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14. ABSTRACT

This project aimed at the development of new protection and configuration management schemes for the next generation DC zonal shipboard electrical systems (DC SES). The research has demonstrated the feasibility of two new options for the protections devices. First approach uses the Voltage Source Converters, and the second approach uses the new solid-state based protection devices (SSPD) for limiting and interrupting the fault currents. Then, a new "agent" based protection scheme using these new devices has been developed for effective protection of DC SES. It has been shown that these protection agents, which are associated with protection devices, can detect and isolate the faults very fast – less than 3-4 ms.

Second part of the research has focused on the main design issues related to configuration management on DC SES after a fault, and a new scheme has been developed. The method uses the protection agents to localize the fault fast and thus assure continuity of supply to the critical loads even under battle damage conditions.

15. SUBJECT TERMS

Power Distribution, Power Electronics, Protection Devices, System Protection, Configuration Management, Agent based monitoring and control.

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Technical Section

Technical Objectives

This project aimed at conducting research towards development of new protection and configuration management schemes for the next generation shipboard electrical systems (SES). The research has focused on PEBB based DC distribution systems in order to make use of many advantages the DC SES offer over conventional AC SES. New "agent" based methods have been developed for this purpose. Agent based design is a new paradigm that borrows heavily from Artificial Intelligence. This research contributes to the development of this emerging field.

Naval/Military Relevance/Impact of this research is that it focused on development of new methods for one of the key functions of new DC SES – protection and configuration management- which are critical for assuring continuity of service fallowing a fault/damage in the system.

The metrics for the research include:

i) Identify the protection requirements and issues on a DC SES and develop protection schemes that will meet the requirements.
ii) Identify the configuration management issues and develop management schemes.

Key S&T Areas (the main tasks involved to accomplish the research objectives) include:

- Design of power electronic converters for fault current withstand and limiting.
- Development of solid-state protection devices for fast fault current interruption.
- Development of protection schemes for fast fault/damage detection and isolation even under battle damage conditions.
- Development of configuration management schemes tailored for DC SES to assure continuity of supply to critical loads.

Technical Approach

I. Introduction

DC distribution for SES has many attractive features compared with the conventional AC distribution [1,2]. The goal of this research is to address the challenges associated with DC SES, specifically the challenges associated with the system protection and configuration management. When a fault occurs on any part of the SES (due to malfunction or battle damage) the protection devices detect and isolate the faulted/damaged part of the system. Then, the configuration management makes the necessary reconfigurations in the system to supply as much of the load as possible. Hence, our research has focused the two main components of protection schemes: the new protection devices to improve the fault current interruption on the system, and new agent based schemes for fault/damage isolation and configuration management. A brief summary of the challenges identified and accomplishments made is given below.

DC SES protection:

Conventional protection schemes used in AC systems will not be able to meet the new DC SES operation requirements, as these schemes are element based, i.e., they are aimed to protect the main elements (lines, transformers) etc. on a system. For the DC SES, on the other hand, "system level" protection is more important. In a battle damage condition, for example, the goal is to make sure that the power can be supplied to the vital parts of the ship. Hence, the main focus of this research has been on the development of new protection schemes.

The research has been comprehensive in that the two main components of the protection - protection devices and protection schemes- have been considered. The accomplishments include the following:

- *Protection Devices*: Two different options have been investigated:
  - First approach uses the Voltage Source Converters (VSCs) for fault current limiting and interruption. Revisions needed on the VSCs to perform these functions have been identified, and feasibility of this approach has been demonstrated [3].
  - The second approach uses the new solid-state based protection devices (SSPD)- current limiters and circuit breakers – to limit and interrupt the fault currents. It has been shown that for DC SES these devices should be hybrid type in order satisfy the protection and operation requirements [4].
- *Protection Scheme*: A new "agent" based protection scheme has been developed for effective protection of DC SES. It has been shown that these *protection agents*, which are associated with protection devices (converter or SSPD), can detect and isolate the faults/disturbances very fast – less than 3-4 ms [3].

Next section summarizes the details of the agent based protection scheme that uses the VSC as the protection devices, and section III summarizes the details of the protection scheme that uses new solid state protection devices.

Configuration Management:

Second part of the research has focused on the main design issues related to reconfiguration and a configuration management on DC SES after a fault, and new schemes have been developed [5]. The new method has two main components:

- Automatic load transfer and bus reconfiguration: The scheme uses the protection agents to localize the fault fast and thus assure continuity of supply to the critical loads even under battle damage conditions. This is accomplished by (i) first having the critical loads to be seamlessly transferred to the alternate bus without any disruption of power, and then (ii) the sectionalizing switches on the main DC bus operate to reconfigure the DC bus in order to minimize the interruption to the non-critical loads to about 10-20 msec.
- Load Management: For extreme contingencies which cause an unbalance between supply and demand for power, a load management scheme has been developed. The method uses a central agent at the generator monitoring the generator loading and then has the authority to curtail the loads when the generator overloads. To further facilitate load management under contingency conditions, the use of distributed generation has also been investigated [6,7].

The main design issue related to reconfiguration involves the placement of sectionalizing switches so that any damage can be localized as much as possible and the continuity of supply to the critical loads are assured under even under battle damage conditions. Details of the proposed scheme are given in section IV. This scheme has the following features:

- Single contingencies, i.e. a single fault on the DC bus, can be localized easily and the continuity of power supply to the critical loads can be assured under these contingencies. Specifically, it is shown that after a contingency all the critical loads can be seamlessly transferred to the alternate bus without any disruption of power. This is mainly achieved by making the power converters buffer the impact of the fault mainly to the part of DC bus which has the fault so that the generators and the alternate bus are not affected by the fault as much as they would in a AC distribution system.
- Placement of sectionalizes on the main DC bus at the boundary of each zone minimizes the interruption the non-critical loads will experience due to a fault to about 10-20 msec. A collaborative restoration scheme has been developed to achieve this fast reconfiguration.
- For extreme contingencies, which cause an unbalance between supply and demand for power, a load management scheme is needed. The agent based platform developed for the configuration management is used as the base for this function also.

II. Agent Based System Protection

The envisioned scheme uses the converters (which are voltage source type) as switches (circuit breakers) to limit and interrupt fault currents. In our previous work [2, 3], it has been demonstrated that this new functionally for VSC can be achieved by proper selection of converter topology and by adopting a revised switch realization scheme that uses the newly emerging robust power electronic devices such as ETO [8-10]. The use of VSC as CB (circuit breaker) is significant, mainly:

i) It eliminates the need to use separate circuit breakers that need to be developed specifically for DC current interruption.
ii) The high fault currents can be limited and interrupted very fast, in the order of a few microseconds.

The use of this fast acting VSC based circuit breakers however introduces a new challenge, that the protection scheme should be able to detect and locate the faults fast. To achieve this goal, we developed an "agent" based collaborative protection system consisting of smart agents embedded into the PEBB. The *protection agents* monitor the system locally to detect disturbances and then collaborate with each other to isolate the disturbance and respond to it by reconfiguring the system. The collaboration scheme ensures that the protection and configuration will be achieved globally at system level, rather than local level, and thus it provides the desired self-healing functionality for the SES.

Since in the proposed scheme, CBs are embedded within the VSCs, the protection zones that will be defined by them will not be device based. Figure 2.1 illustrates the main zones defined by these devices on the prototype DC SES [21,24]. Note that there will be three main zones:

- ***Primary DC Bus Zone***: The primary DC bus supplies power to all the load zones and therefore it is the most critical component for protection as it is also the one that is exposed to the most of the damages. Note that since the switches in the PEBBs will be doing the fault interruption, the protection zone is defined by the switches of PEBBs that are connected to the bus – the rectifiers, and the buck converters. The zone therefore includes not only the bus but also the DC rail of the rectifiers and the buck converters, as the figure illustrates. Note that to protect the DC bus only using conventional schemes; we would need a CB at every connection point, as illustrated in Figure 2.2. The proposed scheme eliminates these CBs.

- ***Secondary DC Bus Zone***: This zone, as illustrated in Figure 2.1, is basically defined by the buck converter and includes the secondary DC bus, the load side buck converter rails and the source side inverter rails. The secondary DC bus supplies power to all the loads within the zone; either directly to the DC loads or via inverters to AC loads. Therefore, the secondary DC bus is the second most critical component for protection. Different load zones on a ship are typically separated by watertight bulkhead compartments of the ship, and therefore, the faults occurring in a load zone are localized to that zone.
- ***Rectifier AC Zone***: As Figure 2.1 illustrates, the rectifiers are connected to the ac source bus supplied by generators. Note that the ac source side of the rectifier which includes the rectifier input filter elements need to be protected, and the rectifier switches cannot be used for this purpose. As the figure illustrates, we propose to use fuses at the input terminal of the rectifier to protect this ac source zone of the rectifier. Note that the generators have usually their own protection zones defined by their CBs as illustrated in the figure. The fuses, rather than ACCB are used here because of three main reasons. First, since the system uses mainly cables for power distribution, any fault in this protection zone, or any other part of the system, will be permanent rather than temporary. Thus, there is no need for fast reclosing capability that the CB can provide. Secondly, as it will be shown later, the provision of two primary busses on the system allows for protection system to transfer the loads affected by a disturbance from the faulted bus to the other healthy bus without interruption; thus the advantages of using a fast reclosing CB are nullified. And thirdly, the maintenance and the paraphernalia (current transducer, CB power supply and relay) that are needed for the proper operation of the CB are not required for a fuse. Hence, fuses are employed for protection in this zone.

Rather than using conventional relays, for detecting the disturbances in these zones and operating the appropriate protective devices, we propose to use an agent based system protection scheme. This scheme will consist of agents that are associated with each VSC. The agents will not be responsible for the protection of a particular zone, rather they will take action based on the local information they will have. This is therefore a distributed protection scheme and the goal here is to provide autonomy to the agents so that they can take fast action. The challenge to be addressed here is to provide enough intelligence for the agents to make sure that they will make correct decisions.

The proposed protection scheme will employ three types of "protection agents", a rectifier agent, a buck converter agent and an inverter agent. To provide the desired protection and minimize the system downtime, these agents will do the following: First they will use the VSCs as **fast** acting circuit breakers (interruption is less than 1ms). Second, each agent will take protective action based solely on the local measurements, which will ensure that there is no delay due to communication between different agents. Third, the protection system will have a hierarchical structure so that if the primary protection fails to isolate the fault, the switch level autonomous protection will provide backup protection and isolate the fault. It will be shown that by properly designing the tasks of the agents at the system level, the time delay for coordination will not be required, which will help us to minimize the system downtime.

