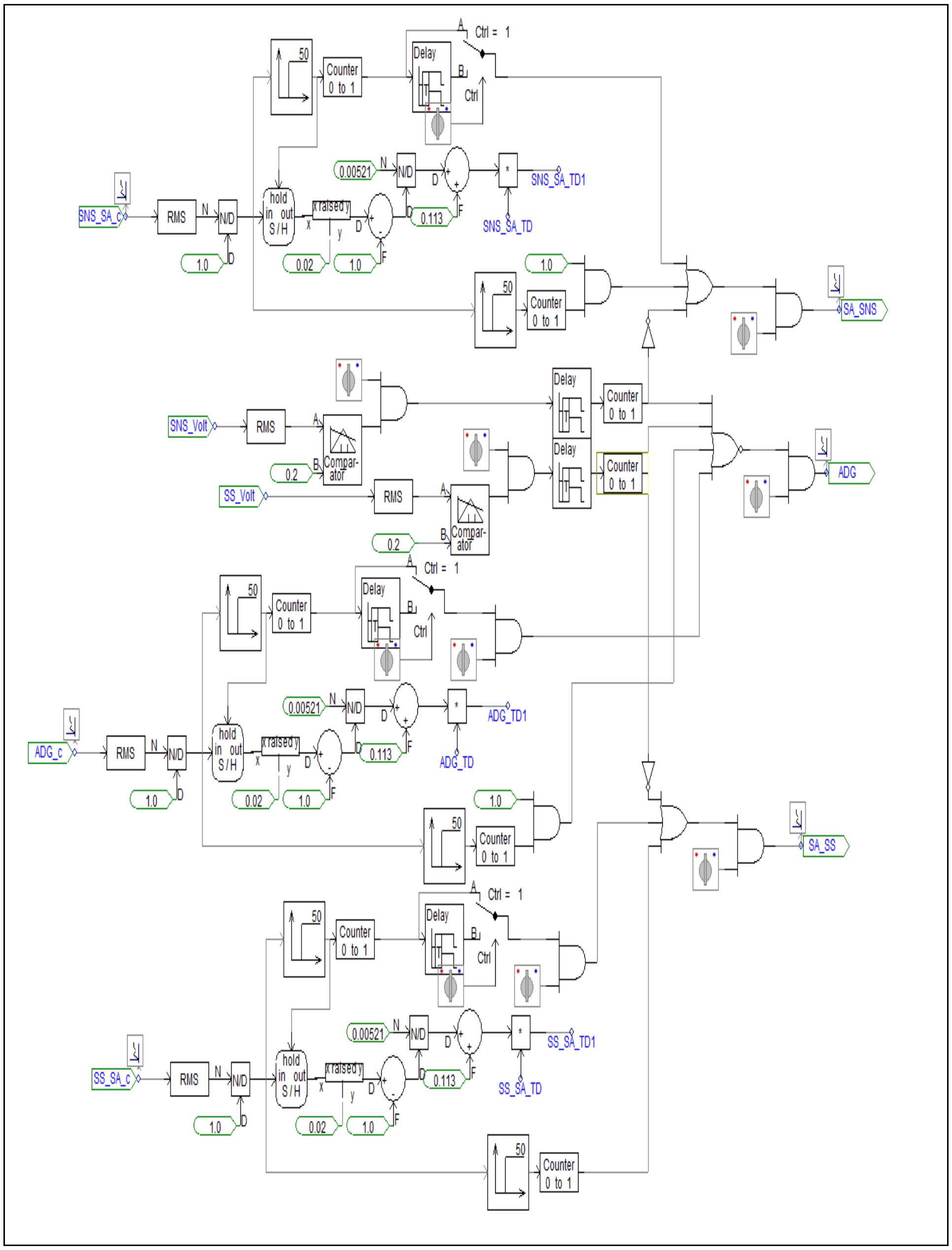

Figure 2.10 Low bustie and EG protection and control.

Table 2.1 lists the main power system components modeled and their associated protective devices. The characteristic curves for the TDOC relays are attached as Appendix A. The settings of 50/51's are provided in Table 3.2 below.

Table 2.1: Equipment and Protection lists.

Device	Protection Provided
Main Generators Emergency Generator	Type 27, Undervoltage Type 32, Reverse Power Relay Type 50, Instantaneous Overcurrent Type 51, Time Delay Overcurrent Type 86, Lockout
Busties	Type 51, Time Delay Overcurrent Type 50, Instantaneous Overcurrent
Main Motors Bow Thruster	Type 27, Undervoltage Type 50, Instantaneous Overcurrent Type 51, Time Delay Overcurrent
Transformers Motor Generators	Type 27, Undervoltage Type 50, Instantaneous Overcurrent Type 51, Time Delay Overcurrent Type 87, Differential
End Loads	Type 50, Instantaneous Overcurrent Type 51, Time Delay Overcurrent

Table 2.2: Relay Coordination Table

Element	Device	Trip Setting (kA)	Time Delay (sec)
Main Motors	Type 50	4	0
	Type 51	2	0.1
Busties	Type 50		
	Type 51	4	0.2
Generators	Type 50	30	0
	Type 51	20	0.3

2-5 Overall Modeling Comments:

This model made use of the both the protection and logic libraries of PSCAD. The protection library included trip elements that are useful for this project; Type 50 Instantaneous Overcurrent Relay, Type 51, Inverse Time Overcurrent Relay, Type 87 Differential Protection Relay, and Type 32 Directional Power Relays, referred to as Reverse Power Relay. Also included are the current transformer, CT, and potential transformer, PT. The trip elements could handle input from either current meters or from CT or PT. This allows for modeling of both molder circuit breakers, MCB, and separate relay and breaker combinations.

PSCAD is designed for use on land based power systems, which are typically grounded systems. As shipboard systems are ungrounded, this causes some issues for PSCAD, mainly “voltage chatter” at nodes on the opposite side of the transformers. The PSCAD manual recommend grounding the ungrounded nodes. This was accomplished through the use of a three phase resistive load of 1 Watt being placed on each bus.

Chapter 3 Testing and Simulations:

3-1 Setup

The objective of the simulations was to observe the system's response to hidden failures during fault conditions, and to determine a method of mitigating the negative response to these hidden failures.

Four sets of simulations were run on the HV buses: 1) Bolted faults (.01 ohm) with all generators online, 2) Non-bolted faults with all generators online, 3) Bolted faults with two generators online, and 4) Non-bolted faults with two generators online. Prior to testing system response to hidden failures, a fault was placed in the system with no hidden failures present. This provided a baseline to compare the response of the system while a hidden failure is present. Full results, including baseline testing, are included in Appendix B. Summaries of the results are presented and analyzed in this chapter.

3-2 Testing

It was speculated that a configuration that maintained one of the HV busties in the open position would limit the region of vulnerability to hidden failures to a maximum of two buses. To test this theory faults were placed, one at a time, in three separate locations: HV Bus #3, Gen 01 Windings, and Main Motor 01 feeder. Figure 2.6 is repeated for clarity.

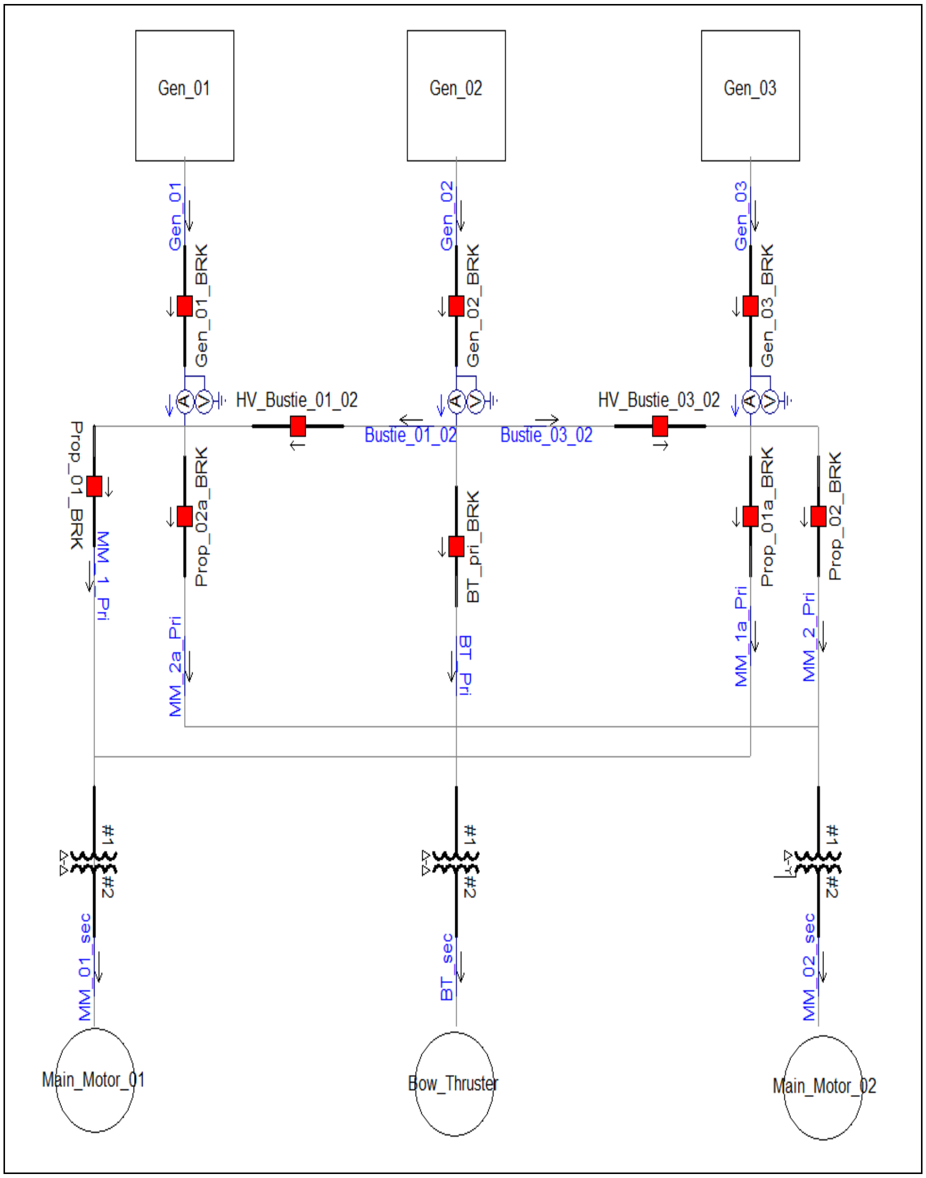

Figure 2.6: One-line diagram of High Voltage model

The following hidden failures were placed on the system one at a time: a) generator TDOC and RP timer and directionality failures, and b) shorted restraint coil on generator differential relay. 16 different sets of simulations where run. Each set had 12 tests for bolted faults or 16 tests for non-bolted faults. 6 sets of simulations were run with 3 generators on-line and busties either both closed, Bustie 12 open and Bustie 23 closed, and Bustie 12 closed and Bustie 23 open. 10 sets of simulations were run for both models with two generators (1&3 and 1&2) online. This resulted in 208 cases. The results of each test are listed in Appendix B.

