ABSTRACT

MAHAJAN, NIKHIL RAVINDRA. System Protection for Power Electronic Building Block Based DC Distribution Systems. (Under the direction of Mesut E Baran)

The purpose of this research has been to develop an agent based protection and reconfiguration scheme for power electronic building block based (PEBB) DC distribution systems. One of the foremost applications would be in the new zonal DC distribution on naval ships. The research involves the design of an agent based protection scheme which uses the PEBBs for current limiting and circuit breaking purposes. Considerations are given to reduce the system downtime under fault conditions, allow proper coordination and provide backup protection. The research also involves the design of a reconfiguration management scheme based on collaborative agents. The collaboration ensures that the reconfiguration is achieved at a global level, enhancing the system survivability under the conditions of multiple faults and damages. The coordination ensures that only the faulted part of the system is isolated and the reconfiguration makes sure that the power to the healthy part of the system is supplied continuously. The reconfiguration management also performs load shedding if the generation does not meet the load demand of the reconfigured system due to a fault or damage in the generator.

Keywords: Agent, Buck converter, Circuit-Breaker, Current-limiting, Distribution, EMTDC, Inverter, PEBB, Protection, PSCAD, Reconfiguration, Rectifier, SES

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System Protection for Power Electronic Building Block Based DC Distribution Systems

By

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LIST OF ABBREVIATIONS

μ	= 10^{-6}, micro, a prefix
A	Ampere, unit symbol abbreviation for current
AC	Alternating Current
BCA	Buck-Converter Agent
BCIS	Buck Converter Inverting Stage
BCRS	Buck Converter Rectifying Stage
CB	Circuit Breaker
CSC	Current Source Converter
CSD	Controlled Semiconductor Device
DC	Direct Current
DCCB	Direct Current Circuit Breaker
EMTDC	Electro-Magentic Transient DC Program
EMTP	Electro-Magnetic Transient Program
ETO	Emitter Turn-Off Thyristor
F	Farad, unit symbol abbreviation for capacitance
FBSOA	Forward Biased Safe Operating Area
FCLCB	Fault Current Limiting Circuit Breaker
Flt	Fault
FTS	Fast Transfer Switch

Gnd	Ground
GTO	Gate Turn-Off Thyristor
H	Henry, unit symbol abbreviation for inductance
HVDC	High Voltage Direct Current
Hz	Hertz, unit symbol abbreviation for frequency
IA	Inverter Agent
IGBT	Integrated Gate Bipolar Transistor
IGCT	Integrated Gate Commutated Thyristor
IGCT	Integrated Gate Controlled Thyristor
k	$= 10^3$, kilo, a prefix
L-G	Line to Ground
L-L	Line to Line
m	$= 10^{-3}$, milli, a prefix
M	$= 10^6$, mega, a prefix
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MOV	Metal Oxide Varistor
NC	Normally Closed
NO	Normally Open
PCFF	Power-Factor Correction with Fixed Frequency
PE	Power Electronic

PEBB	Power Electronic Building Block
PSCAD	Power System Computer Aided Design
PTC	Polymer Temperature Controlled
PWM	Pulse Width Modulation
RA	Rectifier Agent
RBSOA	Reverse Biased Safe Operating Area
RMS	Root Mean Square
s	Second, unit symbol abbreviation for time
SCR	Silicon Controller Rectifier
sec	abbreviation for second
SEM	Semiconductor Unit
SES	Shipboard Electrical System
SLAP	Switch Level Autonomous Protection
SLP	System Level Protection
SOA	Safe Operating Area
TCC	Time-Current-Characteristics
V	Volts, unit symbol abbreviation for Voltage
VSC	Voltage Source Converter
Xmer	Transformer
ZEDS	Zonal Electrical Distribution System

1 INTRODUCTION

The main focus of this dissertation is the investigation of protection issues related to the new power electronic building block (PEBB) based DC distribution systems. One of the main challenges for protection against faults in the DC electrical systems is the unavailability of fast DC circuit breakers. Present day DC systems, therefore, still employ conventional devices such as AC side circuit breakers, fuses and/or crowbars for protection purposes. These circuit breakers and fuses are relatively slow and result in considerable system downtime.

In the PEBB based DC distribution, the PEBBs are multifunctional modules which are expected to perform power conversion, monitoring and limiting current and protecting the system during faults. Therefore, the PEBBs can take over the circuit breaker functions and eliminate separate circuit breakers (CB). Investigation of the feasibility of this functionality for the PEBB has been one of the main focuses of this dissertation. The second part of the dissertation involved the design of an agent based system protection scheme to detect and locate the faults that may occur on these new PEBB based DC distribution systems.