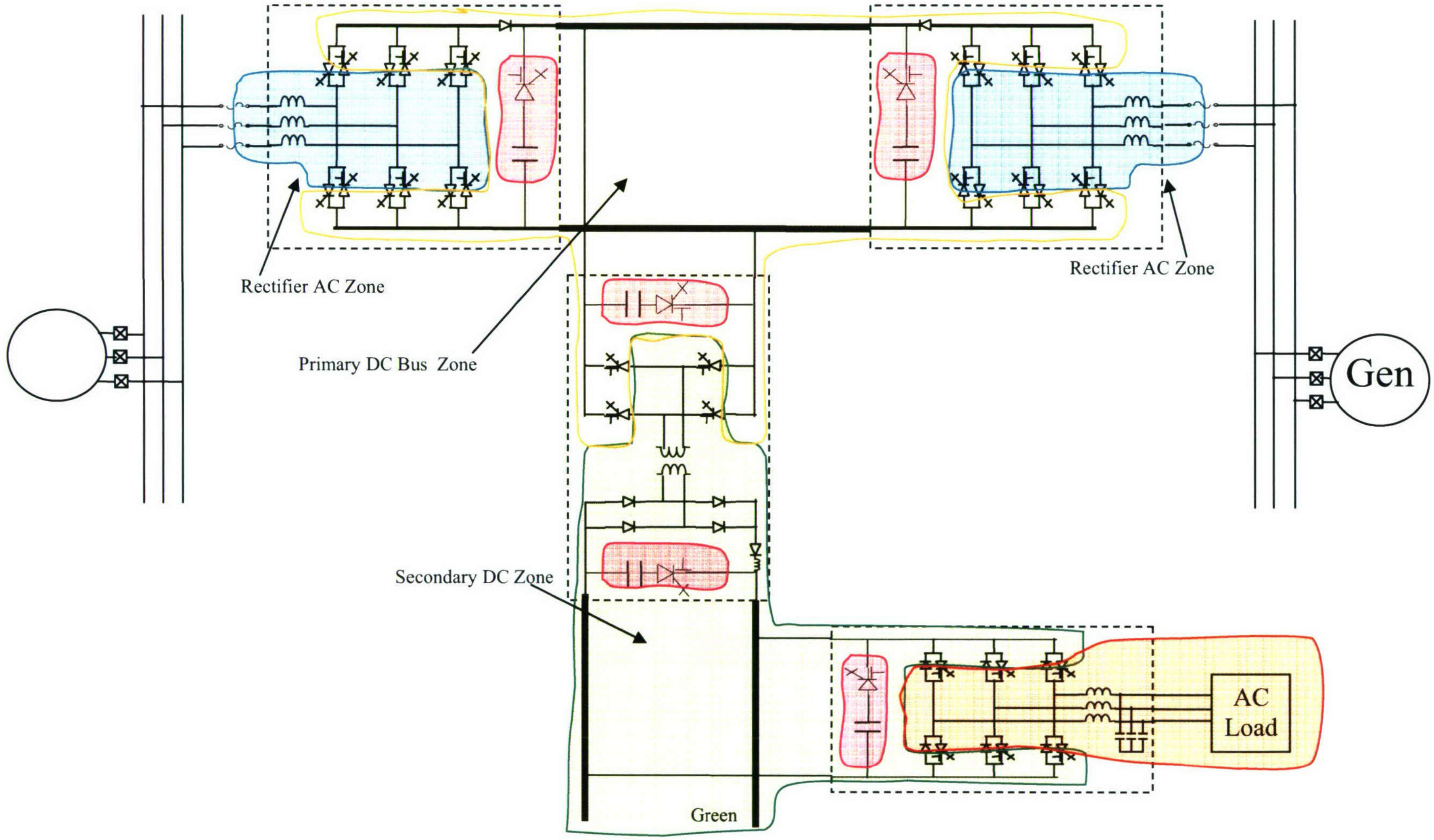


Figure 2.1 : Protection Zones in a DC SES

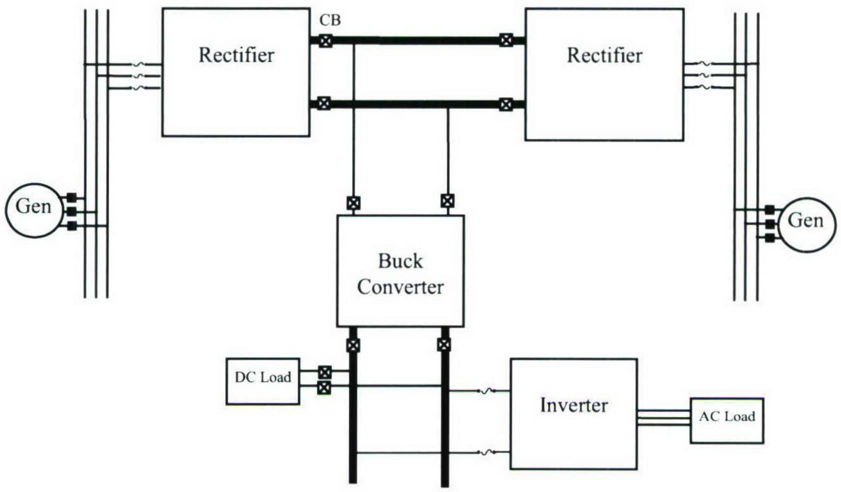


Figure 2.2 : CBs needed on DC SES to create device based zones

Before illustrating how this agent based system protection scheme will work on the DC distribution system; first let us have a look at the main faults/disturbances that the system will be exposed to. The main faults can be listed on a zone basis as follows:

Primary DC Zone

The primary DC zone, as shown in Figure 2.1, includes primary DC bus, the DC rails of the rectifier and the source side DC rails of the buck converter. The main faults included in this zone are:

DC Bus Fault: Faults on cable of the primary DC bus which result in short-circuiting the (+) and (-) terminals of the cable. The faults on the DC bus primarily occur due to cable insulation failure or battle damage like missile hit etc., and they are therefore usually severe permanent faults that need to be isolated as fast as possible. These faults also cause a fast discharge of the energy stored in the capacitors connected to the DC bus. This fast energy discharge may cause the destruction of the cable and/or the capacitors due to the heat and electromagnetic forces.

DC Bus to ground fault: The DC SES is operated with high impedance grounding and therefore any grounding of the DC cable is unintentional and considered as a fault. This DC bus to ground fault can occur either on the positive DC bus or the negative DC bus, but should not cause the interruption of power.

Rectifier DC Rail fault: This fault corresponds to short-circuiting of the DC rails of the rectifier PEBB. The likelihood of this fault is less due to it location within the enclosed converter. This fault is less severe than the Rectifier DC bus fault as only the generator feeds this fault. The fault current discharge by the capacitors is prevented due to the reverse biasing of the DC rail diode as shown in Figure 2.1.

Buck converter source side DC rail fault: This fault occurs on the DC rail of the buck converter connected to the DC bus. It is essentially similar to the rectifier DC bus fault and it is as severe. The only difference being the physical location of the fault and the lesser likelihood of its occurrence due to its location within the converter.

Secondary DC Zone
The secondary DC zone, as shown in Figure 2.1, includes the secondary DC bus, the buck converter isolation transformer, the load side DC rails of the buck converter and the source side DC rails of the inverter. The main faults include the following:

DC Bus Fault: The secondary DC bus is also a cable and therefore all the faults on this bus will be permanent and are caused by cable insulation failure or battle damage. These faults are less severe as the secondary DC bus voltage is about 800 V as compared to 7 kV of the primary DC bus voltage.

DC Bus to ground fault: The positive or negative secondary dc bus to ground faults occurring on the secondary DC bus are localized by the isolation transformer of the buck converter. Therefore, the secondary DC bus to ground fault do not circulate currents through the generator neutral. These DC bus to ground faults also do not cause the interruption of power and therefore again non disruptive in nature.

Buck converter transformer fault (primary and secondary): These are the faults that occur in the isolation transformer of the buck converter. These faults primarily occur due to transformer winding and lamination insulation failure. Transformer terminal faults may also occur due bushings failures. The transformer primary side faults are severe due to the presence of very small inductance in the fault path as compared to the secondary side faults where the presence of transformer inductance helps to reduce the severity.

Buck converter load side DC rail fault: The Buck converter load side DC rail faults are the faults from the positive DC rail to the negative DC Rail and thus physically occurring within the converter.

Rectifier AC side zone
The rectifier AC zone, shown in Figure 2.1, includes mainly the rectifier AC side filters. The faults that can occur in this zone include:

Line – Ground fault (phase A, Phase B and Phase C),
Line – Line faults (phase A-B, B-C and C-A),
Three – phase faults,
These faults can occur either before or after the input inductor.

War Damage
War damage is a special condition wherein multiple faults occur on the DC SES. This kind of damage can affect the whole zone comprising of a watertight bulkhead compartment of the ship and may require the isolation of the zone.

The following sections illustrate how the agents detect these disturbances and take the appropriate protective actions. The principles used for detecting faults and the protective action initiated by the agents to isolate the fault are given. The protective action is to command the circuit breaking units (the ETO based switches of the PEBBs) to turn off (open) for a severe fault or to raise an "alarm" for a non-disruptive fault. To illustrate the proposed schemes and their effectiveness, simulation on the prototype DC SES has been performed using PSCAD /EMTDC [16].

a) Rectifier Fuse

As pointed out above, we propose to use fuses at the source side of rectifiers to protect the rectifier AC zone shown in Figure 2.1. The fuse provides primary protection for the L-L faults and the 3-phase faults on the AC source side of the Rectifier PEBB. These are the faults for which the shutdown of the rectifier PEBB does not isolate the fault. In addition the fuse acts as a backup protection for the faults for which rectifier PEBB provides primary protection.

The fuse chosen for this application should be fast enough so that the generator protection does not trip before the fuse blows. This would ensure that the generator protection acts as the backup protection for the fuses. Secondly, it is required that the fuses should be slow enough so that the downstream protection gets enough time to operate. Since the designed PEBB protection operates in less than 1ms, which is extremely fast as compared to a fuse operation, co-ordination of the fuse with the downstream rectifier PEBB is automatically dealt with. The main specifications for the selection of the proper fuse for the prototype system are as follows:

(1) The normal rated current of the device to be protected is ~450A (rms)
(2) The system startup current (due to initial capacitor charging via rectifier PEBB) is of the order of 1.5 kA (rms) for about 5-10 milliseconds (<0.01 sec).
(3) The magnitude of fault currents to be cleared is of the order 9-10 kA (faults after source inductor) to 30 kA (faults before input inductor).

With these considerations in mind, a 500E type fuse with the rated current of 450A is appropriate. An EJO-1 type 9F62 fuse from General Electric meets these requirements and has been selected for the prototype SES. To demonstrate the fuse operation, simulations have been performed on the prototype SES. The results of a simulation for a phase A-B fault in the Rectifier AC zone (fault B1 in Figure 2.5) are shown in
Figure **2.3**. Following the fault at t = 0.05s, the current I_A and I_B as shown in
Figure **2.3** increase and are limited only by the source impedance. At t_c = 0.0604s, the fuse have dissipated enough energy for melting and clearing and therefore, at t = 0.062s, which is the first zero current crossing of I_A and I_B, the fault currents are interrupted by the two fuses. (The fuse characteristics obtained from the minimum melting curves and total clearing times are used in the form of a lookup table to continuously calculate the energy dissipation and hence determine the time required for the fuse to melt and clear).

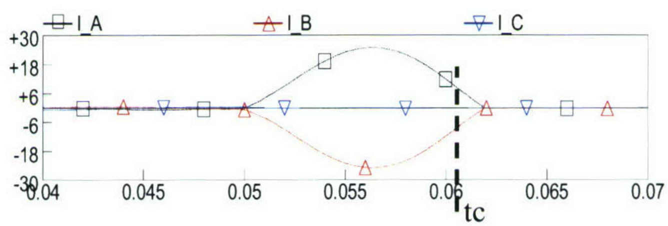


Figure 2.3 : Fuse Operation to clear a L-L fault.

b) Rectifier Agent

The protection agent associated with the rectifier PEBB is called the Rectifier Agent (RA). The RA monitors the local quantities of the rectifier PEBB, and based on these measurements, it locates and detects the existence of any disturbance on both the source side, which is the ac zone, and also the load side, which is the dc primary bus zone, as shown in Figure 2.1, and the close-up view in Figure 2.4. The main faults/disturbances the RA detects and reacts to are shown in Figure 2.5.

Note that the main circuit breaking unit for the RA is the ETO based switches of the rectifier shown in Figure 2.4. The RA uses them to isolate the faults in the DC primary zone. If RA mal-operates and does not detect the fault, the protection implemented at the hardware level on every ETO switch acts as the back-up protection by detecting the fault current and turning off the ETO. The other device that is added to the rectifier is the diode at the output terminals. It will be shown later that this diode aids the rectifier in interrupting and isolating the AC zone faults.

The local measurements the RA monitors are (shown in red in Figure 2.4):

(1) Rectifier input phase currents, (I_A, I_B and I_C)
(2) Rectifier input phase voltages (VA_ref, VB_ref and VC_ref)
(3) Rectifier Output Current (Before Capacitor): (I_R)

The sampling rate for these measurements for the prototype SES is chosen as 15 kHz, which is 2.5x of the PEBB switching frequency of 6 kHz.

The rest of this section describes the principles and methodology used by the rectifier agent to detect, locate and isolate the faults illustrated in Figure 2.5. As noted before, the rectifier agent cannot take any action against ac source side disturbances, and therefore, the fuses at this side are placed for this purpose. Similarly, the output capacitor needs special protection in order to limit the high discharge currents of the capacitor following a close-by fault. Hence, protection scheme for the capacitor is illustrated first.

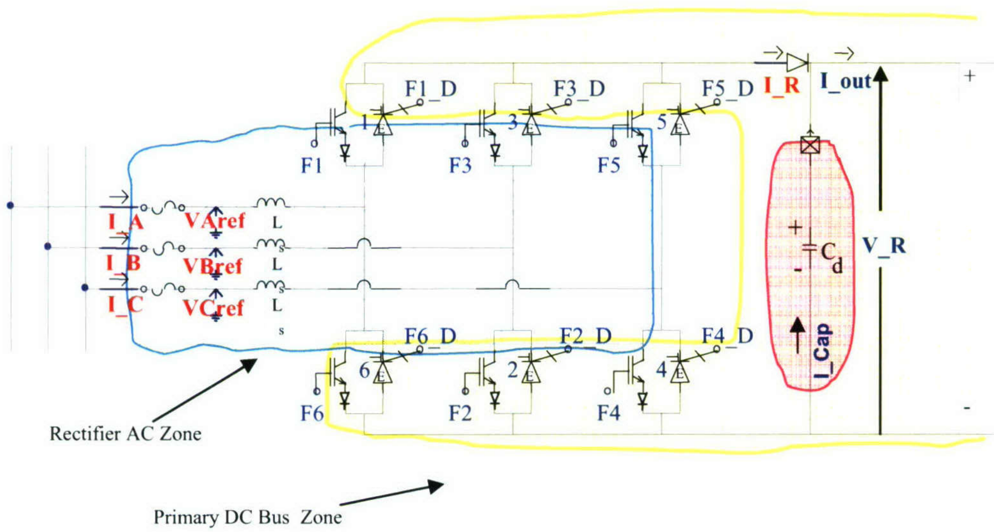


Figure 2.4 : Protection zones around Rectifier PEBB

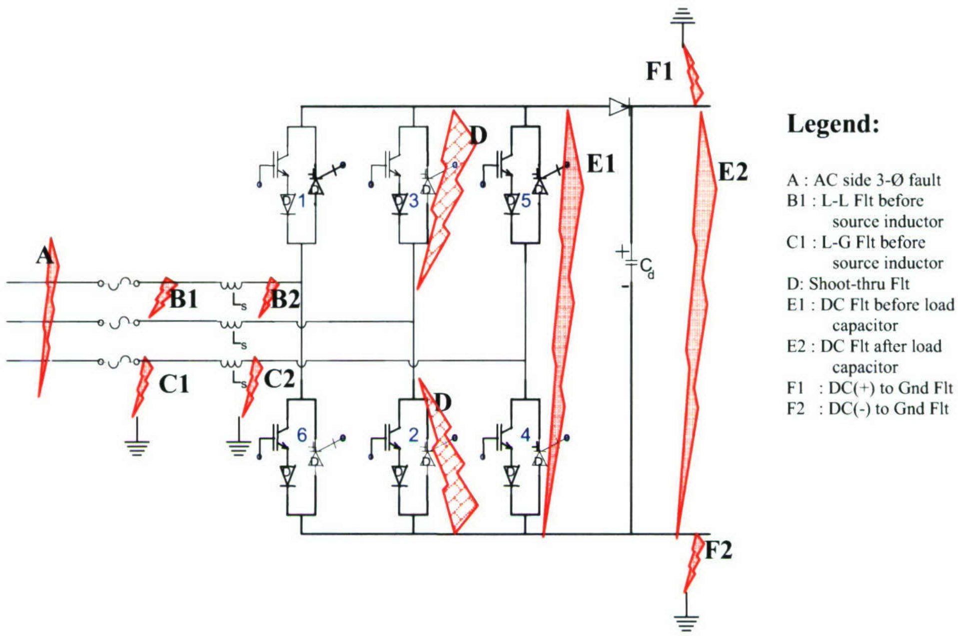


Figure 2.5 : Faults close to Rectifier PEBB

b.1) Capacitor Discharge Current Limiting

As indicated in Figure 2.4, we propose to use a Diode at the output terminal of the rectifier mainly to prevent the output capacitor to discharge back through the switches to an ac side fault. To limit the discharge currents of short duration, the capacitors connected to the DC bus need special protection. Capacitor discharge is typically controlled by RLD snubbers [11] which allow for the capacitor current to decay by a rate determined by the RL time constant of the snubber. For DC SES, however, a DC circuit breaker (DCCB) would be more appropriate. The DCCB is employed between the capacitor and the positive DC bus rail as shown in Figure 2.4. In [9, 10] it is shown that indeed an ETO based DCCB can be used to turn off and interrupt fault current in less than 10 µs. Therefore such a DCCB would limit and interrupt the discharge current within a few µs, and hence it will effectively protect the capacitor from extreme stresses and destruction. The opening of the DCCB at the initiation of a fault will also helps the capacitor to keep its voltage and makes it easier for the rectifier to startup. Furthermore, DCCB eliminates the heat dissipation associated with snubber resistors.