Early in the testing of bolted fault cases, it was noticed that when all three generators were online, timer failures of TDOC and RP relays both resulted in trips at the same time. Test cases were run to determine if this was a valid assumption. A bolted fault was placed on HV Bus #3, and a timer failures and a shorted differential restraint coil were placed on Gen 01. The results are shown in Figures 3.1, 3.2, and 3.3 where it can be seen the TDOC and RP relays, with hidden failure of timer failures, both tripped at the same time for a bolted fault. The tripping time of the differential relay was slower by .006 seconds, or about one third of a cycle. While this response was close to that of the TDOC and RP relays, it was not grouped with the other two as the response would vary significantly with the fault current levels.

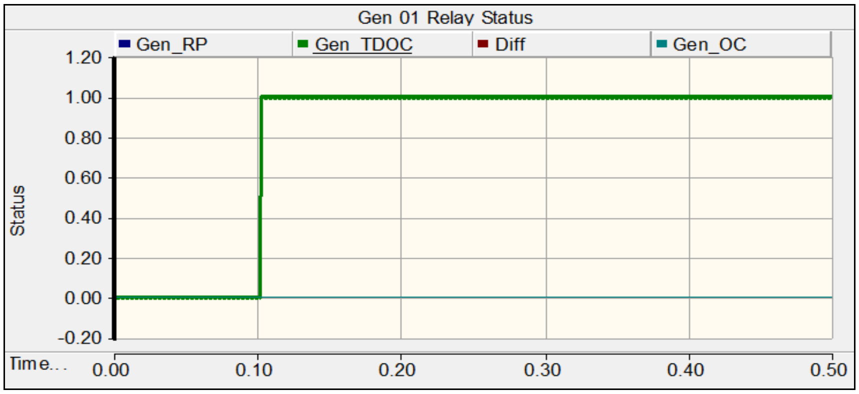

Figure 3.1: Gen 01 TDOC, with hidden failure, response to a fault in HV Bus #3

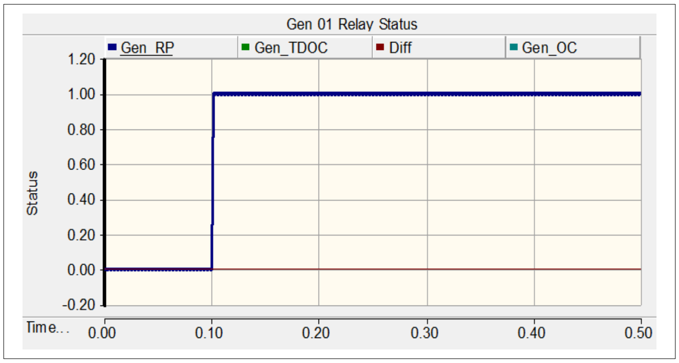

Figure 3.2 Gen 01 RP, with hidden failure, response to a fault in HV Bus #3

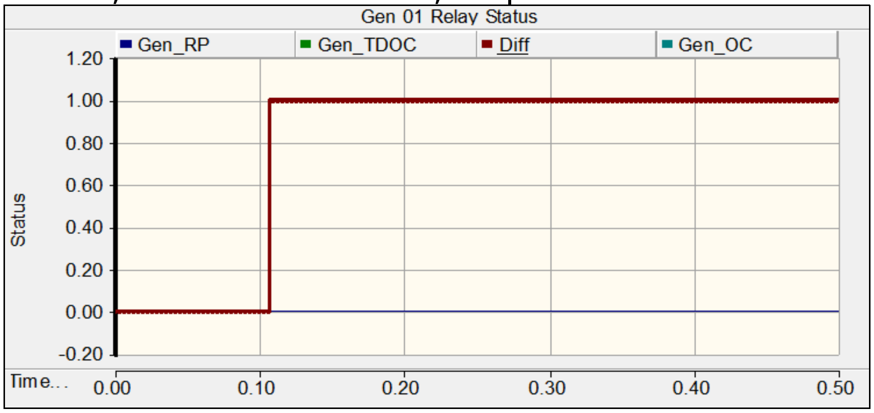

Figure 3.3: Gen 01 Diff, with hidden failure, response to a fault in HV Bus #3

The same tests were run for a non-bolted fault. The results are shown in

Figures 3.4, 3.5, and 3.6. The response of TDOC and RP relays with hidden failures are different from each other and the differential relay, with a shorted restraint coil, did not trip. This is due to the lower fault current levels from the non-bolted fault. Therefore, for non-bolted faults, three separate cases had to be run.

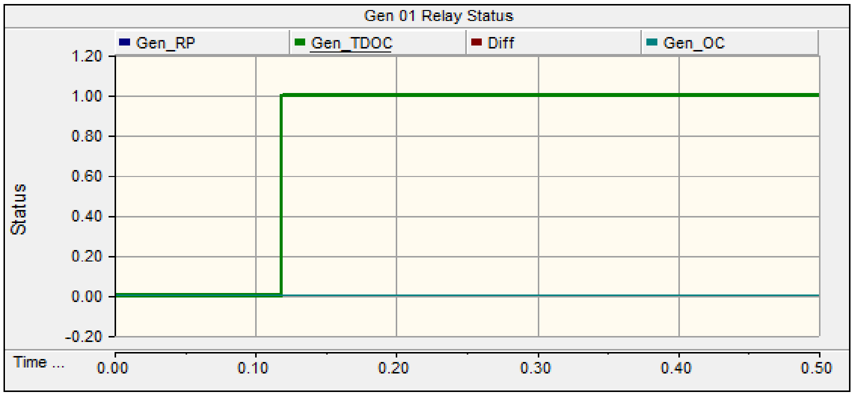

Figure 3.7: Gen 01 TDOC, with hidden failure, response to a fault in HV Bus #3

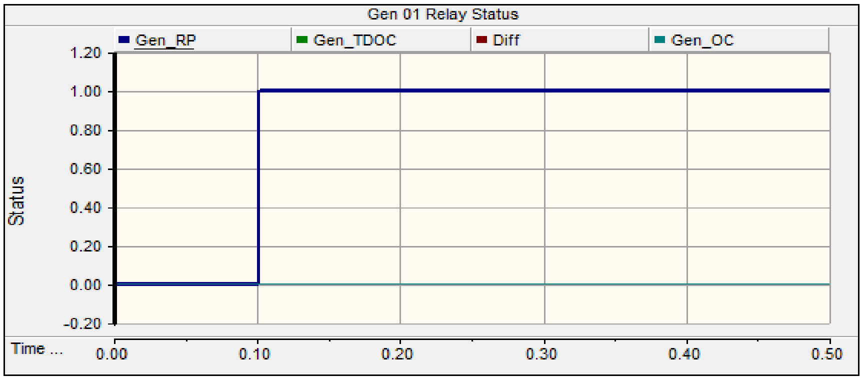

Figure 3.8: Gen 01 RP, with hidden failure, response to a fault in HV Bus #3

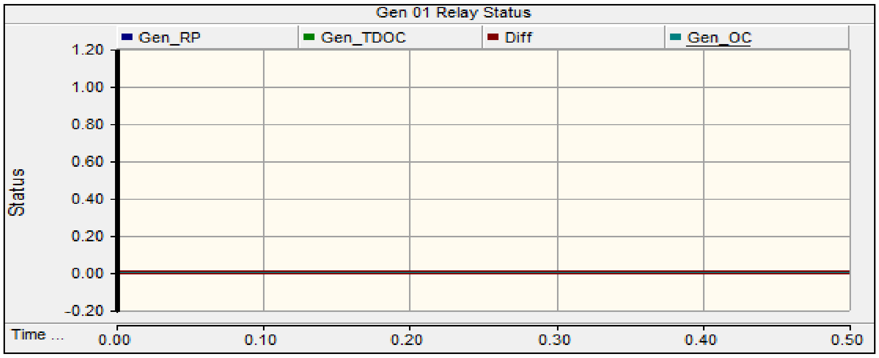

Figure 3.9: Gen 01 Diff, with hidden failure, response to a fault in HV Bus #3

The assumption made for the three generator cases that the tripping time for TD and RP timer failures will be the same is not valid for the two generators cases. For these cases, individual generator currents are higher, as there are only two generators to share the load. At full load, this higher current level is above the RP trip setting. Therefore, the TD and RP tests were run separately for the two generator cases.

3-3 Findings:

The full set of results of the tests are attached in Appendix B. Response to faults in three separate locations was observed and the results will be interpreted in groups based on the number of generators online, fault location and fault level.

3-3-1 Three Generators Online:

A summary of the cases for bolted faults and hidden failures present with three generators online is shown in Table 3.1.

Table 3.1: Response to bolted faults and hidden failures.

Fault Location	Gens Online	Bustie 12	Bustie 23	Ave Gen Lost	Max Gen Lost
HV #3 Bus	1,2,3	Closed	Closed	1.5	2
HV #3 Bus	1,2,3	Open	Closed	1	2
HV #3 Bus	1,2,3	Closed	Open	1	2
Gen 01 Winding	1,2,3	Closed	Closed	2	2
Gen 01 Winding	1,2,3	Open	Closed	1	1
Gen 01 Winding	1,2,3	Closed	Open	1	2
MM 01 Feeder	1,2,3	Closed	Closed	0.75	1
MM 01 Feeder	1,2,3	Open	Closed	0.75	1
MM 01 Feeder	1,2,3	Closed	Open	0.75	1

Table 3.2: Response to non-bolted faults and hidden failures.

Fault Location	Gens Online	Bustie 12	Bustie 23	Ave Gen Lost	Max Gen Lost
HV #3 Bus	1,2,3	Closed	Closed	1.6	2
HV #3 Bus	1,2,3	Open	Closed	1.3	2
HV #3 Bus	1,2,3	Closed	Open	1.3	2
Gen 01 Winding	1,2,3	Closed	Closed	2	2
Gen 01 Winding	1,2,3	Open	Closed	1	1
Gen 01 Winding	1,2,3	Closed	Open	1.3	2
MM 01 Feeder	1,2,3	Closed	Closed	0.3	1
MM 01 Feeder	1,2,3	Open	Closed	0.3	1
MM 01 Feeder	1,2,3	Closed	Open	0.6	1

From Table 3.1 it can be seen that in the case of a bolted fault on the HV buses and the generator windings intentionally opening a bustie reduced the effect of a hidden failure resulting in more generators remaining online. There was no effect from opening a bustie for faults in motor feeders, transformer, or motor-generators.

Table 3.2 summarizes the system response to a non-bolted fault. As with bolted faults, an improvement in response to hidden failures was evident during faults on the HV buses and in generator windings. However, for faults on the main motor feeders system performance is degraded. This is an unintentional consequence of opening a bustie breaker. With all three generators online and all busties closed the fault current contribution of any single generator is less than if any bustie is open. By opening a bustie breaker the fault current contribution is limited to one or two generators, depending on which bustie is closed. As a result, the fault current contributions from the generators on the bus with the fault, will be higher than if all three generators were online. This is shown in Figures 3.10, 3.11, and 3.12.