Following the fault isolation, a reconfiguration of the unfaulted part of the system is desired. The dissertation proposes a reconfiguration management scheme which minimizes the number of system components left without power following the fault isolation by the agent based system protection scheme.

1.1 Background

Power system protection has evolved from relatively primitive devices to complex systems over the years [1]. The functionality and sophistication of the protection systems has also increased with the increased complexity of the power systems [2]. The primary function of typical protection system is to detect the abnormalities, like over-currents, faults, short-circuits etc; limit the damage caused by them; and preferably find the location of the fault for ease during repair operations. In AC power systems, the detection is performed by various types of relays while the CBs isolate the faults to limit the damage.

Modern power electronic (PE) devices such as power Metal Oxide Semiconductor Field Effect Transistor (power MOSFET), Insulated Gate Bipolar Transistor (IGBT), and Emitter Turn Off device (ETO) have the ability to monitor, limit and interrupt high currents [3]. These features of the modern PE devices, to monitor, limit and interrupt currents allow them to be potentially used simpler protection schemes. This is especially true now, when IGBTs and likes are fast replacing thyristors and SCRs in the medium-high power range. The PEBBs employ IGBTs or the newer ETOs in a voltage source converter topology as opposed to the thyristor based current source converter topology. These PEBBs are connected to each other and to the generation and loads to make up a DC power distribution system, and thus envision the whole power handling system within standardized blocks [4].

Present day HVDC systems are typically employed in back-to-back configuration or in a multi-terminal configuration connected by DC lines. In contrast to these present day systems, a new zonal architecture has been proposed for distribution of power by DC to relatively concentrated loads such as industrial parks, loads onboard ships, and other high concentration loads. This new zonal DC distribution architecture comprises of the interconnected standardized PEBB blocks feeding power to the loads via one or more DC buses [5]. In this new DC distribution architecture, the loads are divided into zones and each zone consists of physically closely located loads. A simple single bus zonal DC electrical distribution system with two load zones is shown in Figure 1.

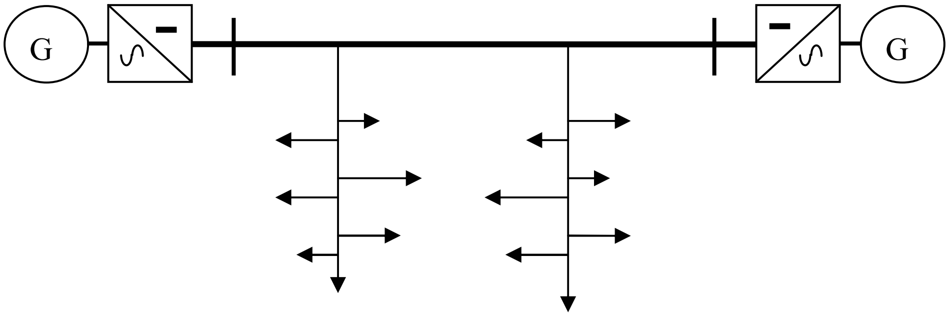


Figure 1 : Simple Single Bus 2 Zone DC Distribution System

In the new DC distribution, the PEBBs are used to convert power from AC to DC, convert voltage from one level to another, commensurate with the loads and also convert power back from DC to AC. The PEBBs also perform frequency conversion and power conditioning.

There are many advantages inherent to such a PEBB based DC power distribution system. First, the PEBBs are multifunctional modules and are expected to perform power conversion, monitoring and limiting current and protecting the system during faults. Thus, DC zonal electrical distribution system will facilitate fault isolation [6]. Since the monitored quantities are DC values, the current sensors and algorithms required to detect the fault conditions are both simpler and faster. As a result, the fault detection and interruption can be achieved much faster.

A second advantage of zonal DC distribution is that variable speed motor control is readily available to many pumps and blowers to operate these devices at the highest efficiencies. In addition substantial inrush currents experienced when starting large motors may be limited or even eliminated, aiding in maintenance of a stable bus voltage. Furthermore, since the PEBBs can perform voltage conversion and current limiting and interruption, the distribution transformers and switchgear may be eliminated. This offers considerable benefit in terms of weight size and cost.

In these modern DC distributions systems, the PEBBs are expected to perform multiple functions like power flow control and voltage transformation, etc [6]. In addition, these modules are also expected to perform monitoring and limiting the current through semiconductor devices, and suitably protecting the system during fault conditions [6], thus opening new avenues for protection. The typical voltage source converter topology that is employed in the present day converters cannot perform current limiting and interruption functions, therefore do not meet the expectations. Therefore additional external devices such as circuit breakers fuses and/or crowbars are needed or protection. These circuit breakers and fuses are relatively slow and result in increased system downtime.