The basic principle of operation of the DCCB is based on the inherent current sensing of the ETO [10]. The measured current is compared to a 3.1 kA threshold (maximum limit of the DCCB ETO= 3.5kA). A hard turn-off is initiated when the current crosses this threshold. This hard turn-off limits the current from increasing further and interrupts the current in 3-7 µs. Operation of the DCCB will be illustrated below in considering different faults the RA would interrupt.

b.2) Protection against faults in primary DC bus zone

Primary DC Bus fault

Faults on primary DC bus will cause high fault currents initially due to the discharging of all the capacitors connected to the DC bus, and then from the source (generators). The protection against capacitor discharge is provided by the DCCB as explained before. To detect and interrupt the fault current through the rectifier, we monitor the current I_R, which is the rectifier output current before the capacitor, as shown in Figure 2.4. Detection scheme for this fault involves comparing the magnitude of I_R to a preset threshold (2.75kA for the prototype SES). The protective action is to turn-off the rectifier PEBB and thereby interrupt the fault current (note that the DCCB opens and isolates the capacitor).

Simulation results for a primary DC Bus fault are shown in Figure 2.6. Following a fault at t=0.05s, the bus capacitor discharges into the fault with a very short time constant. Figure 2.6(c), shows DCCB limits and interrupts the discharge current in 9μs. Following the fault, the generator also starts contributing fault current as seen by the I_A, I_B, I_C, in Figure 2.6(b). RA monitor I_R shown in Figure 2.6(a), and when I_R exceeds the threshold of 2.75 kA at t=0.051s, it detects the fault and interrupts it by turning the rectifier PEBB off.

Shoot-thru fault

A shoot thru fault by definition is the shorting of the DC capacitor by accidental misfiring of the switching devices of a given leg. When a misfiring by the controller causes the switching devices in a given leg to turn on simultaneously, the interface diode at the output terminals gets reverse biased .The reverse biasing of the diode prevents any high discharge current by the capacitor through the misfired devices.

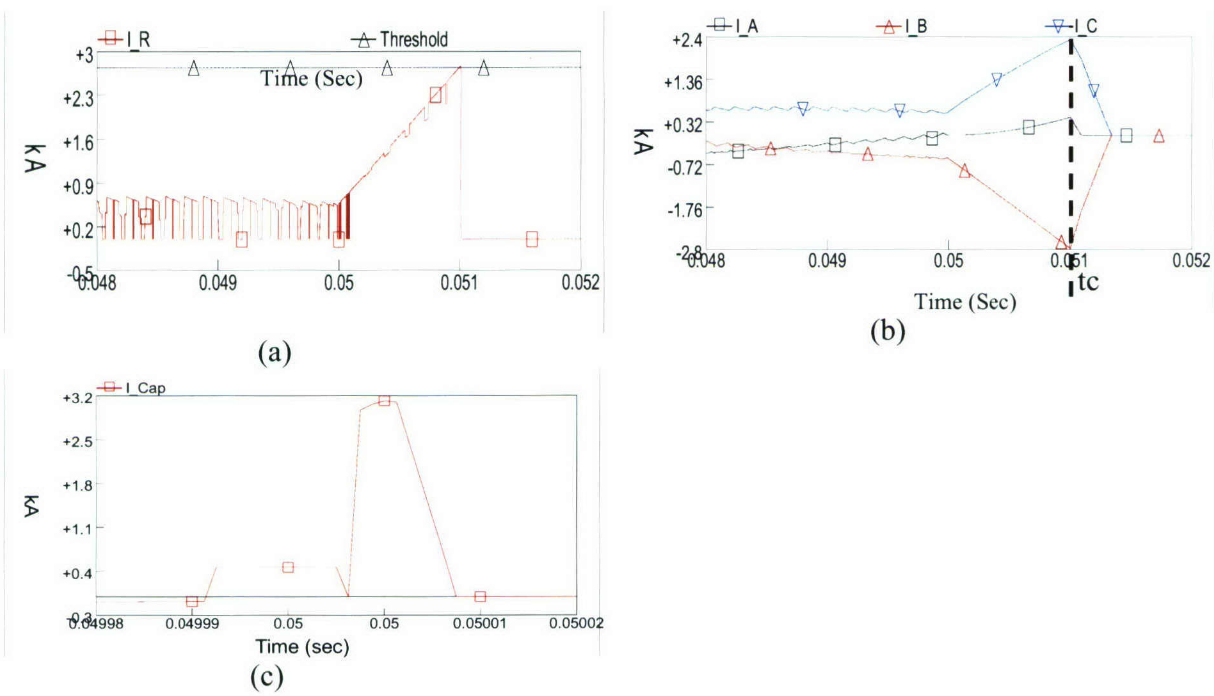


Figure 2.6 : Simulation results of Rectifier DC Bus fault

The shoot-thru fault also creates a short circuit path for the AC source. Usually, this shorting is not long enough for a substantial current rise. But, if a shoot-thru fault is sustained for long time intervals, the fault would cause an increase the input phase currents. The RA detects this fault when both the following conditions are satisfied (a) diversion of load current into fault (i.e. I_R ≈ 0) and (b) high values of I_A, I_B, and I_C. The RA turns the PEBB off for a sustained shoot-thru fault.

Figure 2.7 shows the simulation of a shoot-through fault on the prototype rectifier. A fault occurring at t =0.05s causes the current I_R to drop below the threshold of 0.025kA as shown in Figure 2.7(a). At t = 0.0502s, the condition (b) is satisfied as the current I_B exceed I_{th2}. The current I_R remains below the threshold for a time interval of 150 μs (>$2T_s$) from t =0.05027s to t =0.05042s indicating a fault condition.. At t_c=0.05042s, the RA detects it as a fault and commands the PEBB to turn off. This limits the input current from increasing further, and at t = 0.05064 the fault current is completely interrupted as seen from Figure 2.7(a). The capacitor current is seen to decay into the load in Figure 2.7(b).

Rectifier DC Bus to ground fault

When a Positive or negative DC bus to ground fault occurs, it is observed that it causes the same polarity DC component in all the three input phase voltages. For example, when a positive DC bus to ground fault occurs, it causes a negative DC component in all the phase voltages VA_ref, VB_ref and VC_ref. Therefore, RA monitors the phase voltages and extracts their DC component by Fast Fourier Transform. A ground fault is inferred when the DC component of the phase voltages exceeds the threshold and persists for 1ms. The RA avoids incorrectly detecting this fault during startup due to the fact that the DC offsets during normal startups are all not of the same polarity, and therefore does not meet the polarity check criterion of the detection scheme. One DC bus to ground fault is non-disruptive, and therefore the RA only raises an *alarm* and the operation of the system continues normally.

Figure 2. 8 shows the simulation results for a positive DC bus to ground fault. The fault at t=0.05s causes a negative DC offset to appear in the phase voltages as Figure 2. 8(a) illustrates. The phase voltages are shown in Figure 2. 8(b). At t=0.0604s, the DC components of all the three phases crosses the threshold of -1 kV. When this negative DC offset condition is sustained

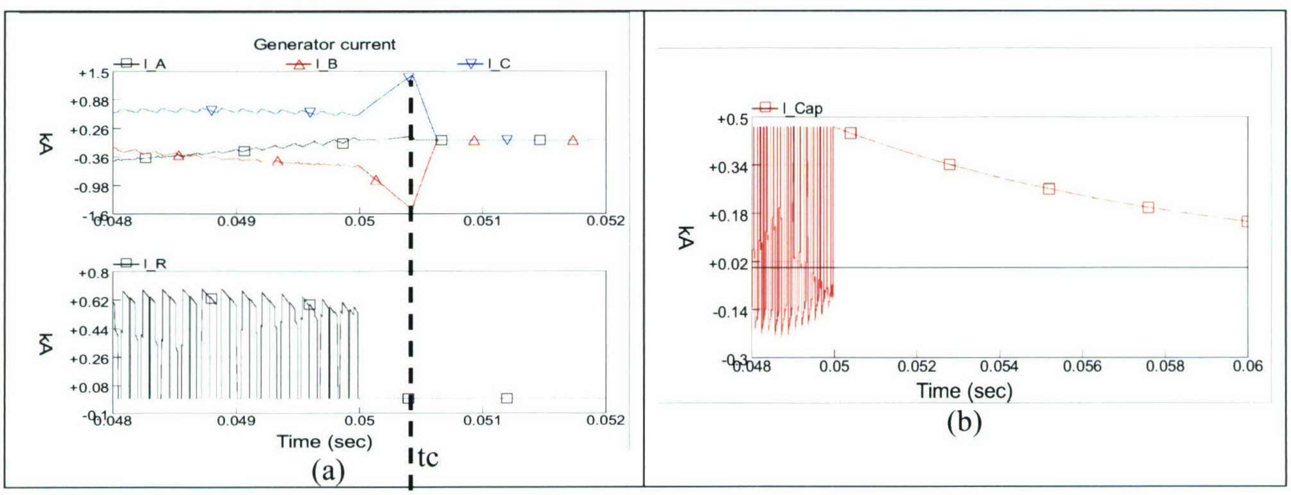


Figure 2.7 : Sustained shoot-thru fault simulation results

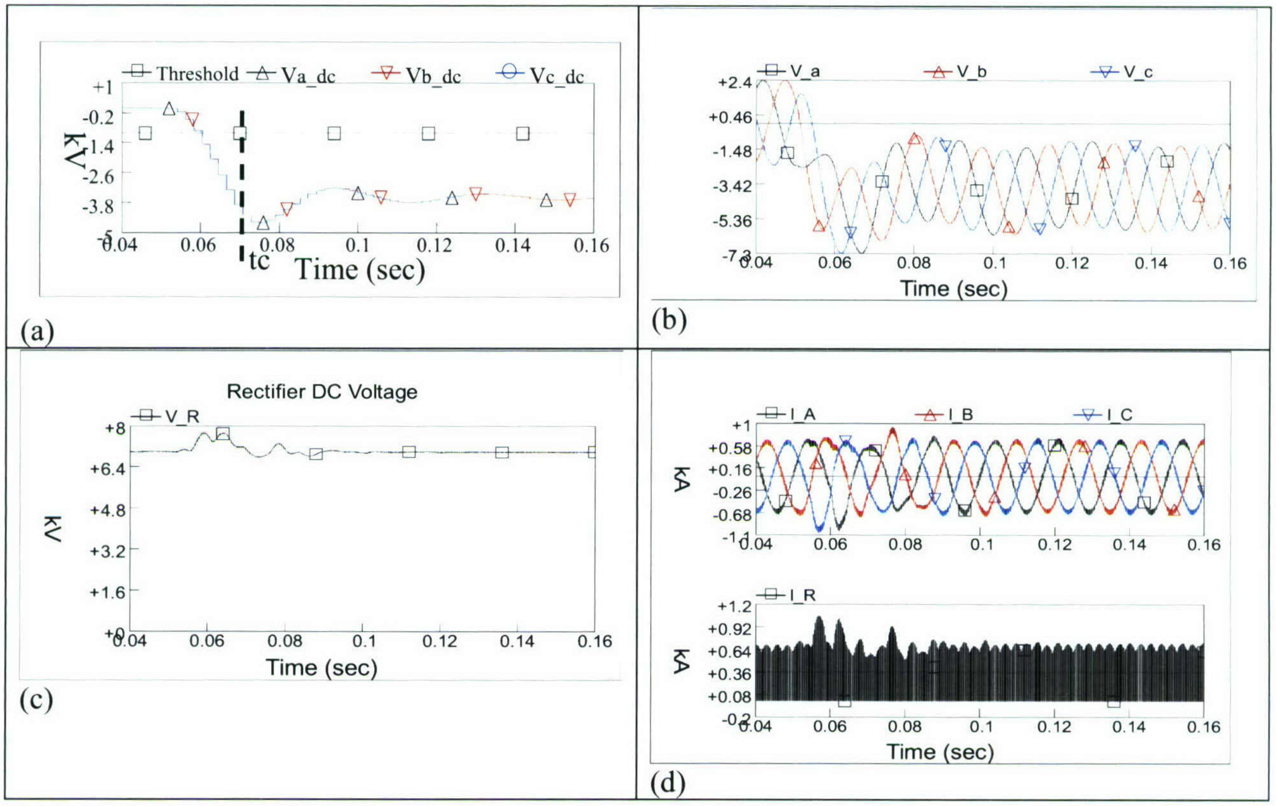


Figure 2. 8 : Simulation results of phase C to ground fault

for 1 ms, the RA determines that there is ground fault on the DC bus at t_c=0.0704s. Figure 2. 8(b) shows the input currents I_A, I_B and I_C. The PCFF controller has been modified by the authors to improve system performance under DC bus to ground faults [2], which minimizes the harmonics in the input currents and the ripples at the output voltage, As seen from the Figure 2. 8(c) and (d). These results confirm that the system performance is temporarily affected and therefore with the modified controller, the fault is a non disruptive and the system operation is therefore continued normally without any disruption of service.

b.3) Protection against Faults in Rectifier AC zone

The rectifier cannot take protection action against the faults in the rectifier AC zone. The goal for RA is therefore, to locate them so that this information can be used later during reconfiguration. Also, RA can isolate the fault by turning the rectifier off.