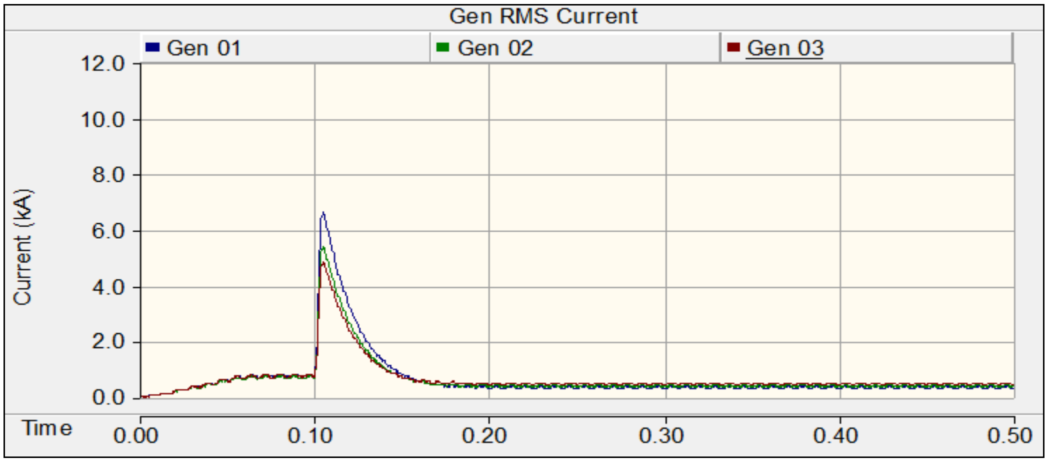

Figure 3.10: Generator current for non-bolted fault on MM 01 Feeder, busties closed, with no hidden failures present.

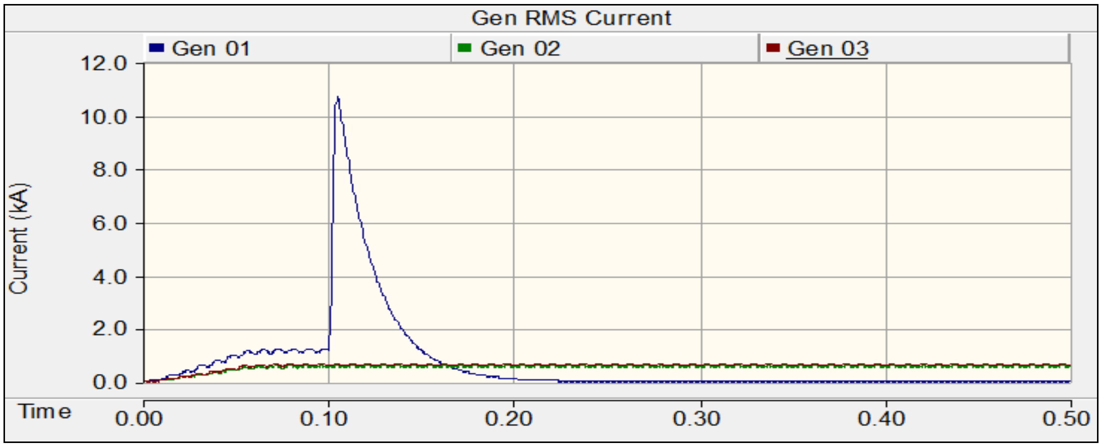

Figure 3.11: Generator current for non-bolted fault on MM 01 Feeder, bustie 12

open, with no hidden failures present.

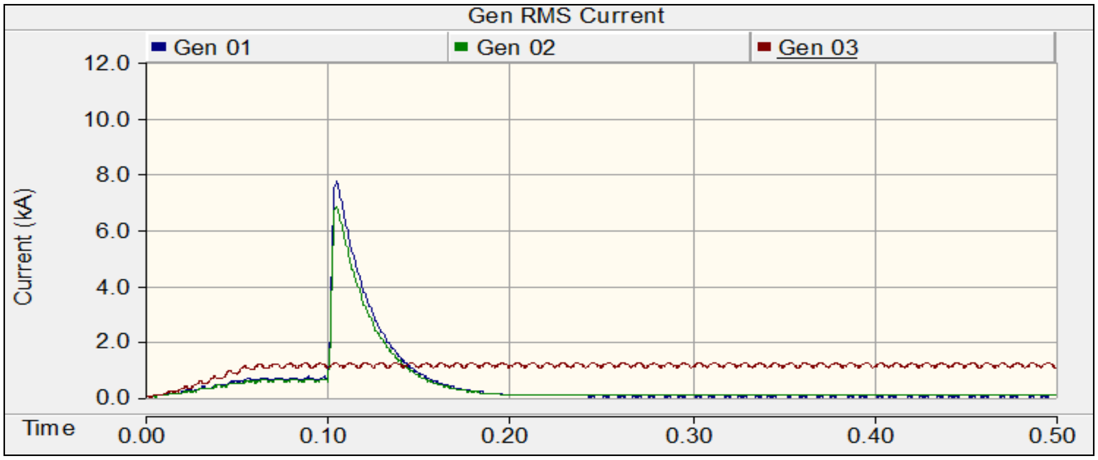

Figure 3.12: Generator current for non-bolted fault on MM 01 Feeder, bustie 23 open, with no hidden failures present.

It can be seen from the simulation results that the fault current level is approximately 33% and 15% above the TDOC trip setting for having bustie 23 and bustie 12 open, respectively. When a timer failure is present the relay will act as an instantaneous trip relay and will trip for any value above the TDOC or RP trip settings, which are approximately one third and one twentieth of the OC settings.

The second unintended consequence of opening a bustie breaker is improper operation of the RP relays. The behavior of the Gen 01 RP relay depends on which bustie breaker is open. RP relays are typically set to open if reverse power is above 33% of maximum power [13]. If bustie 12 is open and there is a hidden failure on the Gen 01 RP relay, then Gen 01 will open once the generator current reaches the RP trip setting, 1 kA, as shown in Figures 3.13 and 3.14 below.

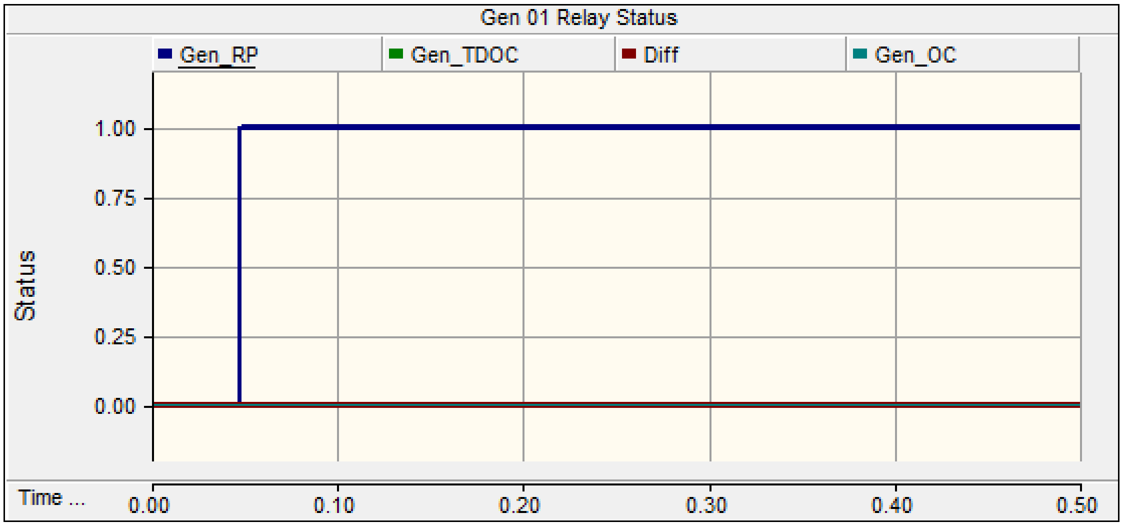

Figure 3.13: Gen 01 Response for RP Hidden Failure with bustie 12 open.

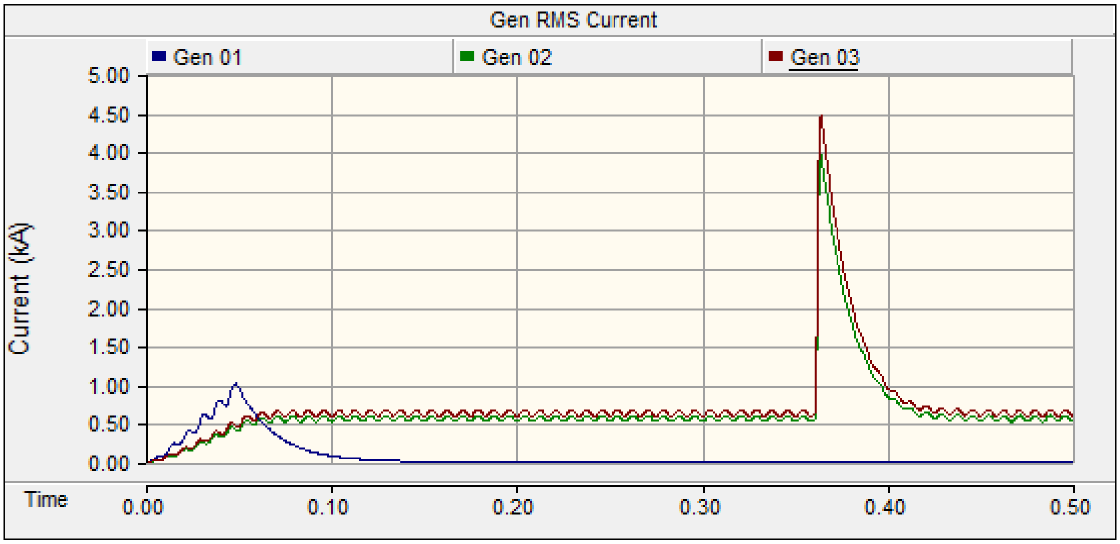

Figure 3.14: Generator Current for RP Hidden Failure and MM 01 Feeder Fault with bustie 12 open.

Figure 3.14 shows the current in Gen 01 rising and the then dropping once it exceeded 1 kA and the Gen 01 breaker opened. This is due to a timer and directional hidden failure on the RP relay. The current spike at .36 seconds is a the result of the alternate power breaker for Main Motor 01 closing, after a time delay, due to an undervoltage trip on HV Bus 1. As described in section 2-4-2-1, the main motor, TF, and MG protection will only prevent the alternative power from closing into a fault if the primary source is opened on OC, TDOC, or a differential trip.

3-3-1-1 Two Generators (1 & 3) Online:

The same cases that were run for three generators online were run for two different sets of having two generators online. The first set is for generators 01 and 03 online. The results are summarized in Tables 3.3 and 3.4.

Table 3.3: Response to bolted faults and hidden failures.

Fault Location	Gens Online	Bustie 12	Bustie 23	Ave Gen Lost	Max Gen Lost
HV #3 Bus	1,3	Closed	Closed	2	2
HV #3 Bus	1,3	Open	Closed	1	2
HV #3 Bus	1,3	Closed	Open	1	2
Gen 01 Winding	1,3	Closed	Closed	2	2
Gen 01 Winding	1,3	Open	Closed	1	1
Gen 01 Winding	1,3	Closed	Open	1	2
MM 01 Feeder	1,3	Closed	Closed	0.6	1
MM 01 Feeder	1,3	Open	Closed	0.5	1

MM 01 Feeder	1,3	Closed	Open	0.5	1

Table 4.3: Response to bolted faults and hidden failures

Table 3.4: Response to non-bolted faults and hidden failures.

Fault Location	Gens Online	Bustie 12	Bustie 23	Ave Gen Lost	Max Gen Lost
HV #3 Bus	1,3	Closed	Closed	1.3	2
HV #3 Bus	1,3	Open	Closed	1	2
HV #3 Bus	1,3	Closed	Open	1	2
Gen 01 Winding	1,3	Closed	Closed	1.3	2
Gen 01 Winding	1,3	Open	Closed	1	1
Gen 01 Winding	1,3	Closed	Open	1	1
MM 01 Feeder	1,3	Closed	Closed	0.5	1
MM 01 Feeder	1,3	Open	Closed	0.5	1
MM 01 Feeder	1,3	Closed	Open	0.3	1

Table 4.4: Response to non-bolted faults and hidden failures.