This dissertation, therefore, focuses on (a) modifying the switch realization of the PEBBs, so that these PEBBs can additionally function as current limiting circuit breakers and meeting their expectations, (b) investigating the stresses on the switches when the PEBBs act as circuit breakers, (c) the design of Protection-Agents for the detecting, locating and taking proper protective action for interruption of different faults on the system, and (d) the reconfiguration of the system to maintain continuity of the supply to the loads.

1.2 Motivation

Recent advances in Voltage Source Converter (VSC) technology has made possible for power to be transmitted and distributed by DC. HVDC light systems based on VSCs are now even available in the market for power ranging from as low as few 100s of KVA to the order of 100s of MVA. The U.S. Navy is also presently investigating the implementation of DC Zonal Electrical Distribution System, also called Shipboard Electrical System, SES, for its next generation ships to replace the current AC radial distribution system [6, 7]. The SES is a typical example of the PEBB based DC distribution system. A prototype SES as shown in Figure 2 is based on the PEBB concept which realizes the complete power system in standardized converter building blocks. The DC distribution on the SES allows for the decoupling of the generator frequency from the loads, and thereby allowing the generators and the various loads to operate at their highest efficiency. This results in cost, weight and size optimizations [8]. Thus the advantages of using zonal DC distribution for power onboard ships includes cost savings, elimination of switchgear for protection and isolation without sacrificing performance or safety requirements.

The new DC distribution systems, such as the SES, would essentially comprise of the various interconnected PEBB modules, with the protection functions still performed by relatively slow acting mechanical circuit breakers on the AC side. Investigations were performed, which suggested the feasibility of combining circuit breaker functions into the PEBB modules. We propose to eliminate separate mechanical circuit breakers and perform the current limiting and circuit breaking by the PEBBs themselves, thereby meeting the expectations of the PEBBs set forth earlier. This change would also lend itself to cost, size, weight, maintenance and space reductions as envisioned in [8]. The PEBB based circuit breakers, by their very fast time of operation would reduce the system down-time and provide better continuity of service to the loads of the system.

This study is motivated by these advantages, for using the PEBBs to function as current limiting circuit breakers and replace mechanical circuit breakers in novel protection schemes in the new era of power electronics based DC electrical distribution systems.

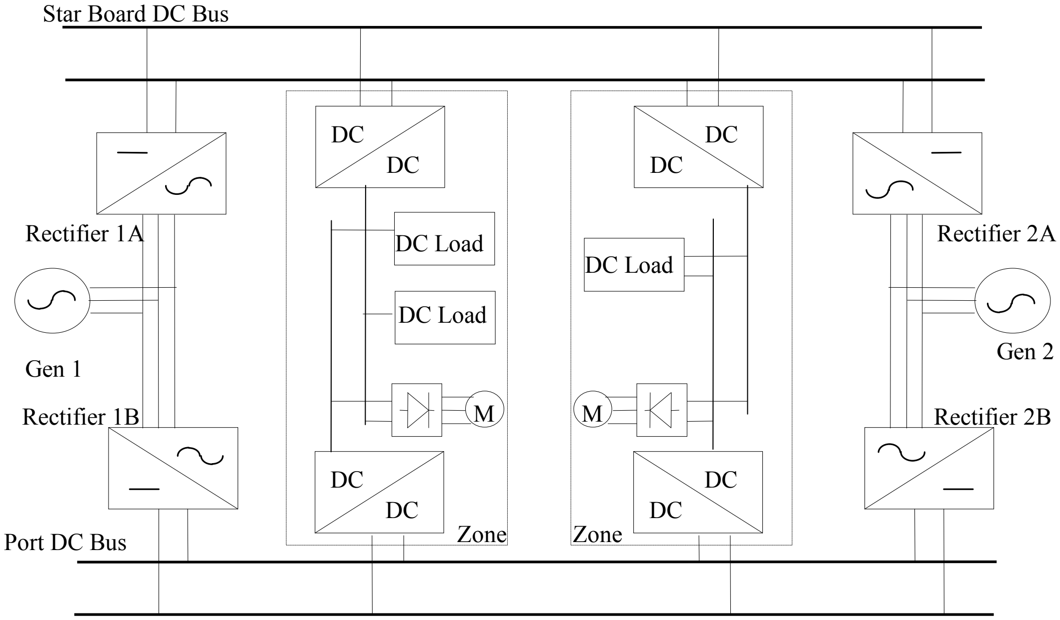


Figure 2 : DC Zonal Electrical Distribution System (also, SES)