L-L faults

RA uses the ac side phase current measurements I_A, I_B and I_C to detect and locate a fault in this zone. As in conventional over-current protection schemes, we propose to use a simple detection scheme which compares these current magnitudes with a preset threshold to detect the fault. But since a DC side fault will also cause these input currents to go high, RA needs to segregate L-L faults from the DC faults. This can be done by using the fact that a DC fault is detected faster than an L-L fault by the RA. As illustrated above, the RA commands the PEBB to turn off as soon as it detects a DC bus fault. The turn-off prevents the phase currents to exceed the threshold (of 2.75kA), as **Figure 2.6** illustrates. Whereas, for an AC side fault, the phase currents exceeds the threshold (of 3.5 kA > 2.75kA) since it takes more time for the fuse to interrupt the current. Hence, when two of the three phase currents exceed the preset threshold, a L-L fault is inferred and is segregated from a DC fault.

Once the RA detects a L-L fault, it commands the PEBB to turn off. As it is illustrated earlier, this action does not interrupt the fault current, hence the input phase currents continue to increase until the currents cause the fuses to melt, clear and interrupt the fault current. The shutdown of the PEBB and the blowing of the fuse complete the protective action to isolate the faulted part of the system.

The EMTDC /PSCAD simulation results for AC L-L fault at rectifier input are shown in Fig.2.9. The magnitudes of phase currents I_A, I_B and I_C, as shown Fig.2.9(a) (which is the same as Fig.2.3), rise following the fault at t=0.05s. At t=0.051s the current magnitudes exceed the threshold of 3.5 kA thereby ruling out a DC fault and inferring the existence of an AC L-L fault. The RA commands the PEBB to turn off at t_c=0.051s as a result of the detection of the AC fault. The high currents I_A and I_B cause the fuse to melt and clear at t=0.0604s and successively interrupt the fault at the following current zero at t=0.0618s. The output DC voltage and current I_R are shown in Fig.2.9(b) and (c) respectively. Following the PEBB turn-off; as a result of the discharging of the capacitor into the isolated load, the DC voltage decay to zero. Fig.2.9(c) shows I_R drops to zero right after fault as the fault causes the interface diode to open.

Three Phase faults

RA employs the same technique it uses to detect L-L faults to detect three phase faults; it monitors the three input phase currents, and when all the currents exceed the threshold value

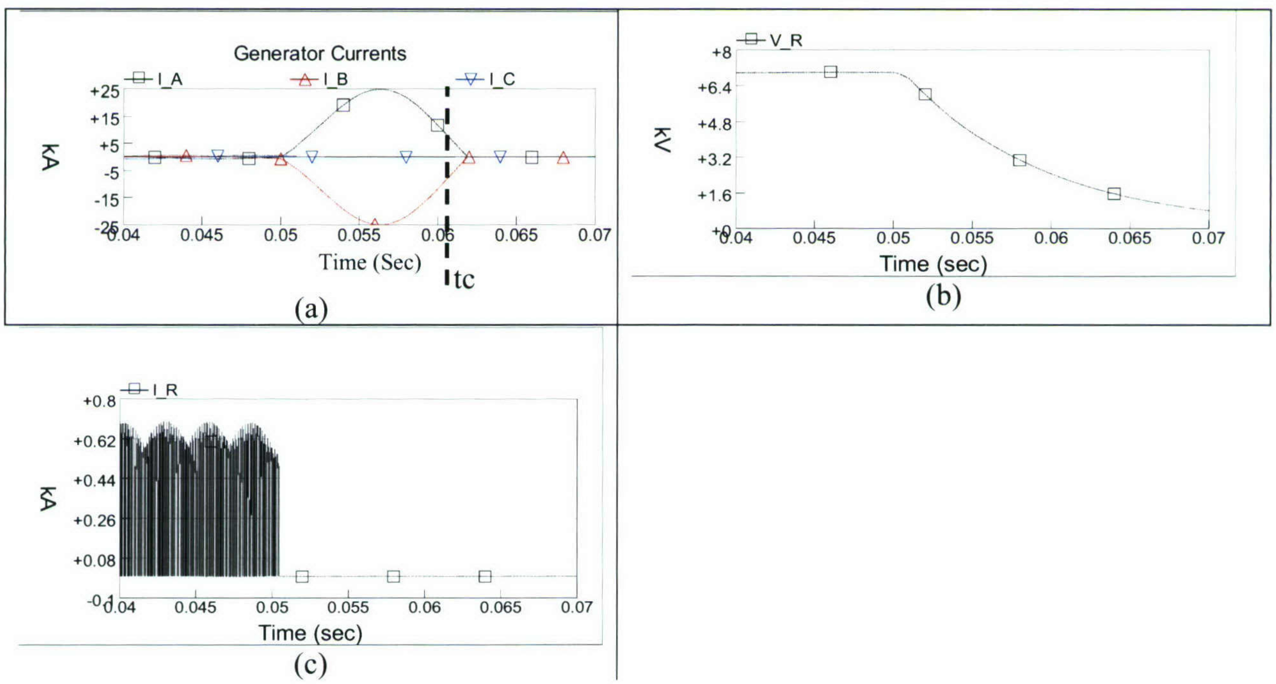


Figure 2.9 : Simulation results of L-L fault before Inductor

(ok 3.5 kA for the prototype SES) RA infers that it is a three phase fault. Once the fault is detected the RA turns the PEBB off. However, as in L-L fault, this action does not interrupt the current, and the increased fault current causes the fuses to melt, clear and interrupt the fault current. The shutdown of the PEBB and the blowing of the fuse complete the protective action to isolate the faulted part of the system.

Simulation results of a 3-phase fault are shown in Figure 2.10. A 3-phase fault occurs at t=0.05s. The currents I_A , I_B and I_C as shown Figure 2.10 (a) rise following the fault. At t_{ca}=0.0506s the current magnitudes I_A and I_C exceed the threshold of 3.5 kA thereby ruling out a DC fault and inferring the existence of a fault. The RA commands the PEBB to turn off at t=0.0506s thereby interrupting I_R. At t=0.0518s, the current magnitude I_B exceeds the threshold of 3.5 kA too, indicating a 3-phase fault rather than an L-L fault. The high currents I_A, I_B and I_C cause the fuses to melt and clear at t_{c2} = 0.0625s and successively interrupt the fault at the following current zero at t=0.0661s. The PEBB turn-off and the blowing of the fuse isolate the faulted portion of the system.

Rectifier AC L-G

The detection scheme for an L-G fault is based on the observation that for an L-G fault, the fundamental component of the faulted phase voltage collapse to near zero. Therefore, the RA monitors the 3 phase voltages, VA_ref, VB_ref and VC_ref as in Figure 2.4 and extracts the fundamental component of the phase voltages. The RA detects an L-G fault when the fundamental component crosses the threshold of 0.2 kV and stays below the preset threshold for 1ms. This ensures that the L-G fault is a sustained/permanent fault. In addition to detecting the existence of an L-G fault, the RA is able to identify the faulted phase as well. For example if the fundamental component of phase C falls below the threshold of 0.2 kV, then it is phase C to ground fault. Since the first L-G fault on a high impedance system is not

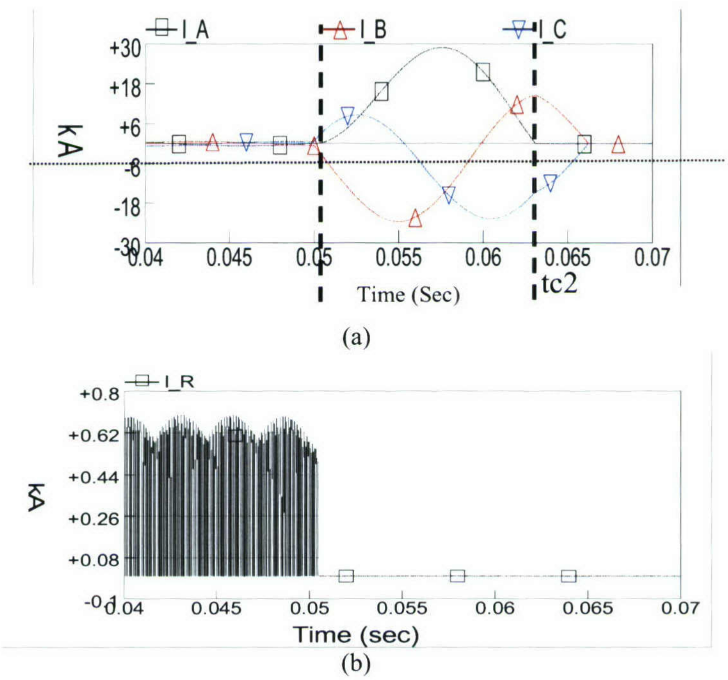


Figure 2.10 : Simulation results of 3-phase fault

disruptive in nature, the RA does not take any protective action and it only raises an alarm to notify the existence of a L-G fault.

Simulation results for a C-G fault are shown in Figure 2.11. A C-G fault at t = 0.05s causes the fundamental component of phase C to decrease from its nominal value of 2.4kV as shown in Figure 2.11(a). At t = 0.07396s, the value of the fundamental component of phase C falls below the threshold. At t_c=0.07496s when the fundamental component has remained below the threshold for 1 ms, the RA flags a C-G fault. Figure 2.11(b) shows input currents I_A, I_B and I_C, which indicate that the fuses do not mal-operate under the L-G fault condition. Figure 2.11(c) shows the output voltage. The output ripple is less than 10 % under the faulted condition. These figures show that the L-G fault on the system is not disruptive in nature, but additional harmonics are introduced. A modification or compensation to the controller may be implemented to obtain improved performance. Figure 2.11(d) shows the intermittent capacitor overload due to the L-G fault. Figure 2.11(e) shows the generator neutral current under the AC L-G fault is less than 16A peak.

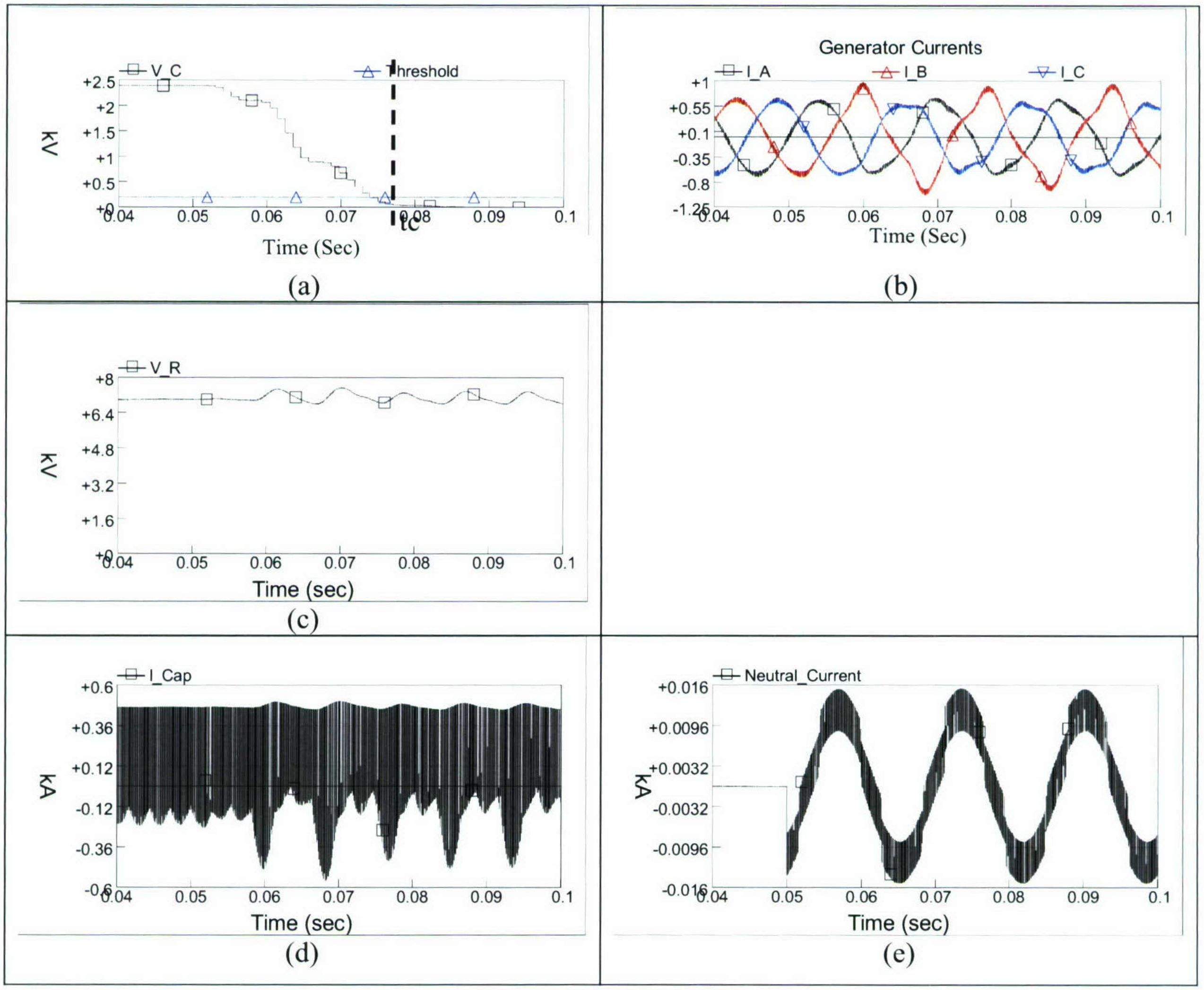


Figure 2.11 : Simulation results of phase C to ground fault

c) Buck Converter Agent

The Buck Converter PEBB with the proposed switch and control scheme for fault current interruption is shown in Figure 2.12. The figure also shows the zones of protection related to the buck converter. This converter can interrupt only the faults on the load side, which is the secondary DC bus zone, by turning off the controllable switches (CSD) of the inverter stage. Therefore, the protection agent associated with this converter (BCA) would detect and interrupt the faults in this zone. The agent need also to detect the faults on the source side, which is the primary DC bus zone, and isolate them by turning the CSDs off.