3-3-1-2 Two Generators (1 & 2) Online:

Tables 3.5 and 3.6 summary the results for the cases with only generators 1 and 2 online, and only opening bustie 12. It would not make any sense to open bustie 23, as there would then be no power on HV #3 bus. With Bustie 12 open Gen 02 will be powering both HV #2 bus and HV #3 bus.

Table 3.5: Response to bolted faults and hidden failures.

Fault Location	Gens Online	Bustie 12	Bustie 23	Ave Gen Lost	Max Gen Lost
HV #3 Bus	1,2	Closed	Closed	0.6	1
HV #3 Bus	1,2	Open	Closed	0.6	1

Gen 01 Winding	1,2	Closed	Closed	1.6	2
Gen 01 Winding	1,2	Open	Closed	1	1
MM 01 Feeder	1,2	Closed	Closed	0.6	1
MM 01 Feeder	1,2	Open	Closed	0.3	1

Table 3.6: Response to non-bolted faults and hidden failures.

Fault Location	Gens Online	Bustie 12	Bustie 23	Ave Gen Lost	Max Gen Lost
HV #3 Bus	1,2	Closed	Closed	0.6	1
HV #3 Bus	1,2	Open	Closed	0.6	1
Gen 01 Winding	1,2	Closed	Closed	1.3	2
Gen 01 Winding	1,2	Open	Closed	1	1
MM 01 Feeder	1,2	Closed	Closed	0.6	1
MM 01 Feeder	1,2	Open	Closed	0.3	1

The response of both models, with two generators online, follow the same trend as the model with three generators online; improvement was seen in the cases with faults on HV #3 bus and in Gen 01 windings. However, response to hidden failures and faults was degraded in the case of a fault on the Main Motor Feeders. The reasons for this behavior is the same as was explained for the three generator model. Results for faults in the main motor feeders could be improved if the RP relays were disabled when an HV bus is isolated and only one generator is on the bus.

3-4 Adaptive Protection Scheme:

When an HV bus is isolated and only one generator is providing power to that bus, reverse power protection is not needed as there is no source to backfeed, or “motor” the generator. This can be implemented through the use of the very simple adaptive protection scheme of disarming the RP relay when only one generator is on an isolated bus.

To test this theory, the protection for Gen 01 was modified to include an input for the status of Busties 12 and 23 and Gen 01. Using these three inputs the RP relay for Gen 01 will be disarmed for two situations: 1) Bustie 12 is open and 2) Bustie 23 is open and Gen 02 breaker is open. In both of these cases, only one generator is providing power for HV #1 bus. Figure 3.15 shows the control logic for this scheme. For maximum security, the control for the RP relay could be programmed or designed in such a way that a loss of a control signal would result in the RP relay disarming.

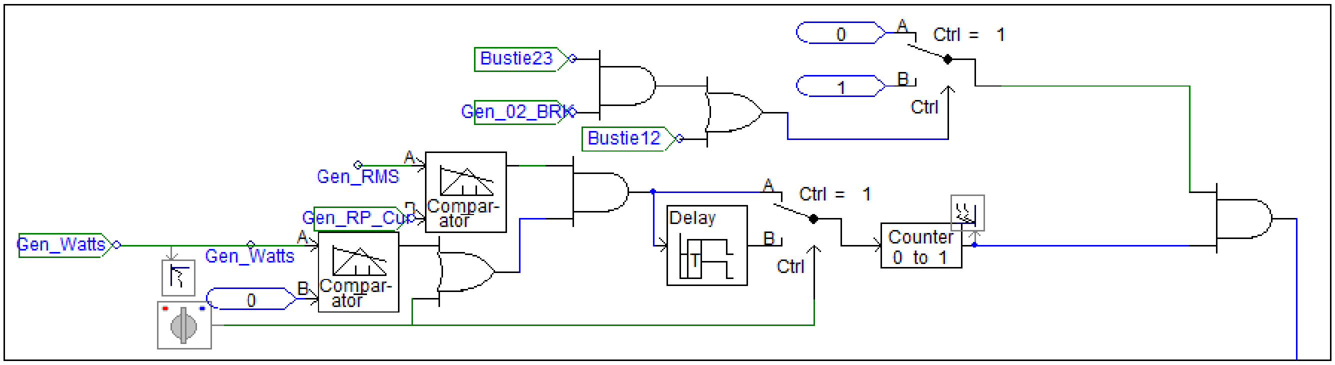

Figure 3.15: Adaptive Control Scheme for RP Relay

To test this scheme, the cases of hidden failures and faults in the Main Motor 01 feeders were retested. The results are summarized in Tables 3.7, 3.8 and 3.9, where it can be seen that for each set of simulations system response to a fault improved or remained the same. Full results are presented in Appendix C. The improvement can be attributed to removing the RP relay from service when only one generator is connected to a bus. When more than one generator is connected to a bus, hidden failures in RP relays will still result in the loss of a generator. The adaptive scheme for RP relays did not change the effect of loss of timer hidden failures for TDOC relays.

Table 3.7 Response Summary for non-bolted faults and hidden failures with an adaptive RP relay.

Fault Location	Gens Online	Bustie 12	Bustie 23	Ave Gen Lost	Δ	Max Gen Lost
MM 01 Feeder	1,2,3	Closed	Closed	0.3	-0.2	1
MM 01 Feeder	1,2,3	Open	Closed	0.3	-0.2	1
MM 01 Feeder	1,2,3	Closed	Open	0.3	0	1

Table 3.8 Response Summary for non-bolted faults and hidden failures with an

adaptive RP relay.

Fault Location	Gens Online	Bustie 12	Bustie 23	Ave Gen Lost	Δ	Max Gen Lost
MM 01 Feeder	1,3	Closed	Closed	0.5	0	1
MM 01 Feeder	1,3	Open	Closed	0.17	-0.33	1
MM 01 Feeder	1,3	Closed	Open	0.17	-0.13	1

Table 3.9 Response Summary for non-bolted faults and hidden failures with an adaptive RP relay.

Fault Location	Gens Online	Bustie 12	Bustie 23	Ave Gen Lost	Δ	Max Gen Lost
MM 01 Feeder	1,3	Closed	Closed	0.6	0	1
MM 01 Feeder	1,3	Open	Closed	0.17	-0.17	1

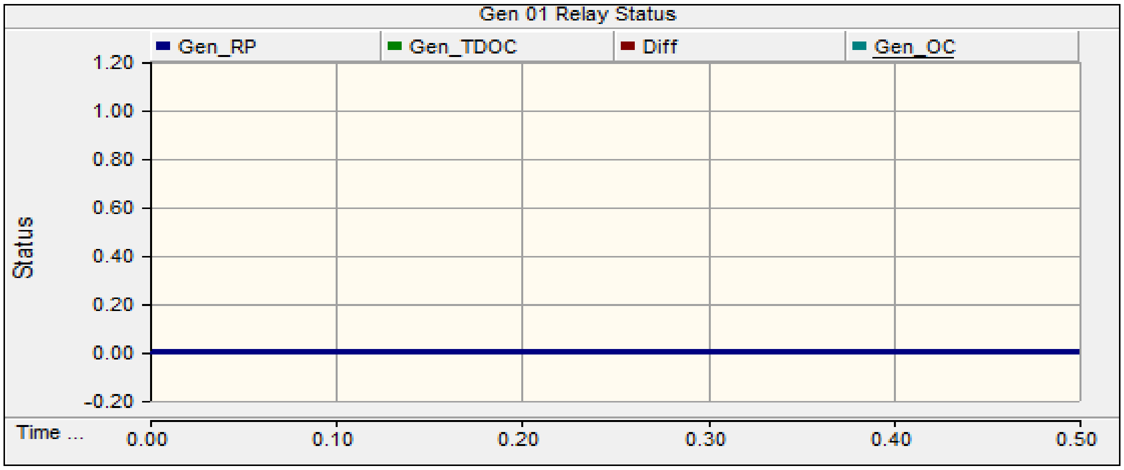

Figure 3.16: Gen 01 Response for RP Hidden Failure with a fault on MM 01 Feeder, with an adaptive protection scheme.

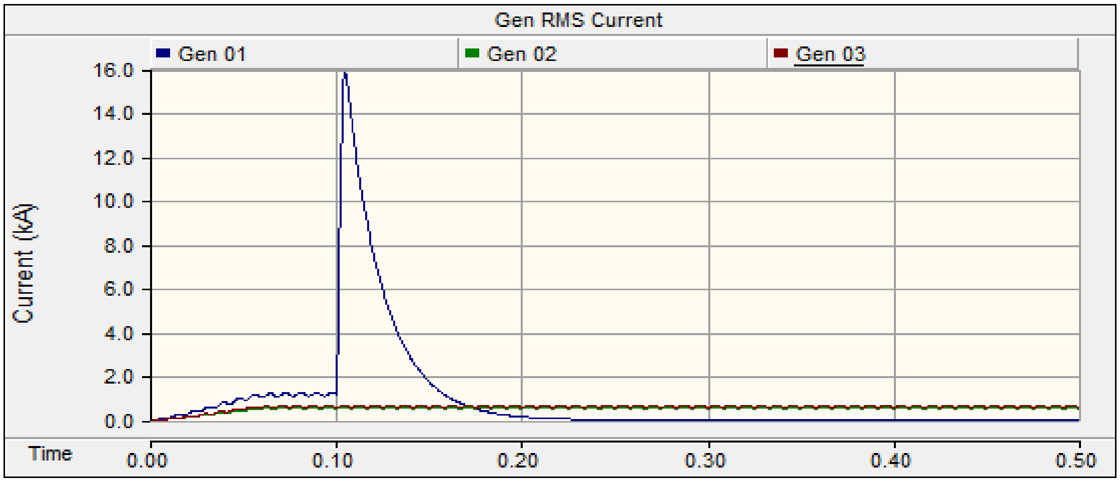

Figure 3.17: Gen 01 Current for RP Hidden Failure with a fault on MM 01 Feeder, with an adaptive protection scheme.

By reducing the number of generators lost, the RP adaptive protection scheme allowed the OC to operate correctly by opening before any other protective device operated. As a result, the Main Motor 01 alternate power breaker would not close into a fault; thus, preventing the opportunity for additional damage. Additionally, as the Gen 01 is still providing power to HV Bus #1, Main Motor #2 still has an alternative source of power. The same results should be seen for the cases with bolted faults.

Chapter 4: Recommendations and Further Work:

4-1 Recommendations

Two recommendations can be made based on the findings of this work:

1) Configuring the system with one bustie breaker open can provide additional security to the power system and
2) An adaptive protection scheme can be used to eliminate the effect of some hidden failures.

The summary of results shows that configuring the HV buses with an open bustie breaker prior to any damage, or faults, will result in more generators remaining online and able to handle the ship's loads. Without an adaptive protection scheme in the simulated cases, only six of the 208 cases ran showed a negative effect, i.e. additional loss of a generator, by opening a bustie breaker. There was no negative effect of the combination of opening a bustie breaker and implementing an adaptive scheme. The decision on which bustie breakers to open must be based on the reliability of each individual generator and prime mover combination. It would be wise to pair the weakest and strongest generator/prime mover combinations together so that the stronger of the two units can provide a crutch for the weaker unit.