One of the important issues that need special consideration from the protection and safety perspective is the system grounding. From the point of view of detection of faults, higher currents are easy to detect, but for safety reasons, the ground currents on the SES need to be limited to a low value. The generator grounding impedance plays an important role in minimizing these ground currents. Therefore, investigations were performed to select the type of grounding (solid, low impedance, high impedance or isolated) for the zonal DC SES such as the one shown in Figure 2. Investigations were also performed to determine the ground loop interaction of generators sharing the same ground [9-11] . It was shown that when the generators are solidly grounded, large ground circulation currents of the order of 100A flow through the generator neutrals. It is also indicated in [11], that high impedance grounding of the generator neutral gives a compromise between the ground loop currents, safety and protection. Therefore, the zonal DC SES as shown in Figure 2 is high impedance grounded.

1.3 Outline

Chapter 2 starts with laying down the requirements of a CB and follows it up with a review of the state-of-the-art on current limiting circuit breakers. It then proposes to unify the concept of the PEBB and circuit breaking and explains the required switch modifications needed in order to use the PEBB as current limiting circuit breaker. The chapter considers three typical converters, the rectifier, the inverter and the buck converter, for the purpose of current limiting and circuit breaking. It uses simulations to substantiate the claims.

Chapter 3 introduces protection at system level followed by a survey of present HVDC protection schemes. It defines system protection as applicable to the DC distribution system under consideration – the DC zonal SES. The chapter further presents the principles of agent based system protection. Specifically, it details the detection principles and protective actions of the rectifier Protection-Agent, the Buck Converter Protection-Agent and the Inverter Protection-Agent. Simulation results are provided to demonstrate the detection and operation principles. In addition to the detection principles, the chapter also deals with the coordination and backup requirements. The chapter concludes with the demonstration of the operation of backup protections for some of the important faults on the DC SES.

Chapter 4 investigates the issues relevant to the problem of system reconfiguration due to faults, damages and material casualty on a DC zonal SES. It explains the main issues that need consideration for the reconfiguration management scheme to provide uninterrupted supply to all the loads subsequent to the detection and protection action of the protection scheme. The main design issues are the choice of number of generators, choice of number of sectionalizers, location of the sectionalizers, and the intra zonal secondary DC bus configuration. The chapter then explains the operation of the reconfiguration management under different contingencies such as generation failure, multiple faults, etc. Finally, simulation results for two of the main contingencies are provided to demonstrate that the reconfiguration management can seamlessly transfer power to the load from the main supply bus to the alternate supply bus.

Chapter 5 concludes the dissertation, states the author's contributions and indicates the possible future research efforts that could further add to the findings of the dissertation.

2 CURRENT LIMITING DC CIRCUIT BREAKER

2.1 Introduction and Overview

With the introduction of different types of converters into the AC systems, protection issues related to fault interruption emerged. To protect the system against the non self-extinguishing DC faults, a need for DC circuit breakers (DCCB) was immediately felt. Protection philosophies from AC system protections drifted into the protection of these new mixed AC-DC systems and fault interruption was done by employing high voltage high power AC circuit breakers on the AC side. The use of AC circuit breakers (ACCB), therefore deferred the development of the high power DCCB. Low cost alternatives for fault interruption involving crowbars and fuses were also borrowed from AC protections. In addition to this, the ability to control the complete converter delayed the development of DCCB.

The advent of complete gate controllable silicon based solid state devices like the GTO, IGCT and ETO, stimulated the development of the DCCB. Various types of DCCBs based on such devices have been reported in literature [12-16].

The principal function of a CB is to interrupt short circuit current under fault conditions. All the same, under normal/non-fault operating conditions it should also carry the normal rated load current with high efficiency. Thus, the main requirements for a CB are [17]:

(1) The CB should be able to interrupt a short circuit current, normal rated current, or lower, and interrupting this current quickly without causing an abnormal voltage.

(2) The CB should be good conductors and have low voltage drop and losses, withstand normal currents as well as short circuit currents, thermally and mechanically.

(3) The CB should withstand the short circuit for a certain time required to decide whether it is a sustained or a transient fault and whether to interrupt the circuit or not.

(4) When open, the CB should be excellent insulators, and withstand the normal as well as the transient voltages between phases and phase to ground.

(5) The CB should be able to close a shorted circuit quickly and safely.