The faults the BCA would detect and isolate are illustrated in Figure 2.13. The main measurement the BCA will use to detect the faults in the load side is the input current measurement I_{in} shown in Figure 2.4. To help the BCA locate the faults within the buck converter, BCA needs three more measurements shown in Figure 2.12: transformer input Current (I_{x1}) and output Current (I_{x2}), and converter output current (I_o). The measurement I_{in} needs to be a high bandwidth current sensor (~1 Mhz), and the other three measurements can have a lower bandwidth (of 30 kHz, 5 times switching frequency of 6 kHz for the prototype SES). Some of the main faults the BCA will respond to are given below.

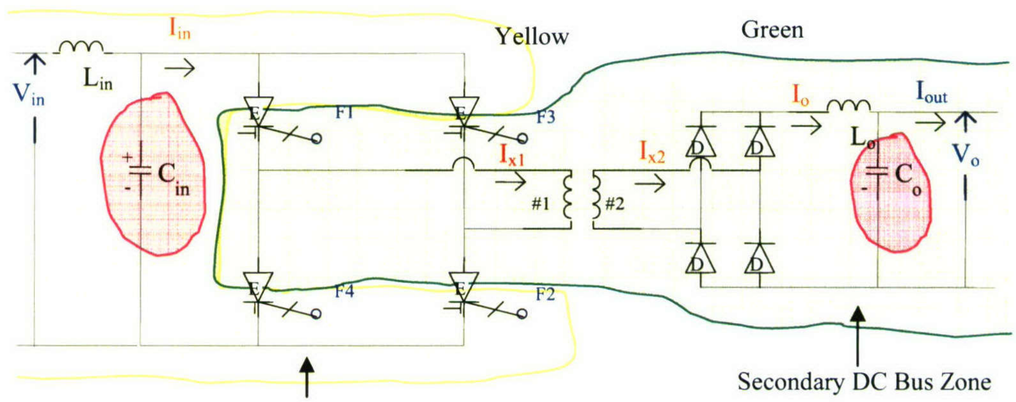


Figure 2.12 : Buck Converter Associated Protection Zones

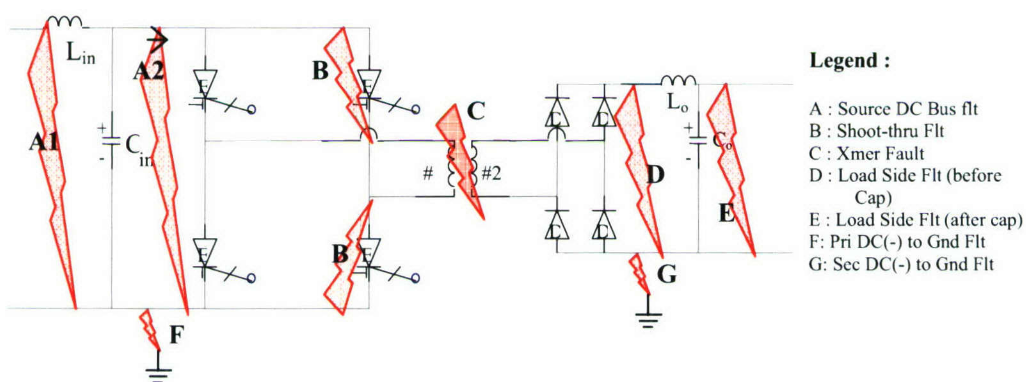


Figure 2.13 : Faults close to Buck Converter PEBB

Secondary DC Zone fault

The main fault on this zone corresponds to a short circuit on the DC secondary bus. This fault causes both the input current I_{in} and output current I_o to increase rapidly. The BCA can therefore use the simple detection scheme by comparing both I_{in} and I_o with their threshold values. When these currents exceed their threshold values for a certain amount of time (a few μs) the fault is detected and is located.

Simulations on the buck converter of Figure 2.12 with a fault on the secondary dc bus are given in Figure 2.14. As the figures illustrate, the fault at t=0.014, causes the monitored currents I_{in} and I_o to increase, and at t_c=0.01447, I_{in} crosses the threshold of 0.75 kA thereby detecting the fault. The BCA takes the protective action by commanding the CSDs to turn-off. At t=0.01447, I_o crosses the threshold of 3.75 kA too, which helps the BCA to determine that the fault is on the load side. The protective action of turning off of the CSDs interrupts the current from the primary side, but the current flowing on the load side does not cease immediately. The energy stored in the output inductor is free-wheeled through the diodes as indicated by the I_out shown in Figure 2.12(c)

Primary DC zone faults

The faults occurring upstream of the buck converter CSDs belong to the primary DC bus zone, and therefore they are interrupted by the rectifier agents. The buck converter however needs to detect these faults so that it can isolate the fault by turning off the CSDs of the converter. The detection of a source side fault is based on fact that such a fault will cause the current I_{in} to drop rapidly to zero. When this low current condition is detected and persists for a certain time interval (=300 μs), a source side fault is detected. A startup restraint is provided to allow for the buck converter to startup from zero current condition.

The simulation result for this fault on the buck-converter of Figure 2.12 is given in Figure 2.15. The fault at t=0.0140s causes the current, I_{in} to drop very quickly to a very low

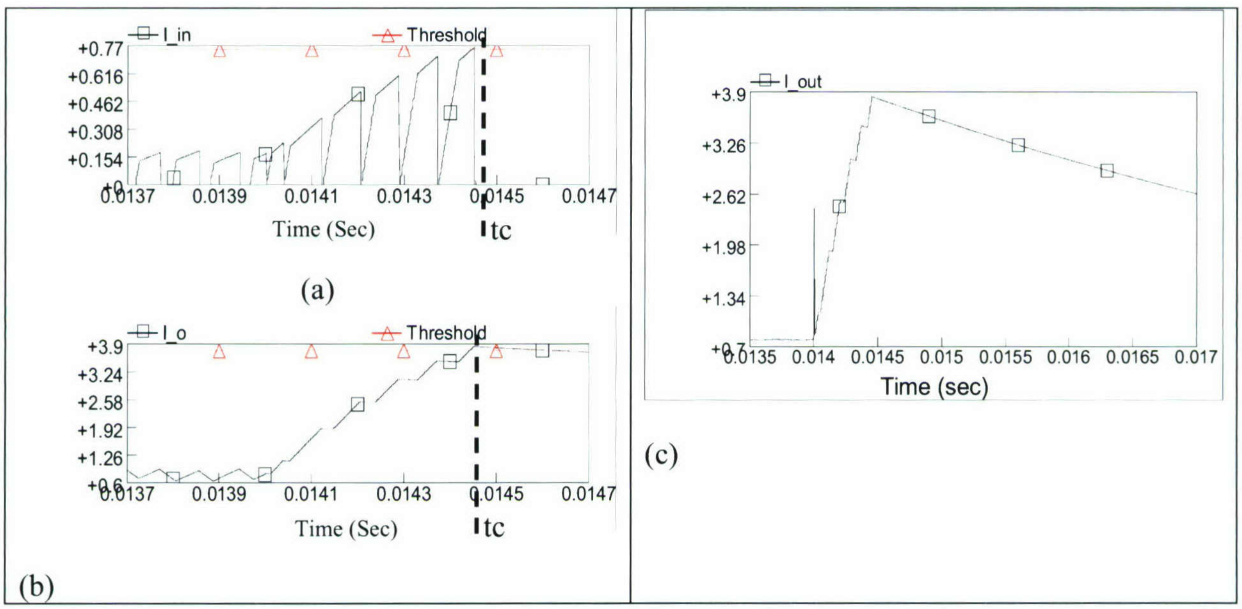


Figure 2.14 : Buck converter load side fault

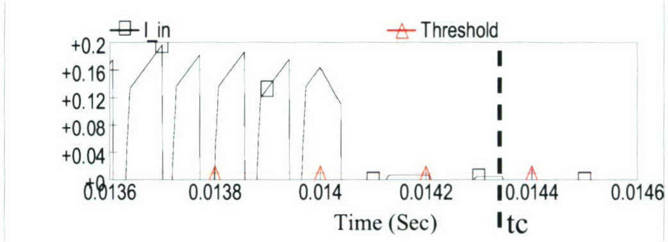


Figure 2.15 : Buck Converter Source side fault

value. The I_{in} drops below the threshold of 10A and stays below the threshold for 300 us indicating a source fault at t_c =0.01435s.

BCIS shoot-thru fault

A shoot thru fault occurs when a fault in the firing causes the CSDs in the same leg (F1 and F4 or F3 and F2) to be fired simultaneously. Single shoot-thru faults are common, but sustained shoot-thru fault is very drastic and shutdown of the devices is mandatory. Characteristics of this fault are that it causes the input capacitor to discharge into the fault. Since the monitored current I_{in} will see this discharge current, the BCA detects the fault by detecting the capacitor discharge current. The protective action for sustained shoot-thru fault is to command the CSDs to turn off.

A shoot-thru fault has been simulated on the buck converter of Figure 2.12 and the simulation results are shown in Figure 2.16. A single shoot-thru fault is simulated followed by a sustained shoot-thru fault. The shoot-thru fault causes the current I_{in} to rise to ~1kA limited by the CDCCB. Detecting that I_{in} crosses the threshold indicating a buck converter fault. The protective action of hard-turning off the CSDs is performed to interrupt the current and thereby turning off the PEBB. Figure 2.16(b) shows the device currents. Under normal

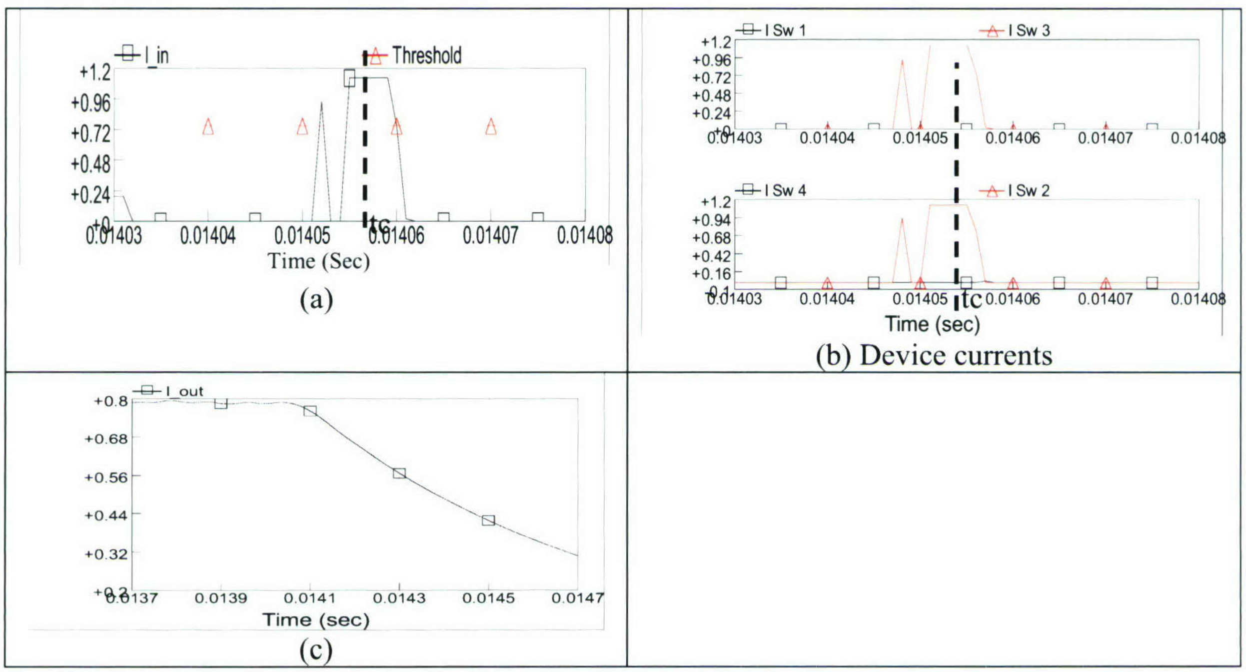


Figure 2.16 : Buck Converter Shoot-through fault

conditions, prior to fault, I_{sw1} and I_{sw2} or I_{sw3} and I_{sw4} conduct indicating the normal operation. During the shoot-thru fault, I_{sw3} and I_{sw2} start conducting simultaneously, which is detected as high current thru I_{in}, indicating the shoot-thru fault.