Using this different configuration to reduce the region of vulnerability has the benefit of simplicity in that no software or hardware changes are required. A full analysis of the specific ship system would be required to best determine which configurations would be the most advantageous to implement. Once a study of an individual ship's electrical plant is completed, implementation of this protection would be as simple as updating the ship's engineering doctrine.

The trade off for this configuration is that power sharing between HV buses will be limited. With one of the bustie ties closed, one bus will be powered by only one generator. Therefore, use of this configuration should be evaluated based on the operational situation. In cases where the ship is not at full power, such as cruising, mooring, or drifting, this configuration would provide additional security. However, if full power is needed for long periods, this configuration may not be the best. Another option may be to open both busties and idle generator 02. A fault would be contained to a single HV bus. Once a fault was identified, HV Bus 2 could be closed to the unaffected bus, thus providing full propulsion power.

Additional security can be gained through the use of a simple adaptive protection scheme. The small number of buses and close physical proximity lends itself well to this type of system. A brief test of adaptive protection was shown with the generator RP relay being disabled when not needed. An adaptive system could be designed using either hardware, software, or both. The relatively small physical size and low number of buses and components would allow for complete modeling of the system, to the point of modeling almost every possible fault location and configuration combinations, and providing a more in-depth adaptive protection system.

4-2 Future Work:

This work could be improved by

1) real world validation of the model through use of actual data, system architecture and component values,
2) full analysis of the model to determine the effect of opening both HV Busties and LV Busties on the low voltage system, and
3) investigation of an adaptive scheme for TDOC and differential relay to prevent the occurrence of hidden failures.

It has been shown that reconfiguring the high voltage system has a positive effect of reducing the unneeded loss of generators in this model. However, there are many types of shipboard electrical propulsion systems in use that were not considered in this work.

The effects on the low voltage system were not considered. However, it can be assumed the effects would be positive in that preventing the unneeded loss of generators results in more sources of power. Reference [5] requires low voltage systems to be segregated under certain critical conditions. This requirement should be evaluated for its effectiveness in reducing the region of vulnerability for hidden failures.

An adaptive protection scheme may be developed for preventing hidden failures in TDOC and differential relays. Developing the scheme for RP relays was based on the whether the RP was needed in a given configuration. However, TDOC relays are needed in all configurations so they can not simply be disabled. Changing the trip setting or the characteristic curves may reduce their tripping in the presence of a timer failure. Further options could include fault location detection algorithms or voting schemes to prevent unneeded tripping. Any options selected should require as little supporting hardware or software to keep the risk of failures as small as possible.

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Appendix A: TDOC characteristic curves:

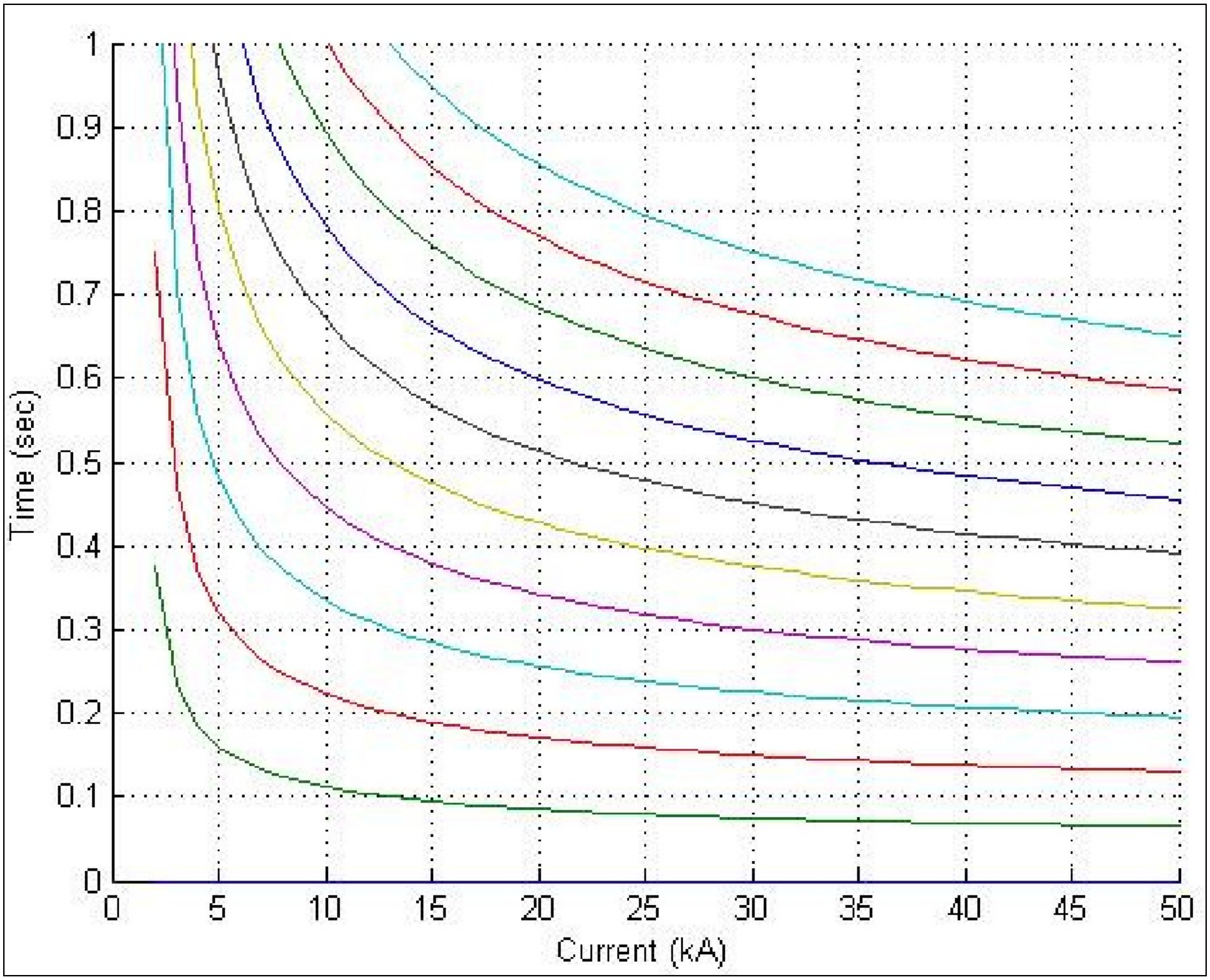

Figure A.1 Characteristic Curves for TDOC for Generators and Busties.

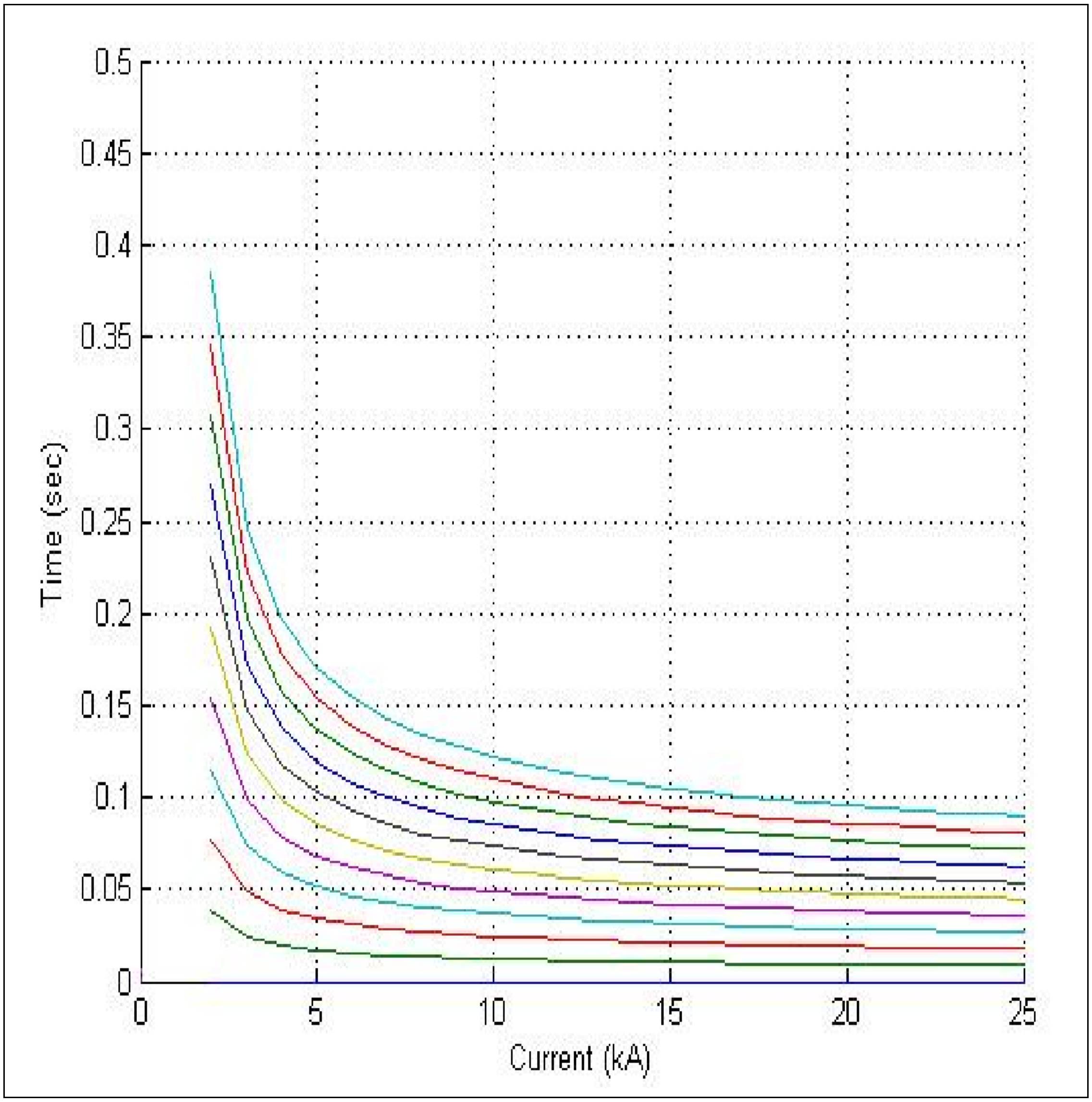

Figure A.2 Characteristic Curves for TDOC for Main Motors, TFs, MGs.

Appendix B Results:

The results of the 208 cases are shown on the following pages. There are 4 sets of 3 tests for having all 3 generators online and 2 set of 4 sets of 2 tests for 2 generators online.

The results section lists the breakers that operated during the test in chronological order of operation. Where two breakers are listed side by side, MM01/MM01a Open, the breakers operated at the same time. This notation was used to help provide more readable results.