Thus, for the new solid state DC circuit breakers to be put to practical use and to operate successfully, these new solid-state-device based circuit breakers must provide at least the same level of functionality as mentioned above and that has been provided by the AC circuit breakers, while still operating at high efficiency.

The following sub-section describes one of the state-of the art hybrid DC circuit breaker which performs these functions successfully.

2.2 Fault Current Limiting Circuit Breaker: A Literature Survey

In the early days of HVDC, there was no need for DCCB, when all transmissions were point-to-point, allowing complete control of current by converter action, even under fault. In principle, the same approach is valid for multi-terminal HVDC systems as well. However, it would be necessary to shut-down the entire system in order to isolate and remove a fault from any branch of a multi-terminal current source converter (CSC) based DC system. This situation encouraged the development of DCCB, which, with or without converter control action (depending on their design) can switch out or return parts of the system [18]. This section reviews one of the state-of-the-art DC fault current limiting circuit breaker (FCLCB).

Modern semiconductor devices like GTO, IGBT and IGCT are now available with moderate to high current and voltage ratings. They also have very robust short circuit Safe Operating Area [19], and in combination with metal-oxide varistors, they have started competing with the thyristor based CBs. Novel concepts for FCLCB have been proposed in recent literature [14, 16, 20].

A hybrid arrangement of 3 different parallel paths for fault current limiting and interruption is presented in [14]. The hybrid FCLCB consists of 3 parallel paths, path A as shown in Figure 3, consists of a fast operating mechanical transfer switch, path B consists of a semiconductor unit & a fast disconnecting switch and a third path C consists of a current limiting impedance (with positive temperature coefficient) and a load switch. Since a single GTO can carry the current only in one direction, it is installed with a four-Diode Bridge to save costs (see D_1 to D_4 of path B in Figure 3), thus providing unipolar conditions for the GTO for both polarities of the fault current. This semiconductor unit is called SEM.

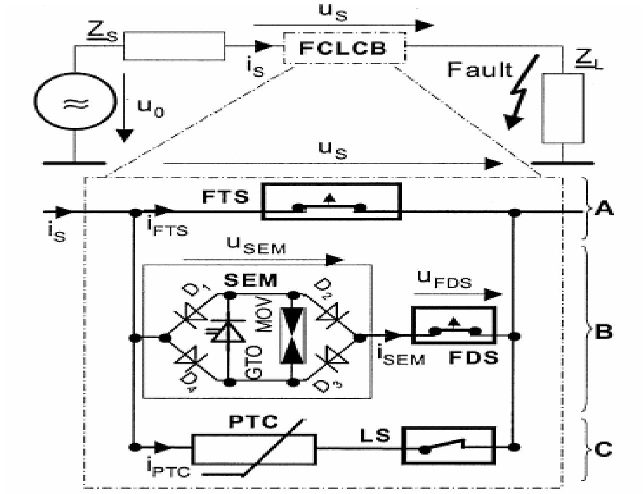


Figure 3 : Hybrid Fault Current Limiting Circuit Breaker

The operation of the FCLCB is discussed here in brief. When a fault occurs, the ultra fast transfer switch (FTS) opens within a few hundred µs and produces an arc voltage drop of several tens of volts. However, the arc voltage is much too small for the purpose of short-circuit current limitation. Therefore, a gate-turn-off thyristor (GTO) with high–current turnoff capability is employed to force the fault-current onto limiting impedance (path C).

Under normal operation, all three switches (FTS, FDS, and LS) are closed. When a fault occurs, the FTS is triggered by a separate sensing and control unit within 50µs. Due to contact separation of the FTS, an arc voltage of approximately 40V builds up across the opening double-contact gap. Since the on-state voltage drop across the SEM (which is connected in parallel to the FTS) of typically 10 to 15V, is smaller than the arc voltage, the current starts to commutate from path A onto path B. To ensure complete current commutation within a short time interval <100µs, the self-inductance of the loop A-B must be sufficiently low on the order of 0.5µH for the given current ratings. Such a low inductance can be achieved through close connection of the paths A and B using compact design.

Approximately 150µs later, the GTO is turned off, forcing the current onto the PTC-resistor in path C. Turning off the GTO causes a very high di/dt , and thus, an excessive voltage rise due to the self-inductance of the loop B-C (on the order of 10µH). As a consequence, the voltage u_S jumps up to approximately 4.5kV, and a further rise is limited by the metal-oxide varistor (MOV). At this moment, the FTS sufficiently recovers. In the presented example, the peak of the current through the semiconductors (I_{SEM}) exceeds the rating of a single GTO, so that two GTOs connected in parallel were chosen.