Transformer fault

The BCA monitors the transformer currents I_{x1} and I_{x2}, and uses a current differential scheme to determine if a fault is internal to the transformer or not. A transformer fault is flagged when the input-output current differential exceeds a threshold. A transformer internal fault causes the input capacitor to discharges to the fault through the CSDs. Since I_{in} will see this discharge current, the BCA monitors I_{in} and detects the fault by detecting the discharge current through I_{in}. BCA then turns off the PEBB to interrupt the fault current and isolate the fault. An important point to note here is that for the transformer faults, the reverse biasing of the diodes prevents the output capacitor from discharging into these faults.

The simulation result for a transformer primary side fault on the buck converter of Figure 2.12 is given in Fig.17. Prior to a fault at t=0.014s, the current differential is less than 2A indicating a normal operation. Following the fault on the primary of the transformer, at t=0.014s, the current I_{x1} (= I_{in}) increases. The BCA detects the overcurrent condition in I_{in} and flags a fault. Due to this increase in the I_{x1}, the current differential increases to 112 A, and exceeds the threshold of 20A at t=0.01403s thereby locating the fault to the transformer.

Ground Fault

Ground faults on the source side of the buck converter are detected by the upstream Rectifier Agents, as illustrated before. Ground faults on the load side do not have a low impedance path to source, since the transformer secondary is ungrounded. Therefore, the first ground fault on the load side is not critical and does not affect the system operation.

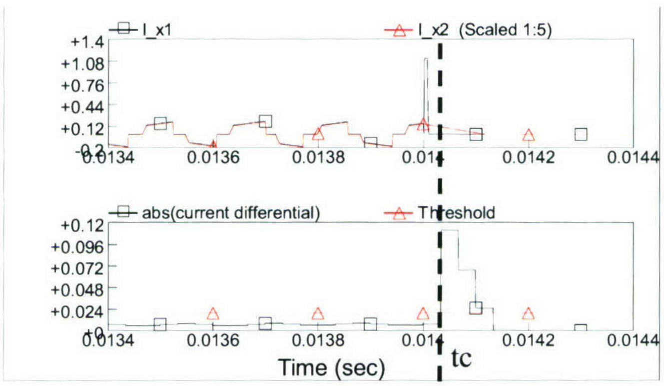


Figure A.17 : Transformer Primary side Fault Detection

III. System Protection using Solid State Protection Devices

One of the main challenges in protection of DC SES is that the semiconductor switches (GTO etc.) used in converters have very limited overcurrent carrying capabilities (usually 2 times their rated current). Hence, fault currents have to be interrupted very fast before they reach the overcurrent capabilities of the semiconductor switches. Another approach that has been taken to address this challenge is the use of recently emerging solid-tate based protection devices (circuit breakers and fault current limiters) [17-20].

One of the key advantages of solid-state CBs for DC SES is its ability to interrupt DC fault currents. Also, the solid sate based protection devices can replace the conventional devices to interrupt the fault faster. They also offer the capability to limit the fault current. Our investigation involved development of two different schemes. To illustrate them, we will consider faults on the DC bus, as a fault on the DC bus will cause quite high currents and the challenge is to isolate the faulted bus as quickly as possible. The two approaches are summarized below:

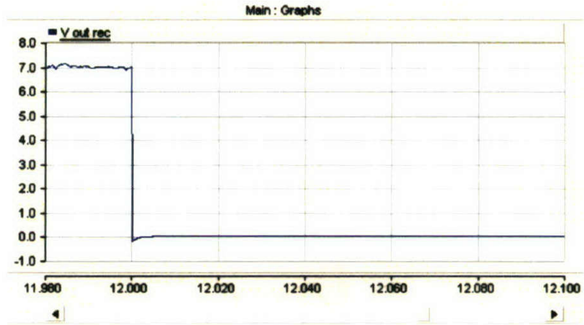
3.1 VSC as Crowbar

Currently, commonly used approach to isolate the faults on the DC bus involves the use of a crowbar at the ac side of the converter. The crowbar shorts the input and thus protects the converter from high currents, and the fault current is then interrupted by the AC circuit breaker on the source side (as shown in Fig. 2.1). For a 3-phase rectifier that is considered here, a separate crowbar may not be needed as we can short the ac side by setting all the switches on one side of the bridge (upper or lower) ON and the ones on the other side OFF during the fault. Hence, this is a good solution provided that the switches on the bridge can handle the high current stress during the fault, and the AC CB is fast enough to interrupt the fault.

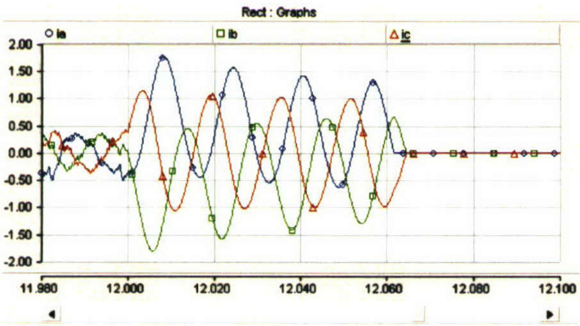
To assess the effectiveness of this scheme, simulations on the sample system has been performed using EMTDC. For this application, the CB is assumed to be a 3 cycle breaker. In the simulations a fault on DC bus occurs at 12^{th} sec. of the simulation. Figure 1.a shows the DC bus voltage profile after the fault. The bus voltage drops immediately to zero right after the fault. Figure 1.b shows the ac side current profile which is a typical profile for current interruption by an AC CB. The fault is interrupted in about 3 cycles as expected.

The rectifier output current following the fault is given in Fig.1.c, which shows that there is an initial high current due the DC capacitor discharge and then the rectifier acts like a crowbar and reduces the fault current on the DC bus, as expected.

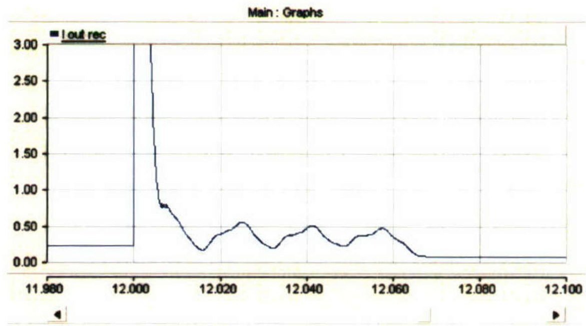
Note that the fault current after the capacitor discharge is quite limited due mainly to the coupling reactor (7%) on the AC side. Nevertheless, the switches on the rectifier are subjected to high currents, the switches will carry is about 2/0.25 = 8 times that of the normal current in this case. It should also be noted that the initial discharge current by the DC link capacitor is higher than 3 kA, and hence, limiting this current requires special protection on the capacitor [3].



(a) Rectifier output voltage (voltage in kV, time in sec).



(b) Rectifier input currents (kA)



(c): Rectifier output current (kA).

Figure 3.1: Rectifier currents and voltages due to a fault on DC bus

3.2 SSCB

As indicated before, power electronics based solid state CBs (SSCBs) have been developed recently, and they offer the possibility of interrupting fault currents very fast. These devices can therefore be used in DC applications. Hence, as an alternative approach, a SSCB is placed at the DC terminals of the VSC (as shown in Fig. 2) to interrupt the fault current. Figure 3 shows the detail of the SSCB. The SSCB is set to interrupt the fault when the current on the DC bus exceeds threshold value of 3 times the rated current. Meanwhile, to prevent overvoltage on the capacitor after the SSCB is open, a blocking signal is sent to the switches of the VSC.

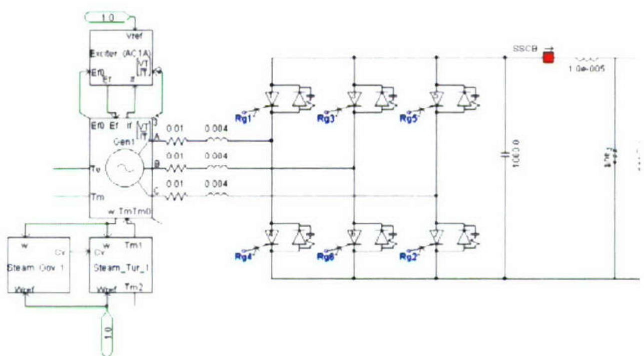


Figure 3.2: Using SSCB at DC bus for fault current interruption.

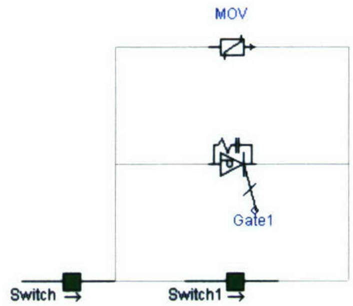
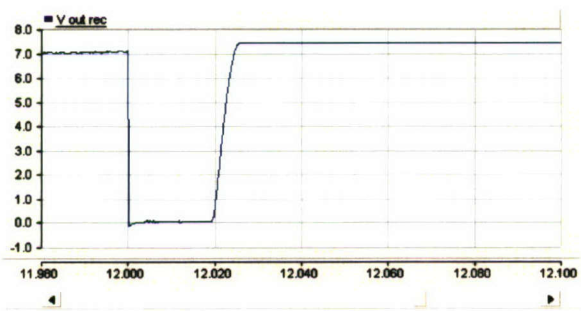


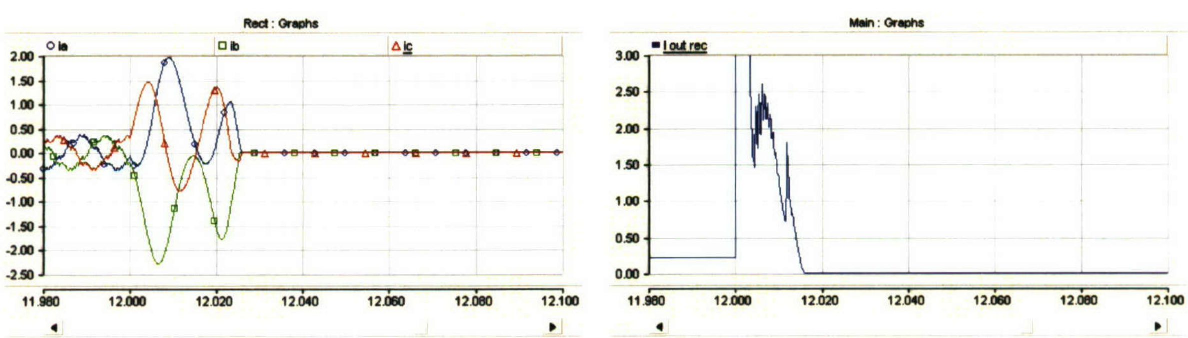
Figure 3.3: Hybrid SSCB (Switch1 is high speed mechanical CB).

Figure 4.c shows the rectifier output current during the fault and its interruption by SSCB. Since the current raises very fast after the fault, the SSCB detects the fault current very fast (within a few microsecond). Then the SSCB operates to interrupt the fault current. It is seen from the figure that the SSCB forces rectifier output current to become zero within 20 ms which is much faster than a conventional circuit breaker.

Figure 4.b shows the currents on the ac side. It is seen that after 20ms, the currents become zero. Note that as the SSCB is interrupting the fault current, the VSC is turned off (switch signals are blocked) to prevent the VSC overcharging the DC capacitor. Hence, as can be seen from Fig.4.a, the rectifier output voltage drops to zero during the fault and it raises back to around 7 kV as the capacitor starts charging after the fault is cleared.



(a) Rectifier output voltage (kV).



(b) Rectifier input currents (kA)

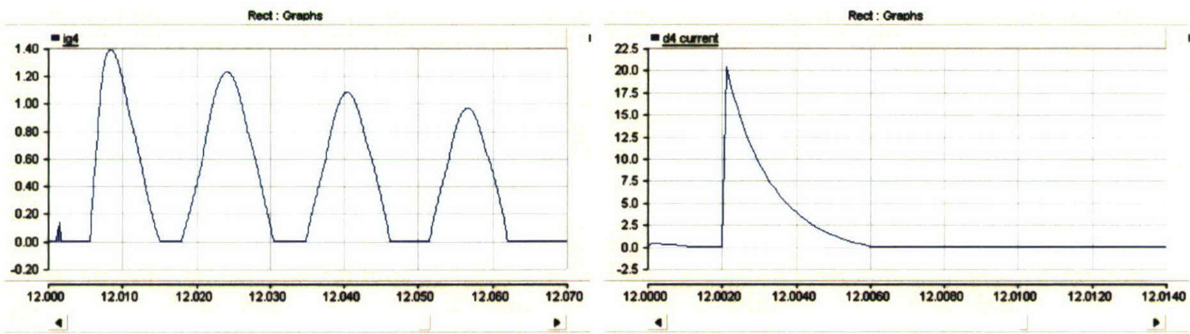
(c): Rectifier output current (kA).

Figure 3.4: Rectifier currents and voltages due to a fault on DC bus interrupted by a SSCB

3.3 ***Switch Realization***

The simulations given above are used not only to assess the feasibility of the proposed protection schemes, they also give us data needed to determine the proper ratings of the actual semiconductor switches that will be used to realize the protection devices considered. For this, both normal operation and operation during the fault is considered.