Condition	Fault = .01	Gen's Online	1, 2, 3
Bustie 12	Closed	Bustie 23	Closed
Fault Location	BRKs of Interest	Status	Result
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 01	Oper Oper Oper Oper	Bustie 23 Open Gen 03 Open
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 01	Oper Oper Oper TD/RP Fail	Bustie 23 Open Gen 01 Open Gen 03 Open (Note 1)
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 01	Oper Oper Oper Diff Fail	Bustie 23 Open Gen 03 Open
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 02	Oper Oper Oper TD/RP Fail	Bustie 23 Open Gen 02 Open Gen 03 Open
Gen 01 Windings	Gen 01	Oper	Bustie 12 Open Gen 01 Open MM 01 Open MM 01a Close
Gen 01 Windings	Gen 01 Gen 02	Oper TD/RP Fail	Gen 02 Open Bustie 12 Open Gen 01 Open MM 01 Open MM 01a Close
Gen 01 Windings	Gen 01 Gen 03	Oper TD/RP Fail	Gen 03 Open Bustie 12 Open Gen 01 Open MM 01 Open MM 01a Close
Gen 01 Windings	Gen 01 Gen 03	Oper Diff Fail	Gen 03 Open Bustie 12 Open Gen 01 Open MM 01 Open MM 01a Close
MM 01 Feeder	MM 01	Oper	MM01/MM01a Open Bustie 12 Open (Note 2)
MM 01 Feeder	MM 01 Gen 01	Oper TD/RP Fail	MM01/MM01a Open Gen 01 Open Bustie 12 Open (Note 2)
MM 01 Feeder	MM 01 Gen 01	Oper Diff Fail	MM01/MM01a Open Bustie 12 Open Gen 01 Open

			(Note 2)
MM 01 Feeder	MM01 Gen 03	Oper TD/RP Fail	MM01/MM01a Open Bustie 12 Open Gen 03 Open

Condition	Fault = .01	Gen's Online	1, 2, 3
Bustie 12	Open	Bustie 23	Closed
Fault Location	BRKs of Interest	Status	Result
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 01	Oper Oper Oper Oper	Bustie 23 Open Gen 03 Open
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 01	Oper Oper Oper TD/RP Fail	Bustie 23 Open Gen 03 Open
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 01	Oper Oper Oper Diff Fail	Bustie 23 Open Gen 03 Open
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 02	Oper Oper Oper TD/RP Fail	Gen 02 Open Gen 03 Open (Note 1)
Gen 01 Windings	Gen 01	Oper	Gen 01 Open MM 01 Open MM 01a Close
Gen 01 Windings	Gen 01 Gen 02	Oper TD/RP Fail	Gen 01 Open MM 01 Open MM 01a Close
Gen 01 Windings	Gen 01 Gen 03	Oper TD/RP Fail	Gen 01 Open MM 01 Open MM 01a Close
Gen 01 Windings	Gen 01 Gen 03	Oper Diff Fail	MM01/MM01a Open
MM 01 Feeder	MM 01	Oper	MM01/MM01a Open
MM 01 Feeder	MM 01 Gen 01	Oper TD/RP Fail	MM01/MM01a Open Gen 01 Open (Note 2)
MM 01 Feeder	MM 01	Oper	MM01/MM01a Open

Condition	Fault = .01	Gen's Online	1, 2, 3
	Gen 01	Diff Fail	Gen 01 Open (Note 2)
MM 01 Feeder	MM01 Gen 03	Oper TD/RP Fail	MM01/MM01a Open Gen 01 Open (Note 2) (Note 3)

Condition	Fault = .01	Gen's Online	1, 2, 3
Bustie 12	Closed	Bustie 23	Open
Fault Location	BRKs of Interest	Status	Result
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 01	Oper Oper Oper Oper	Gen 03 Open
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 01	Oper Oper Oper TD/RP Fail	Gen 03 Open
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 01	Oper Oper Oper Diff Fail	Gen 03 Open
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 02	Oper Oper Oper TD/RP Fail	Gen 03 Open (Note 2)
Gen 01 Windings	Gen 01	Oper	Gen 01 Open
Gen 01 Windings	Gen 01 Gen 02	Oper TD/RP Fail	Gen 02 Open Gen 01 Open MM 01 Open MM 01a Close BT Open
Gen 01 Windings	Gen 01 Gen 03	Oper TD/RP Fail	Gen 01 Open
Gen 01 Windings	Gen 01 Gen 03	Oper Diff Fail	Gen 01 Open
MM 01 Feeder	MM 01	Oper	MM01/MM01a Open
MM 01 Feeder	MM 01	Oper	MM01/MM01a Open

Condition	Fault = .01	Gen's Online	1, 2, 3
	Gen 01	TD/RP Fail	Gen 01 Open
MM 01 Feeder	MM 01 Gen 01	Oper Diff Fail	MM01/MM01a Open Gen 01 Open
MM 01 Feeder	MM01 Gen 03	Oper TD/RP Fail	MM01/MM01a Open Gen 01 Open (Note 2) (Note 3)

Condition	Fault = .1	Gen's Online	1, 2, 3
Bustie 12	Closed	Bustie 23	Closed
Fault Location	BRKs of Interest	Status	Result
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 01	Oper Oper Oper Oper	Bustie 23 Open Gen 03 Open
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 01	Oper Oper Oper TD/RP Fail	Bustie 23 Open Gen 01 Open Gen 03 Open (Note 1)
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 01	Oper Oper Oper Diff Fail	Bustie 23 Open Gen 03 Open (Notes 4)
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 02	Oper Oper Oper TD/RP Fail	Gen 02 Open Bustie 23 Open Gen 03 Open (Notes 5)
Gen 01 Windings	Gen 01	Oper	Bustie 12 Open Gen 01 Open
Gen 01 Windings	Gen 01 Gen 02	Oper TD/RP Fail	Gen 02 Open Gen 01 Open MM 01 Open MM 01a Close
Gen 01 Windings	Gen 01 Gen 03	Oper TD/RP Fail	Bustie 12 Open Gen 03 Open Gen 01 Open MM 01 Open MM 01a Close
Gen 01 Windings	Gen 01 Gen 03	Oper Diff Fail	Bustie 12 Open Gen 03 Open Gen 01 Open

			MM 01 Open MM 01a Close
MM 01 Feeder	MM 01	Oper	MM01/MM01a Open
MM 01 Feeder	MM 01 Gen 01	Oper TD Fail	MM01/MM01a Open
MM 01 Feeder	MM 01 Gen 01	Oper RP Fail	MM01/MM01a Open Gen 01 Open
MM 01 Feeder	MM 01 Gen 01	Oper Diff Fail	MM01/MM01a Open
MM 01 Feeder	MM01 Gen 03	Oper TD Fail	MM01/MM01a Open
MM 01 Feeder	MM01 Gen 03	Oper RP Fail	MM01/MM01a Open Gen 03 Open

Condition	Fault = .1	Gen's Online	1, 2, 3
Bustie 12	Open	Bustie 23	Closed
Fault Location	BRKs of Interest	Status	Result
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 01	Oper Oper Oper Oper	Bustie 23 Open Gen 03 Open
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 01	Oper Oper Oper TD/RP Fail	Bustie 23 Open Gen 03 Open
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 01	Oper Oper Oper Diff Fail	Bustie 23 Open Gen 03 Open
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 02	Oper Oper Oper TD/RP Fail	Gen 02 Open Gen 03 Open (Note 2)
Gen 01 Windings	Gen 01	Oper	Gen 01 Open MM 01 Open MM 01a Close
Gen 01 Windings	Gen 01 Gen 02	Oper TD/RP Fail	Gen 01 Open MM 01 Open MM 01a Close
Gen 01 Windings	Gen 01 Gen 03	Oper TD/RP Fail	Gen 01 Open MM 01 Open MM 01a Close

Gen 01 Windings	Gen 01 Gen 03	Oper Diff Fail	Gen 01 Open MM 01 Open MM 01a Close
MM 01 Feeder	MM 01	Oper	MM01/MM01a Open
MM 01 Feeder	MM 01 Gen 01	Oper TD Fail	MM01/MM01a Open Gen 01 Open
MM 01 Feeder	MM 01 Gen 01	Oper RP Fail	MM01/MM01a Open Gen 01 Open
MM 01 Feeder	MM 01 Gen 01	Oper Diff Fail	MM01/MM01a Open
MM 01 Feeder	MM01 Gen 03	Oper TD Fail	MM01/MM01a Open
MM 01 Feeder	MM01 Gen 03	Oper RP Fail	MM01/MM01a Open

Condition	Fault = .1	Gen's Online	1, 2, 3
Bustie 12	Closed	Bustie 23	Open
Fault Location	BRKs of Interest	Status	Result
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 01	Oper Oper Oper Oper	Bustie 23 Open Gen 03 Open
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 01	Oper Oper Oper TD/RP Fail	Bustie 23 Open Gen 03 Open
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 01	Oper Oper Oper Diff Fail	Bustie 23 Open Gen 03 Open
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 02	Oper Oper Oper TD/RP Fail	Gen 02 Open Gen 03 Open
Gen 01 Windings	Gen 01	Oper	Gen 01 Open MM 01 Open MM 01a Close
Gen 01 Windings	Gen 01 Gen 02	Oper TD/RP Fail	Gen 01 Open Gen 02 Open MM 01 Open MM 01a Close

			MM 01a Open
Gen 01 Windings	Gen 01 Gen 03	Oper TD/RP Fail	Gen 01 Open
Gen 01 Windings	Gen 01 Gen 03	Oper Diff Fail	Gen 01 Open
MM 01 Feeder	MM 01	Oper	MM01/MM01a Open
MM 01 Feeder	MM 01 Gen 01	Oper TD Fail	MM01/MM01a Open Gen 01 Open
MM 01 Feeder	MM 01 Gen 01	Oper RP Fail	MM01/MM01a Open Gen 01 Open
MM 01 Feeder	MM 01 Gen 01	Oper RP Fail	MM01/MM01a Open Gen 01 Open
MM 01 Feeder	MM01 Gen 03	Oper TD Fail	MM01/MM01a Open
MM 01 Feeder	MM01 Gen 03	Oper RP Fail	MM01/MM01a Open Gen 03 Open

Two Generators:

Ships will not be running all three generators all the time. They will only run all three when max power, or security, is needed.

Condition	Fault = .01	Gen's Online	1, 3
Bustie 12	Closed	Bustie 23	Closed
Fault Location	BRKs of Interest	Status	Result
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 01	Oper Oper Oper Oper	Bustie 23 Open Bustie 12 Open Gen 03 Open BT Open
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 01	Oper Oper Oper TD/RP Fail	Gen 01 Open Gen 03 Open BT Open MM1/MM2 Open MM1a/MM2a Open
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 01	Oper Oper Oper Diff Fail	Gen 01 Open Gen 03 Open BT Open MM1/MM2 Open MM1a/MM2a Open
Gen 01 Windings	Gen 01	Oper	Gen 01 Open
Gen 01 Windings	Gen 01 Gen 03	Oper TD/RP Fail	Gen 03 Open Gen 01 Open MM 01 Open BT Open MM 02 Open MM 01a Close MM 01a Open MM 02a Close MM 02a Open
Gen 01 Windings	Gen 01 Gen 03	Oper Diff Fail	Gen 03 Open Gen 01 Open MM 01 Open BT Open MM 02 Open MM 01a Close MM 01a Open MM 02a Close MM 02a Open
MM 01 Feeder	MM 01	Oper	MM01/MM01a Open
MM 01 Feeder	MM 01 Gen 01	Oper TD Fail	MM01/MM01a Open Gen 01 Open
MM 01 Feeder	MM01 Gen 03	Oper RP Fail	MM01/MM01a Open Gen 01 Open
MM 01 Feeder	MM 01 Gen 01	Oper Diff Fail	MM01/MM01a Open
MM 01 Feeder	MM01 Gen 03	Oper TD Fail	Gen 03 Open MM01/MM01a Open
MM 01 Feeder	MM01	Oper	Gen 03 Open