When the current is completely transferred onto the PTC-resistor the massive power dissipation within the PTC-resistor leads to a temperature rise which, in turn, results in a significant increase of resistivity due to its positive temperature coefficient. Along with the further rise of the current, a nonlinear increase of the voltage across the FCLCB occurs. The drive of the fast-opening disconnecting switch (FDS) is triggered immediately after the GTO is switched off and opens without arcing, thus protecting the SEM from further voltage rise. The FDS takes over the major portion of rising voltage ($u_{FDS} = u_S - u_{SEM}$) according to the capacitance ratio of the SEM and the FDS.

When the current finally crosses zero, it is interrupted by the switch LS. Contrary to the FTS, this has a voltage-free pause after arcing, and the FDS that opens without arcing at all, this switch has to withstand a small voltage transient. The switch LS needs only a low interrupting capability because of two reasons: First, because the circuit is resistive due to the PTC-resistor so that the amplitude of the TRV is rather small, and second, because the di/dt as well as the RRRV are low. However, the LS must operate quickly enough to interrupt in less than 6ms after fault detection.

The actual test results in [14] demonstrate that this FCLCB meets all the requirements previously put forth. It also withstands the through fault current for about 6ms while limiting the fault current. This long withstand time ensures that the segregation of the transient fault from the sustained fault can be done by the overall system protection scheme.

2.3 PEBB as Current Limiting Circuit Breaker

The discussions in the previous section of hybrid current limiting circuit breaker indicate towards the feasibility of using GTO-like devices to interrupt fault currents successfully by gate control. This section builds up on this fact and proposes to unify the concept of solid-state circuit breaking and the PEBB [21]. This is quite desirable in DC distribution, as the extremely fast operation of the PEBB based circuit breakers would allow for reduced system downtime and increased system's continuity of service. In addition, it would allow us to eliminate separate CBs to reduce space, weight maintenance and price requirements.

In this study, the option of using PEBBs for current limiting and circuit breaking is preferred over using separate DC circuit breakers which may be employed on the DC bus. The main advantage is that the DCCB cannot protect the system against the DC rail faults on the Rectifier.

This section demonstrates that by properly revising the switch realization of the PEBBs, the PEBBs can function successfully as current limiting CBs. Results of simulations performed in PSCAD/EMTP [22, 23] are also given.

2.4 Rectifier Fault Current Limiting CB

A typical 3-phase PWM boost voltage source converter PEBB along-with its filters is shown in Figure 4.

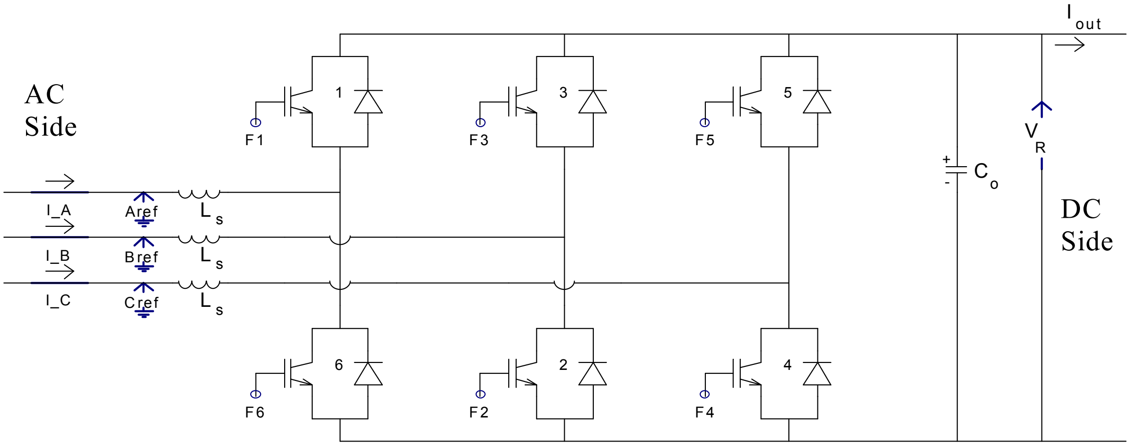


Figure 4 : Rectifier as a Typical PEBB

A 3-phase Voltage Source Converters (VSC) as shown in Figure 4, by itself, is helpless during faults. When a short circuit occurs on the DC side, the six anti-parallel diodes, which are a part of the VSC's switch realization, start to conduct as shown in Figure 5; and the VSC acts as a diode bridge rectifier. The fault is fed continuously through the red dotted path as shown and cannot be extinguished by converter action alone. It requires an ACCB to interrupt the fault. Figure 6 shows simulation results of the current through the diodes under fault condition. The fault is fed indefinitely until some external protection devices operate.