- Normal Operation: During normal operation, the switches should withstand VDC-link of 7000 kV and carry peak current of 400 A.
- During Fault: Currents through the switches of the VSC during the fault – the main switch, and in the antiparallel diode- are given in Fig.5.a and Fig.5.b, respectively. It is seen from Fig.5.a that we need switches which can carry 1.4 kA during the fault. And, from Fig. 5.b, we need diodes that can carry the surge current of 20 kA during the fault.



(a) Main switch current (b) Diode current

Figure 3.5: Current through the switches of the VSC during a DC bus fault.

Based on these results, these switches can be realized with the existing devices – IGCT and IGBT- as follows:

- *IGCT:* We can use 3 IGCTs (ABB 5SHY 30L6010) which have V_{DClink} of 3600 V and $I_{T(RMS)}$ of 2000 A in series with 3 antiparallel diodes (ABB 5SDF 08H6005) which have V_{DClink} of 3300 V and I_{FSM} of 40000 A for one switch. Figure 6 shows this switch realization. Note that we use 3 IGCTs to satisfy n-1 contingency.
- *IGBT:* We can use 4 IGBTs (ABB 5SNR 10H2500) which have V_{CES} of 2500 V and I_{CM} of 2000 A in series with 4 antiparallel diodes (ABB 5SDF 08H6005) which have V_{DClink} of 3300 V and I_{FSM} of 40000 A for one switch. Note again that the use of 4 IGBTs satisfies the n-1 contingency.

These switches can also be used for SSCB provided that the discharge current from the DC capacitor is limited by a protection device on the capacitor itself.

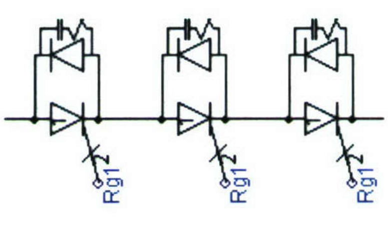


Figure 3.6: Switch realization using real IGCTs.

IV. Reconfiguration Management on a DC SES

For the shipboard systems, it is becoming critical that the reconfiguration can seamlessly transfer loads to an alternate source since a small interruption in power to equipment like weapons system may have catastrophic results [1,22,23]. The DC Zonal architecture offer opportunities to achieve this goal. The goal in this task is to show the feasibility of this goal by developing new reconfiguration management for the DC SES.

The reconfiguration on a system is performed after the protection system first detects and isolates the disturbance. Reconfiguration is done by the opening or closing of switches, sectionalizers and/or CBs, to minimize the power supply disruption to the loads, without exceeding the limits of the system components (generators, lines etc). We have shown that the new agent based System Protection scheme for the DC SES can detect and isolate single faults very fast. As it will be illustrated below, such a fast protection scheme facilitates and simplifies system reconfiguration on a DC Zonal SES considerably.

Figure 1 illustrates the placement of sectionalizers on the prototype DC SES considered in this study. Normally closed sectionalizers are provided at the boundary of each zone. They can be opened during reconfiguration when a DC bus fault or zone flooding is detected. This would help to isolate a given zone (after the protection agents have detected and interrupted the fault and de-energized the bus) so that the adjacent zones are not affected. Providing sectionalizers will ensure that only the zone affected by battle damage or zone flooding can be isolated individually. This minimizes the number of loads to be interrupted. The normally open sectionalizers are provided to improve system survivability under the condition of multiple DC bus fault due to battle damage.

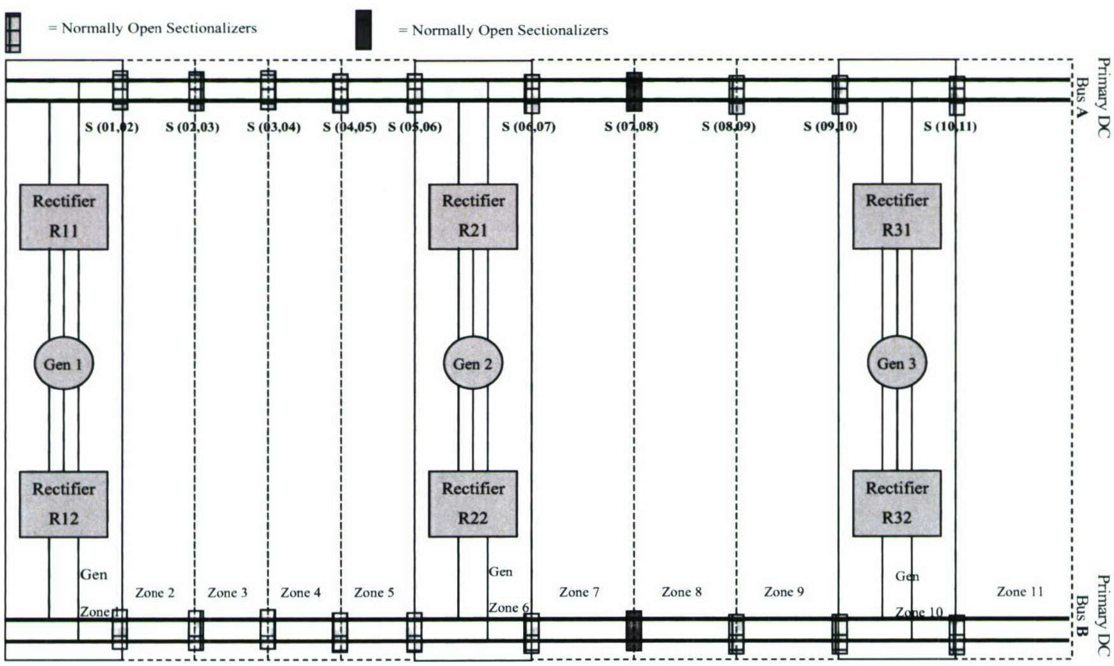


Figure 4.1: Shipboard Electrical System with Three Generator Configuration

Another key feature of the DC SES that will facilitate the reconfiguration is the way power is distributed within a zone, which is illustrated in Fig. 2. The Buck converters interface the primary DC bus to the secondary DC bus. The non-critical loads are fed by either of the secondary DC buses. The vital or the critical loads are fed by auctioneering diodes as illustrated in Fig.2. The auctioneering diodes ensure that the transfer of power from main bus to alternate bus is seamless and without interruption. To allow the proper operation of the auctioneering scheme, the output of the buck converters which are fed from the alternate bus is kept just below (at 750V) the output of the buck converter from the main bus (800V). The converter module or the inverter module which interfaces the load to the secondary bus absorbs the glitch when the power is transferred from one bus to the other, therefore making the transfer seamless to the load. In addition, the two buck converter agents of the given zone collaborate with each other, so that when the power is transferred from the main bus to the alternate bus, the output of the alternate buck converter is raised to 800V.

Different fault and battle damage conditions are considered to make sure that in each case the power can be transferred seamlessly from the main DC bus to the alternate DC bus following the fault and that the agents reconfigure the system as desired. The reconfiguration procedures for the main damage conditions are described next.

a) Reconfiguration after a fault on the primary DC bus

Under normal operation, the loads within a zone are supplied from one of the primary DC bus. In Fig. 2, for example, the loads are supplied from the Port Side Primary DC Bus **A** via the Buck Converter **A**. The auctioneering diode that connects the critical load to the alternate bus is open under normal operation as the bus voltage of the alternate bus B is lower than the main bus A.

When a fault on the primary DC bus occurs, the protection agents for the rectifiers (RA) that supply power to the bus detect the fault and isolate it by isolating the DC bus. The fault on the

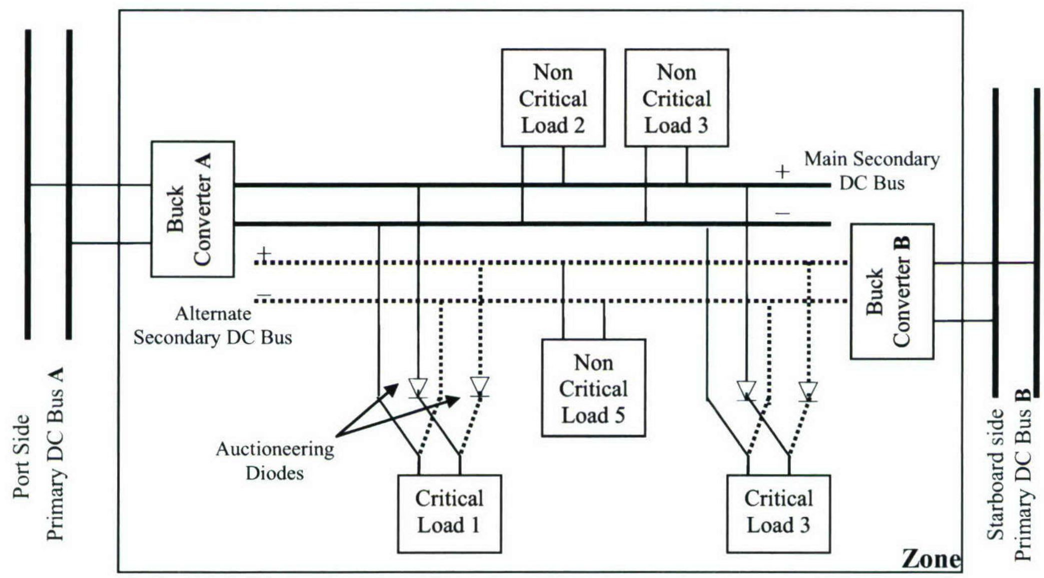


Figure 4.2 : Intra Zonal Bus Configuration

DC bus will cause the voltage on the secondary bus of the zone to collapse and when this voltage falls below 750V, the critical loads in the zone is automatically transferred to the alternate DC bus via the auctioneering diodes. Meanwhile, the agent BCA on the buck-converter connected to the faulted bus also detects the fault and identifies it as a source fault. After detecting the fault, the agent sends a message to the buck converter B agent to increase the voltage from 750V to 800V. This completes the transfer of critical loads from the main bus to alternate bus, and it is the first step of reconfiguration.

To illustrate the effectiveness of this scheme, simulations were performed with EMTDC /PSCAD on the system shown in Fig.3 [24]. Simulation results for a fault on the primary DC bus **A** at t = 0.1s are shown in Fig.4. Following the fault, the output voltage of the rectifier V_R1 collapses, as shown in Fig.4.a. Correspondingly, the rectifier output current, I_R1 rises as shown in Fig.4.b. The fault is detected by the agent of R1A and it shuts down the rectifier. Following the shutdown, the voltages of the secondary DC Bus **A** in both zones 1 and 2 (V_DC_Sec_1A and V_DC_Sec_2A) start decaying. This is seen in Fig.4.c and (d). When the BCA of B1A and B2A detect the source fault, they send a message to B1B and B2B respectively to increase the reference voltage from 750V to 800V. Therefore, the voltages V_DC_Sec_1B and V_DC_Sec_2B increase from 750 to 800V as seen in Figure 4.(c) and (d).

The BCA of B1A detects the fault at t = 0.01055s, therefore, the loads in zone 1 see the voltage dip for a transient time interval of 0.0056s. The voltage dip is less than 8%. The BCA of B2A detects the source fault much earlier at t = 0.101s, and therefore sends the message to the BCA of B2B to increase the voltage within 0.001s, therefore the loads of zone 2 see the voltage dip for about 0.001s. The rise in the voltage V_DC_Sec_2B causes the load current to be commutated from the secondary DC bus **A** to the secondary DC bus **B.** The voltage across the loads of the zone 1 and zone 2 are shown in Figure 4.(e) and (f).

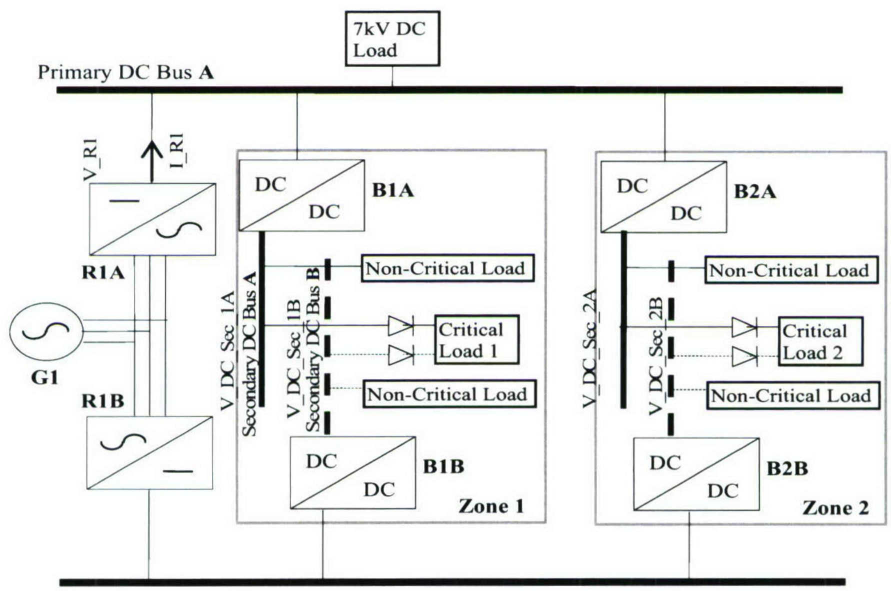
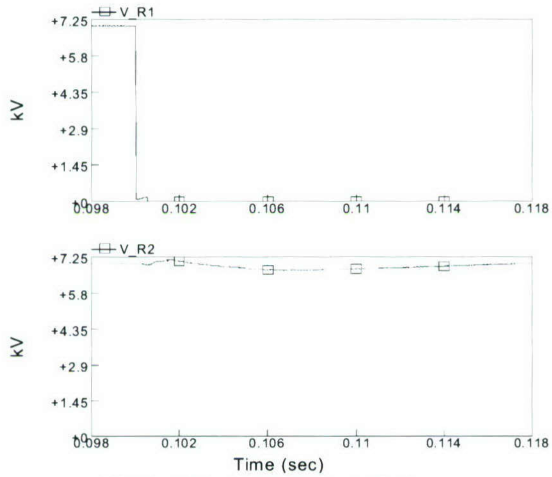
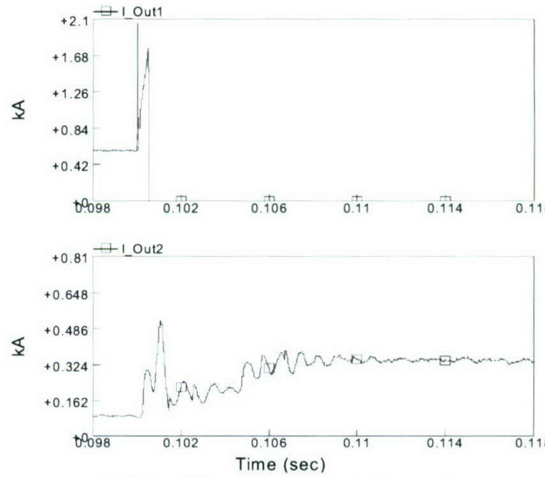