	Gen 03	RP Fail	MM01/MM01a Open

Condition	Fault = .01	Gen's Online	1, 3
Bustie 12	Open	Bustie 23	Closed
Fault Location	BRKs of Interest	Status	Result
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 01	Oper Oper Oper Oper	Gen 03 Open
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 01	Oper Oper Oper TD/RP Fail	Gen 03 Open BT Open
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 01	Oper Oper Oper Diff Fail	Gen 03 Open BT Open
Gen 01 Windings	Gen 01	Oper	Gen 01 Open MM 01 Open MM 01a Close MM 01a Open
Gen 01 Windings	Gen 01 Gen 03	Oper TD/RP Fail	Gen 01 Open MM 01 Open MM 01a Close MM 01a Open
Gen 01 Windings	Gen 01 Gen 03	Oper Diff Fail	Gen 01 Open MM 01 Open MM 01a Close MM 01a Open
MM 01 Feeder	MM 01	Oper	MM01/MM01a Open
MM 01 Feeder	MM 01 Gen 01	Oper TD Fail	MM01/MM01a Open Gen 01 Open
MM 01 Feeder	MM01 Gen 03	Oper RP Fail	MM01/MM01a Open Gen 01 Open
MM 01 Feeder	MM 01 Gen 01	Oper Diff Fail	MM01/MM01a Open Gen 01 Open
MM 01 Feeder	MM01 Gen 03	Oper TD Fail	MM01/MM01a Open
MM 01 Feeder	MM01 Gen 03	Oper RP Fail	MM01/MM01a Open

Condition	Fault = .01	Gen's Online	1, 3
Bustie 12	Closed	Bustie 23	Open
Fault Location	BRKs of Interest	Status	Result
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 01	Oper Oper Oper Oper	Gen 03 Open
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 01	Oper Oper Oper TD/RP Fail	Gen 03 Open
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 01	Oper Oper Oper Diff Fail	Gen 03 Open
Gen 01 Windings	Gen 01	Oper	Gen 01 Open MM 01 Open MM 01a Close
Gen 01 Windings	Gen 01 Gen 03	Oper TD/RP Fail	Gen 01 Open MM 01 Open MM 01a Close MM 01a Open
Gen 01 Windings	Gen 01 Gen 03	Oper Diff Fail	Gen 01 Open MM 01 Open MM 01a Close MM 01a Open
MM 01 Feeder	MM 01	Oper	MM01/MM01a Open
MM 01 Feeder	MM 01 Gen 01	Oper TD Fail	MM01/MM01a Open Gen 01 Open
MM 01 Feeder	MM01 Gen 03	Oper RP Fail	MM01/MM01a Open Gen 01 Open
MM 01 Feeder	MM 01 Gen 01	Oper Diff Fail	MM01/M01a Open Gen 01 Open
MM 01 Feeder	MM01 Gen 03	Oper TD Fail	MM01/MM01a Open
MM 01 Feeder	MM01 Gen 03	Oper RP Fail	MM01/MM01a Open

Condition	Fault = .1	Gen's Online	1, 3
Bustie 12	Closed	Bustie 23	Closed
Fault Location	BRKs of Interest	Status	Result
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 01	Oper Oper Oper Oper	Bustie 23 Open Bustie 12 Open Gen 03 Open BT Open
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 01	Oper Oper Oper TD/RP Fail	Gen 01 Open Gen 03 Open BT Open MM1/MM2 Open MM1a/MM2a Open
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 01	Oper Oper Oper Diff Fail	Bustie 23 Open Bustie 12 Open BT Open Gen 03 Open
Gen 01 Windings	Gen 01	Oper	Gen 01 Open
Gen 01 Windings	Gen 01 Gen 03	Oper TD/RP Fail	Gen 01 Open MM 01 Open MM 01a Close MM 01a Open
Gen 01 Windings	Gen 01 Gen 03	Oper Diff Fail	Gen 03 Open Gen 01 Open MM 01 Open MM 02 Open MM 01a Close MM 01a Open MM 02a Close MM 02a Open
MM 01 Feeder	MM 01	Oper	MM01/MM01a Open
MM 01 Feeder	MM 01 Gen 01	Oper TD Fail	MM01/MM01a Open Gen 01 Open
MM 01 Feeder	MM01 Gen 03	Oper RP Fail	Gen 01 Open MM01/MM01a Open
MM 01 Feeder	MM 01	Oper	MM01/MM01a Open

	Gen 01	Diff Fail	
MM 01 Feeder	MM01 Gen 03	Oper TD Fail	MM01/MM01a Open
MM 01 Feeder	MM01 Gen 03	Oper RP Fail	Gen 03 Open MM01/MM01a Open

Condition	Fault = .1	Gen's Online	1, 3
Bustie 12	Open	Bustie 23	Closed
Fault Location	BRKs of Interest	Status	Result
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 01	Oper Oper Oper Oper	Gen 03 Open BT Open
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 01	Oper Oper Oper TD/RP Fail	Gen 03 Open BT Open
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 01	Oper Oper Oper Diff Fail	Gen 03 Open BT Open
Gen 01 Windings	Gen 01	Oper	Gen 01 Open MM 01 Open MM 01a Close
Gen 01 Windings	Gen 01 Gen 03	Oper TD/RP Fail	Gen 01 Open MM 01 Open MM 01a Close MM 01a Open
Gen 01 Windings	Gen 01 Gen 03	Oper Diff Fail	Gen 01 Open MM 01 Open MM 01a Close MM 01a Open
MM 01 Feeder	MM 01	Oper	MM01/MM01a Open
MM 01 Feeder	MM 01 Gen 01	Oper TD Fail	MM01/MM01a Open Gen 01 Open
MM 01 Feeder	MM01 Gen 03	Oper RP Fail	MM01/MM01a Open Gen 01 Open
MM 01 Feeder	MM 01	Oper	MM01/MM01a Open

	Gen 01	Diff Fail	
MM 01 Feeder	MM01 Gen 03	Oper TD Fail	MM01/MM01a Open
MM 01 Feeder	MM01 Gen 03	Oper RP Fail	Gen 03 Open MM01/MM01a Open

Condition	Fault = .1	Gen's Online	1, 3
Bustie 12	Closed	Bustie 23	Open
Fault Location	BRKs of Interest	Status	Result
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 01	Oper Oper Oper Oper	Gen 03 Open MM 02 Open MM 02a Close
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 01	Oper Oper Oper TD/RP Fail	Gen 03 Open MM 02 Open MM 02a Close
HV 3 Bus	Gen 03 Bustie 23 Bustie 12 Gen 01	Oper Oper Oper Diff Fail	Gen 03 Open MM 02 Open MM 02a Close
Gen 01 Windings	Gen 01	Oper	Gen 01 Open MM 01 Open MM 01a Close
Gen 01 Windings	Gen 01 Gen 03	Oper TD/RP Fail	Gen 01 Open MM 01 Open MM 01a Close
Gen 01 Windings	Gen 01 Gen 03	Oper Diff Fail	Gen 01 Open MM 01 Open MM 01a Close
MM 01 Feeder	MM 01	Oper	MM01/MM01a Open
MM 01 Feeder	MM 01 Gen 01	Oper TD Fail	MM01/MM01a Open Gen 01 Open
MM 01 Feeder	MM01 Gen 03	Oper RP Fail	MM01/MM01a Open Gen 01 Open
MM 01 Feeder	MM 01	Oper	MM01/MM01a Open

	Gen 01	Diff Fail	
MM 01 Feeder	MM01 Gen 03	Oper TD Fail	MM01/MM01a Open
MM 01 Feeder	MM01 Gen 03	Oper RP Fail	MM01/MM01a Open

Condition	Fault = .01	Gen's Online	1, 2
Bustie 12	Closed	Bustie 23	Closed
Fault Location	BRKs of Interest	Status	Result
HV 3 Bus	Bustie 23 Bustie 12 Gen 01	Oper Oper Oper	Bustie 23 Open MM 02 Open MM 02a Close
HV 3 Bus	Bustie 23 Bustie 12 Gen 01	Oper Oper TD/RP Fail	Gen 01 Open Bustie 23 MM 02 Open MM 02a Close
HV 3 Bus	Bustie 23 Bustie 12 Gen 01	Oper Oper Diff Fail	Gen 01 Open Bustie 23 MM 02 Open MM 02a Close
Gen 01 Windings	Gen 01	Oper	Gen 01 Open
Gen 01 Windings	Gen 01 Gen 02	Oper TD/RP Fail	Gen 02 Open Gen 01 Open MM 01 Open MM 02 Open MM 01a Close MM 01a Open MM 02a Close MM 02a Open
Gen 01 Windings	Gen 01 Gen 02	Oper Diff Fail	Gen 02 Open Gen 01 Open MM 01 Open MM 02 Open MM 01a Close

			MM 01a Open MM 02a Close MM 02a Open
MM 01 Feeder	MM 01	Oper	MM01/MM01a Open
MM 01 Feeder	MM 01 Gen 01	Oper TD Fail	MM01/MM01a Open Gen 01 Open
MM 01 Feeder	MM01 Gen 01	Oper RP Fail	Gen 01 Open MM01/MM01a Open
MM 01 Feeder	MM 01 Gen 01	Oper Diff Fail	MM01/MM01a Open
MM 01 Feeder	MM01 Gen 02	Oper TD Fail	Gen 02 Open MM01/MM01a Open
MM 01 Feeder	MM01 Gen 02	Oper RP Fail	Gen 02 Open MM01/MM01a Open

Condition	Fault = .01	Gen's Online	1, 2
Bustie 12	Open	Bustie 23	Closed (Note 7)
Fault Location	BRKs of Interest	Status	Result
HV 3 Bus	Bustie 23 Bustie 12 Gen 01	Oper Oper Oper	Bustie 23 Open MM 02 Open MM 02a Close
HV 3 Bus	Bustie 23 Bustie 12 Gen 01	Oper Oper TD/RP Fail	Gen 01 Open Bustie 23 MM 02 Open MM 02a Close
HV 3 Bus	Bustie 23 Bustie 12 Gen 01	Oper Oper Diff Fail	Gen 01 Open Bustie 23 MM 02 Open MM 02a Close
Gen 01 Windings	Gen 01	Oper	Gen 01 Open MM 01 Open MM 01a Close
Gen 01 Windings	Gen 01 Gen 02	Oper TD/RP Fail	Gen 01 Open MM 01 Open MM 01a Close
Gen 01 Windings	Gen 01 Gen 02	Oper Diff Fail	Gen 01 Open MM 01 Open MM 01a Close
MM 01 Feeder	MM 01	Oper	MM01/MM01a Open
MM 01 Feeder	MM 01	Oper	Gen 01 Open

	Gen 01	TD Fail	MM01/MM01a Open
MM 01 Feeder	MM01 Gen 01	Oper RP Fail	Gen 01 Open MM01/MM01a Open
MM 01 Feeder	MM 01 Gen 01	Oper Diff Fail	MM01/MM01a Open
MM 01 Feeder	MM01 Gen 02	Oper TD Fail	MM01/MM01a Open
MM 01 Feeder	MM01 Gen 02	Oper RP Fail	MM01/MM01a Open