This current is limited only by the input inductor impedance, thereby causing currents as high as 13kA through a device that is rated to handle only about 4kA.

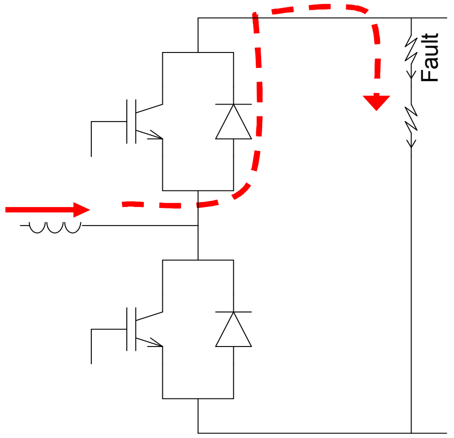


Figure 5 : VSC IGBT Anti-Parallel Diode Switch Realization

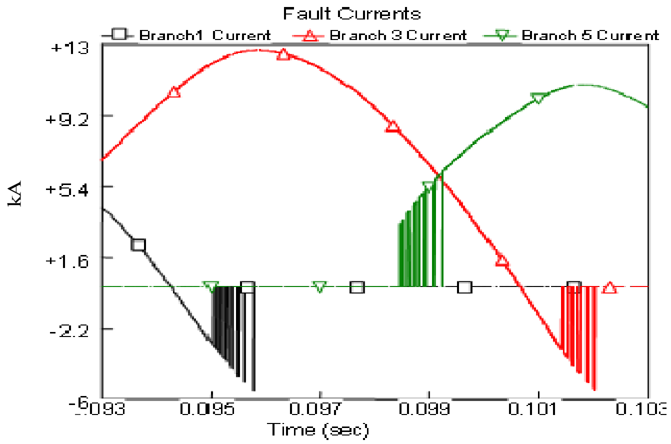


Figure 6 : VSC as a Diode Bridge Under Fault Condition

Some method to extinguish the DC fault is necessary. One of the methods is to use an AC circuit breaker on the AC side of the voltage source converter (VSC) or another method is to use a solid state hybrid FCLCB as discussed earlier.

All these methods require action by devices external to the PEBB to interrupt and isolate the fault. This section investigates the proposal of utilizing the PEBB themselves for interrupting the DC faults.

Similar to the FCLCB discussed above which uses positive temperature coefficient resistor in a hybrid concept for fault current limiting and breaking, semiconductor devices (like MOSFET, IGBT, ETO, etc) also have highly non-linear resistance characteristics in their active region. The operation of semiconductor devices in the active region (by gate voltage control) has been discussed in literature [4, 24, 25] as a useful technique for handling short circuits and for dv/dt control.

An example of current limiting and fault interruption (by operating the device in active region of the device-characteristics) is illustrated in Figure 8. Once a fault is detected, the gate voltage is reduced dynamically. This dynamic reduction of the gate voltage limits the fault current. Again, segregation based on elapsed time is used to differentiate the transient faults from sustained faults. For sustained faults, the gate voltage of the device is reduced until the device is completely turned-off, thereby achieving a complete shut-down in a controlled manner. This technique, known as ***soft shut-down,*** has been effectively used to extend the short circuit withstand time of devices possessing Forward Biased Safe Operating Area (FBSOA), such as the power MOSFET, IGBT and ETO.

As discussed, the conventional PEBBs require external devices like ACCB/fuses and/or crowbar protection for interruption and isolation of fault. Therefore, to eliminate this requirement, it is desirable to modify the topology of a conventional rectifier such that the fault can be interrupted by itself and eliminate the external devices that are required to interrupt the fault. To do so, we replace the anti-parallel diode of Figure 5 with a controllable semiconductor device (CSD), so that under fault condition, the CSD would not free wheel.

Two options – IGBT and ETO, were considered for replacing the diode with a CSD. The study in [19] considered one of the options to replace the anti-parallel diode from switch realization of a conventional rectifier bridge by an anti-parallel IGBT, to obtain the switch realization as shown in Figure 7.