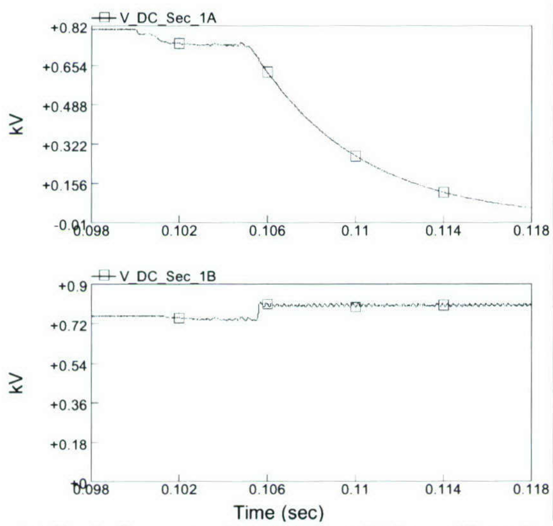
Figure 4.3 : Prototype System for Reconfiguration



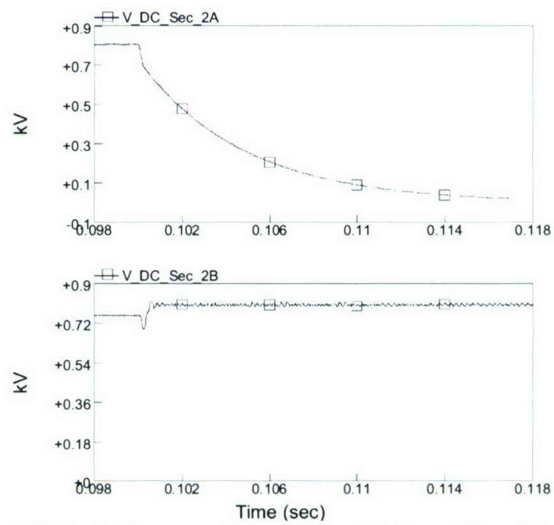
(a) Rectifier 1 &2 Output Voltages



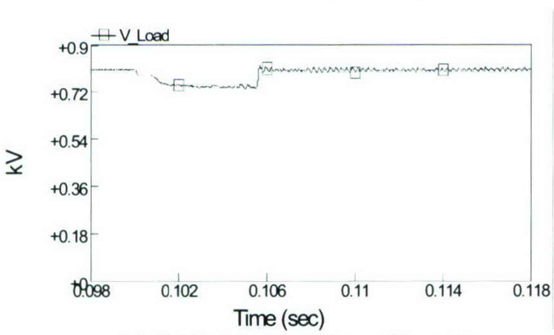
(b) Rectifier 1 &2 Output Currents



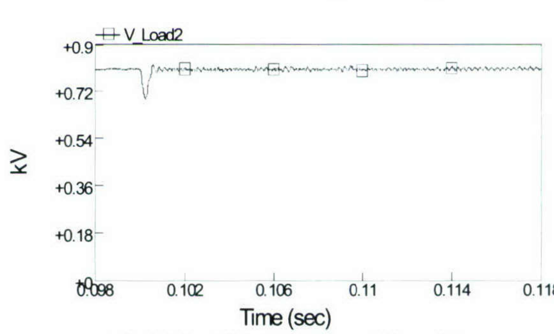
(c) Buck Converter 1 & 2 Output Voltage (Zone 1)



(d) Buck Converter 1 & 2 Output Voltage (Zone 2)



(e) Critical Load Voltage (Zone 1)



(f) Critical Load Voltage (Zone 2)

Figure 4.4: Simulation results of reconfiguration following a Primary DC bus Fault

The second step of reconfiguration in this case involves the reenergizing the non-critical loads that have been interrupted. To supply these non-critical loads, we use the sectionalizers on the primary DC bus to isolate the section of the DC bus where the fault has occurred. The challenge here is therefore, locating the fault. To facilitate this, we need current transducers on the sectionalizing switches. These monitors than will help us to locate exactly which zone the fault is in. Once the fault is located, then the sectionalizing switches for this zone can be opened to isolate the damaged part of the DC bus. Finally, the healthy part of the DC bus can be re-energized by energizing the rectifiers that can supply power to the bus.

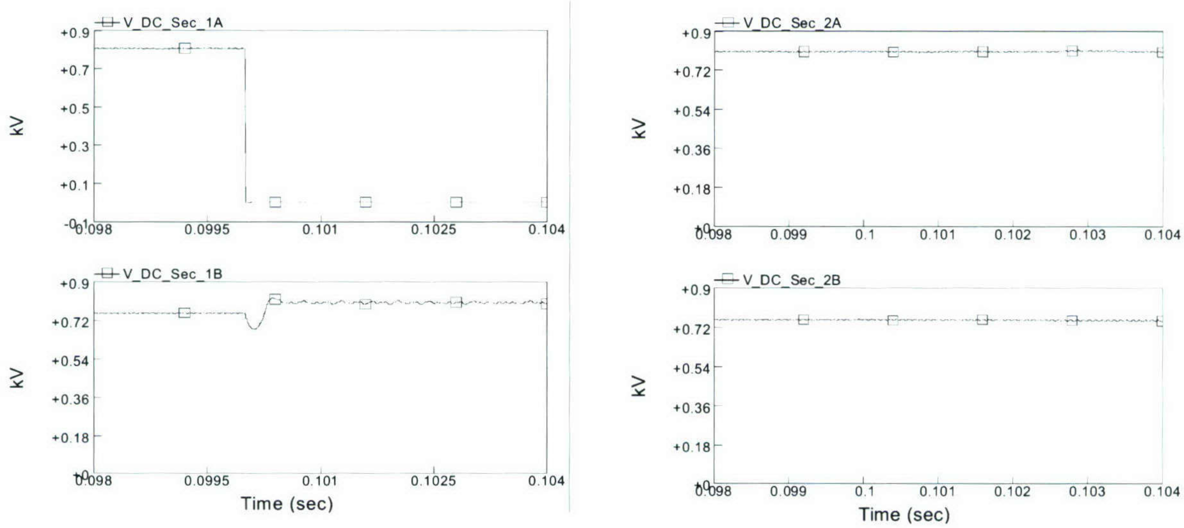
To illustrate this, let us consider that a fault occurs in zone 5 of the system shown in Figure 1. The RAs of rectifier R11 and R21 will detect and interrupt this fault. This will cause the critical loads to be transferred to the alternate bus **B** and the DC bus **A** to be de-energized. Following the isolation of the bus A, in the second stage of restoration, the fault will be located to be in zone 5, and hence the sectionalizing switches S(04,05) and S(05,06) will be opened. This will isolate the faulted zone 5, and now will allow us to re-energize the un-faulted part of the bus to supply the non-critical loads that have been interrupted.

The opening of the above mentioned sectionalizers may also create another challenge of generation-load mismatch. After the fault when the zone 5 sectionalizers have opened and isolated the zone, in the reconfigured system, Gen1 supplies power to the zones 1 through 4 while the Gen2 supplies power to zones 6 and 7. To minimize load mismatch under this condition one strategy is to serve only the non-critical loads from bus A and critical loads from bus B, as both generators will be feeding bus B.

b) Reconfiguration after a fault in a Zone

A fault within a zone will affect only the local load, as the fault will be isolated quickly by the protection agent of the Buck converter that supplies power to the zone. For example, for a fault on the secondary DC bus of zone 1 of Fig. 3, the agent of the buck converter agent will detect the fault, and isolate it by shutting down the converter. This will cause the auctioneering diodes to transfer the critical load in the zone to the alternate bus seamlessly. This action does not affect the loads in the other zone at all.

To illustrate this case, a fault on the secondary DC bus A of zone 1 of Fig. 3 has been simulated. The results are shown in Fig. 5. Prior to the fault at t = 0.01s, the loads of zone 1 are supplied from the main bus A. The buck converter agent BCA detects the fault and isolates the zone by shutting down the converter in 0.4ms. It also sends a message to the BCA of B1B to increase the voltage V_DC_Sec_1B, from 750V to 800V. Therefore, load experiences a voltage dip as seen in Fig.5(a) for 0.4ms. Fig.5(b) show the voltage profiles for zone 2. These figures indicate that the loads of the second zone are not affected in any way, due to the fault in the zone 1.



(a) Buck Converter 1 & 2 Output Voltage (Zone 1)

(b) Buck Converter 1 & 2 Output Voltage (Zone 2)

Figure 4.5 : Load transfer following a fault in a zone

c) Reconfiguration after a Generator Failure

One of the most serious contingencies on a SES is a fault or damage in one of the generators. Any fault on the generator side will be detected by the rectifier agents as the source side fault. The agents then will shut-down the rectifiers to isolate the generator. This will force the remaining generators to increase their outputs to maintain power to the loads. If however there is a shortage of generation in any section of the system, a reconfiguration is needed to help prevent load shedding. This reconfiguration is facilitated by the sectionalizing switches on the primary DC bus. For example, for a failure of G1 in Fig. 1, closing of the NO switch S (07, 08) will allow the G3 to pick up some of the G1 load.

d) Reconfiguration after a battle damage

A battle damage can cause multiple faults on the DC bus, a generation failure, and/or zone damage. Reconfiguration action for multiple faults on the primary DC bus will be the same as a single fault that has outlined before, as the current monitoring through the sectionalizing switches will enable us to locate the damage part of the bus even under multiple faults. The zone flooding, on the other hand, may require special handling. Flooding of a zone may cause fault on the healthy bus, and when this happens, the second bus has also to be sectionalized in order to isolate the damage on the second bus. This again will be done by the proposed reconfiguration scheme. This second reconfiguration on the second bus, however, may cause further generation-load mismatch, and thus may necessitate load-shedding. Currently, we are working on development of load management schemes for operation under such emergency conditions.

V. Conclusions

The results presented show that the two main research goals/metrics have been met: (i) development of new protection schemes for DC SES that will meet the requirements, and (ii) development of new configuration management schemes to assure continuity of service to loads especially during fault/damage conditions.

The first research focus was on development of new protection devices that can provide fast fault current limiting and interruption in DC distribution. The results show that the two approaches considered can address this critical challenge:

- The Voltage Source Converters (VSCs) can be used for fault current limiting and interruption. It has been shown that revisions are needed on the VSCs to perform these functions, and when properly designed, VSCs can limit and interrupt the fault currents very fast - within a few microseconds.
- Alternatively, new solid-state based protection devices (SSPD)- current limiters and circuit breakers – can be employed to limit and interrupt the fault currents. It has been shown that for DC SES these devices should be hybrid type in order satisfy the protection and operation requirements.

The second research focus was on the development of fast *protection schemes* to isolate the faulted/damaged part of a system. It has been shown that the proposed "agent" based scheme provides effective protection of DC SES, in that the *protection agents*, which are associated with protection devices (converter or SSPD), can autonomously detect and isolate any disturbance that can occur on the system, and the speed of response of the agents is very fast, less than 1 ms for disturbances on the DC primary bus, which is the most vulnerable section of a SES.

The third research focus was on the development of configuration management schemes that can automatically reconfigure the distribution circuit so that the impact of the fault/disturbance on the loads will be minimized. The accomplishments include the development of an "agent" based collaborative scheme that performs reconfiguration in two stages:

- Automatic load transfer and bus reconfiguration: The scheme uses the protection agents to localize the fault fast and then assure continuity of power to the critical loads even under battle damage conditions. This is accomplished by (i) first having the critical loads to be seamlessly transferred to the alternate bus without any disruption of power, and then (ii) operating the sectionalizing switches on the main DC bus to reconfigure the DC bus in order to minimize the interruption to the non-critical loads to about 10-20 msec.
- Load Management: For extreme contingencies which cause an unbalance between supply and demand for power, the load management scheme uses a central agent at the generator to curtail the loads when the generator overloads. To further facilitate load management under contingency conditions, the use of distributed generation has also been investigated.

Simulations on a prototype DC SES indicate that these new schemes ensure that the protection and reconfiguration is achieved globally at system level, rather than local level, and thus it provides the desired self-healing functionality for the SES. Hence, this research illustrates the critical importance of these functions for the new DC zonal SESs the navy envisions for its future naval ships, and provides new novel approaches to meet these requirements.

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