Condition	Fault = .1	Gen's Online	1, 2
Bustie 12	Closed	Bustie 23	Closed
Fault Location	BRKs of Interest	Status	Result
HV 3 Bus	Bustie 23 Bustie 12 Gen 01	Oper Oper Oper	Bustie 23 Open MM 02 Open MM 02a Close
HV 3 Bus	Bustie 23 Bustie 12 Gen 01	Oper Oper TD/RP Fail	Gen 01 Open Bustie 23 MM 02 Open MM 02a Close
HV 3 Bus	Bustie 23 Bustie 12 Gen 01	Oper Oper Diff Fail	
Gen 01 Windings	Gen 01	Oper	Gen 01 Open
Gen 01 Windings	Gen 01 Gen 02	Oper TD/RP Fail	Gen 02 Open Gen 01 Open MM 01 Open MM 02 Open MM 01a Close MM 01a Open MM 02a Close MM 02a Open
Gen 01 Windings	Gen 01	Oper	Gen 02 Open

	Gen 02	Diff Fail	Gen 01 Open MM 01 Open MM 02 Open MM 01a Close MM 01a Open MM 02a Close MM 02a Open
MM 01 Feeder	MM 01	Oper	MM01/MM01a Open
MM 01 Feeder	MM 01 Gen 01	Oper TD Fail	MM01/MM01a Open Gen 01 Open
MM 01 Feeder	MM01 Gen 01	Oper RP Fail	Gen 01 Open MM01/MM01a Open
MM 01 Feeder	MM 01 Gen 01	Oper Diff Fail	MM01/MM01a Open
MM 01 Feeder	MM01 Gen 02	Oper TD Fail	Gen 02 Open MM01/MM01a Open
MM 01 Feeder	MM01 Gen 02	Oper RP Fail	Gen 03 Open MM01/MM01a Open

Condition	Fault = .1	Gen's Online	1, 2
Bustie 12	Open	Bustie 23	Closed
Fault Location	BRKs of Interest	Status	Result
HV 3 Bus	Bustie 23 Bustie 12 Gen 01	Oper Oper Oper	Bustie 23 Open MM 02 Open MM 02a Close
HV 3 Bus	Bustie 23 Bustie 12 Gen 01	Oper Oper TD/RP Fail	Bustie 23 MM 02 Open MM 02a Close
HV 3 Bus	Bustie 23 Bustie 12 Gen 01	Oper Oper Diff Fail	Bustie 23 MM 02 Open MM 02a Close
Gen 01 Windings	Gen 01	Oper	Gen 01 Open MM 01 Open MM 01a Close
Gen 01 Windings	Gen 01 Gen 02	Oper TD/RP Fail	Gen 01 Open MM 01 Open MM 01a Close
Gen 01 Windings	Gen 01 Gen 02	Oper Diff Fail	Gen 01 Open MM 01 Open

			MM 01a Close
MM 01 Feeder	MM 01	Oper	MM01/MM01a Open
MM 01 Feeder	MM 01 Gen 01	Oper TD Fail	MM01/MM01a Open Gen 01 Open
MM 01 Feeder	MM01 Gen 01	Oper RP Fail	MM01/MM01a Open Gen 01 Open
MM 01 Feeder	MM 01 Gen 01	Oper Diff Fail	MM01/MM01a Open
MM 01 Feeder	MM01 Gen 02	Oper TD Fail	MM01/MM01a Open
MM 01 Feeder	MM01 Gen 02	Oper RP Fail	MM01/MM01a Open

Note 1) If a timer failure is present on a generator TDOC or RP relay, they will trip before OC relay trips. This is because the trip level of the TDOC or RP relay, 7 kA or 1kA, respectively, is less than that of the OC trip, 20 kA.

Note 2) Busties and generators may open on for faults on the feeders. This is due to low, almost non-existent, impedance between the feeder faults and busties and generators. The result is very little change in fault current making overcurrent coordination impossible.

Note 3) When one bustie is open a maximum of two generators can contribute to fault current, instead of three generators when both busties are closed. This raises the fault contribution of a generator above the generator OC trip level.

Note 4) Differential relay hidden failures present themselves at various levels of current. In this case, the difference between the differential and restraint currents was not enough to indicate a trip.

Notes 5) Bustie 23 trips on TDOC. The trip for this case takes longer that the case with a TD failure of Gen 01. This is because the of the additional impedance, Bustie 12 breaker, which reduces the current in Bustie 23 below the OC trip level.

Note 6) Gen 03 did not open because Bustie 12 prevented Gen 03 from contributing to the fault.

Note 7): In this configuration only Bustie 12 can be opened. If Bustie 23 is open no power will be supplied to HV #3 bus.

Appendix C Adaptive Protection Results

The results of the 48 cases where adaptive protection was tested are shown on the following pages. There are 8 sets of simulations, each with 6 different simulations for various configuration and hidden failure configurations.

The results section lists the breakers that operated during the test in chronological order of operation. Where two breakers are listed side by side, MM01/MM01a Open, the breakers operated at the same time. This notation was used to help provide more readable results.

Generators 1, 2, and 3 Online.

Condition	Fault = .1	Gen's Online	1, 2, 3
Bustie 12	Closed	Bustie 23	Closed
Fault Location	BRKs of Interest	Status	Result
MM 01 Feeder	MM 01	Oper	MM01/MM01a Open Bustie 12 Open
MM 01 Feeder	MM 01 Gen 01	Oper TD Fail	MM01/MM01a Open Bustie 12 Open
MM 01 Feeder	MM01 Gen 01	Oper RP Faill	MM01/MM01a Open Bustie 12 Open Gen 01 Open
MM 01 Feeder	MM 01 Gen 01	Oper Diff Fail	MM01/MM01a Open Bustie 12 Open
MM 01 Feeder	MM01 Gen 03	Oper TD Faill	MM01/MM01a Open Bustie 12 Open
MM 01 Feeder	MM01 Gen 03	Oper RP Faill	MM01/MM01a Open Bustie 12 Open Gen 03 Open

Condition	Fault = .1	Gen's Online	1, 2, 3
Bustie 12	Open	Bustie 23	Closed
Fault Location	BRKs of Interest	Status	Result
MM 01 Feeder	MM 01	Oper	MM01/MM01a Open Bustie 12 Open
MM 01 Feeder	MM 01 Gen 01	Oper TD Fail	MM01/MM01a Open Gen 01 Open Bustie 12 Open
MM 01 Feeder	MM01 Gen 01	Oper RP Faill	MM01/MM01a Open Bustie 12 Open
MM 01 Feeder	MM 01 Gen 01	Oper Diff Fail	MM01/MM01a Open Bustie 12 Open
MM 01 Feeder	MM01 Gen 03	Oper TD Faill	MM01/MM01a Open Bustie 12 Open Gen 03 Open
MM 01 Feeder	MM01 Gen 03	Oper RP Faill	MM01/MM01a Open Bustie 12 Open

Condition	Fault = .1	Gen's Online	1, 2, 3
Bustie 12	Close	Bustie 23	Open
Fault Location	BRKs of Interest	Status	Result
MM 01 Feeder	MM 01	Oper	MM01/MM01a Open Bustie 12 Open
MM 01 Feeder	MM 01 Gen 01	Oper TD Fail	MM01/MM01a Open Gen 01 Open Bustie 12 Open
MM 01 Feeder	MM01 Gen 01	Oper RP Faill	MM01/MM01a Open Bustie 12 Open Gen 01 Open

MM 01 Feeder	MM 01 Gen 01	Oper Diff Fail	MM01/MM01a Open Bustie 12 Open
MM 01 Feeder	MM01 Gen 03	Oper TD Faill	MM01/MM01a Open Bustie 12 Open
MM 01 Feeder	MM01 Gen 03	Oper RP Faill	MM01/MM01a Open Bustie 12 Open

Generators 1 and 3 Online.

Condition	Fault = .1	Gen's Online	1, 3
Bustie 12	Closed	Bustie 23	Closed
Fault Location	BRKs of Interest	Status	Result
MM 01 Feeder	MM 01	Oper	MM01/MM01a Open
MM 01 Feeder	MM 01 Gen 01	Oper TD Fail	MM01/MM01a Open Gen 01 Open
MM 01 Feeder	MM01 Gen 03	Oper RP Fail	Gen 01 Open MM01/MM01a Open
MM 01 Feeder	MM 01 Gen 01	Oper Diff Fail	MM01/MM01a Open
MM 01 Feeder	MM01 Gen 03	Oper TD Fail	MM01/MM01a Open
MM 01 Feeder	MM01 Gen 03	Oper RP Fail	Gen 03 Open MM01/MM01a Open

Condition	Fault = .1	Gen's Online	1, 3
Bustie 12	Open	Bustie 23	Closed
Fault Location	BRKs of Interest	Status	Result
MM 01 Feeder	MM 01	Oper	MM01/MM01a Open
MM 01 Feeder	MM 01 Gen 01	Oper TD Fail	MM01/MM01a Open Gen 01 Open
MM 01 Feeder	MM01 Gen 03	Oper RP Fail	MM01/MM01a Open
MM 01 Feeder	MM 01 Gen 01	Oper Diff Fail	MM01/MM01a Open
MM 01 Feeder	MM01 Gen 03	Oper TD Fail	MM01/MM01a Open
MM 01 Feeder	MM01 Gen 03	Oper RP Fail	MM01/MM01a Open

Condition	Fault = .1	Gen's Online	1, 3
Bustie 12	Close	Bustie 23	Open
Fault Location	BRKs of Interest	Status	Result
MM 01 Feeder	MM 01	Oper	MM01/MM01a Open

MM 01 Feeder	MM 01 Gen 01	Oper TD Fail	MM01/MM01a Open Gen 01 Open
MM 01 Feeder	MM01 Gen 03	Oper RP Fail	MM01/MM01a Open
MM 01 Feeder	MM 01 Gen 01	Oper Diff Fail	MM01/MM01a Open
MM 01 Feeder	MM01 Gen 03	Oper TD Fail	MM01/MM01a Open
MM 01 Feeder	MM01 Gen 03	Oper RP Fail	MM01/MM01a Open

Generators 1 and 2 Online:

Condition	Fault = .1	Gen's Online	1, 2
Bustie 12	Closed	Bustie 23	Closed
Fault Location	BRKs of Interest	Status	Result
MM 01 Feeder	MM 01	Oper	MM01/MM01a Open
MM 01 Feeder	MM 01 Gen 01	Oper TD Fail	MM01/MM01a Open Gen 01 Open
MM 01 Feeder	MM01 Gen 01	Oper RP Fail	Gen 01 Open MM01/MM01a Open
MM 01 Feeder	MM 01 Gen 01	Oper Diff Fail	MM01/MM01a Open
MM 01 Feeder	MM01 Gen 02	Oper TD Fail	MM01/MM01a Open Gen 02 Open
MM 01 Feeder	MM01 Gen 02	Oper RP Fail	Gen 02 Open MM01/MM01a Open

Condition	Fault = .1	Gen's Online	1, 3
Bustie 12	Close	Bustie 23	Open
Fault Location	BRKs of Interest	Status	Result
MM 01 Feeder	MM 01	Oper	MM01/MM01a Open
MM 01 Feeder	MM 01 Gen 01	Oper TD Fail	MM01/MM01a Open Gen 01 Open
MM 01 Feeder	MM01 Gen 03	Oper RP Fail	MM01/MM01a Open
MM 01 Feeder	MM 01 Gen 01	Oper Diff Fail	MM01/MM01a Open
MM 01 Feeder	MM01 Gen 03	Oper TD Fail	MM01/MM01a Open
MM 01 Feeder	MM01 Gen 03	Oper RP Fail	MM01/MM01a Open