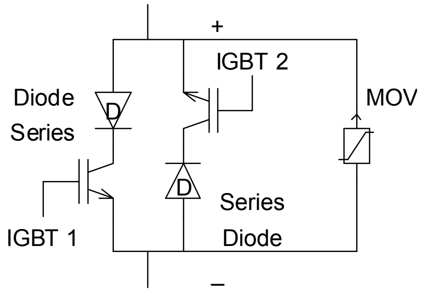


Figure 7 : Bi-Directional Current Control Switch Realization

It was found that the devices embedded in this new topology could be used for fault current interruption by soft turn-off by gate voltage control. The forward biased safe operating area (FBSOA) helps to reduce or even eliminate the snubbers by aiding in dv/dt control during turn-off, thereby aiding to limit over voltages.

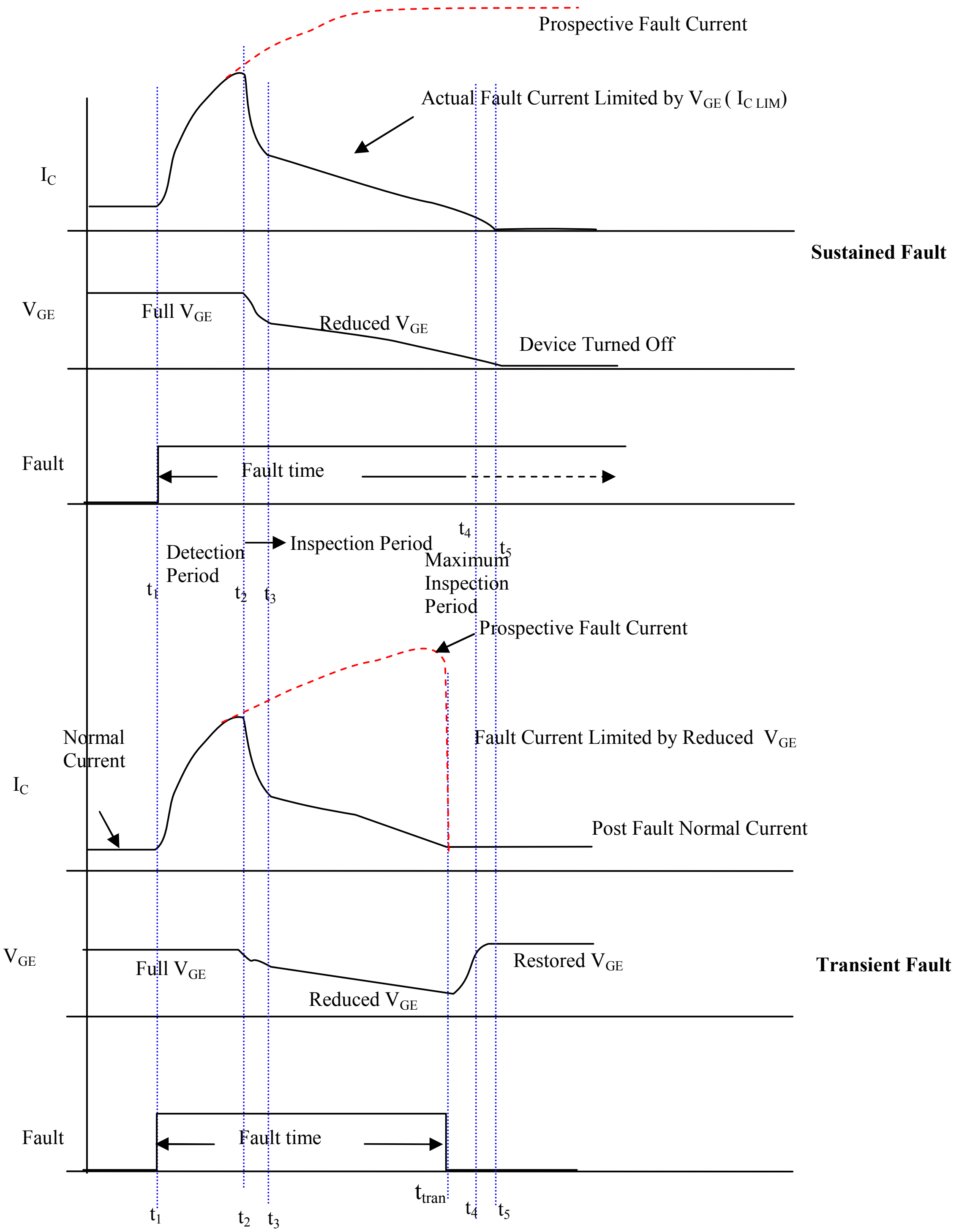


Figure 8 : Fault Handling by Operating Switch in Saturation Region

Analysis was also done to determine voltage stresses on the devices of the bridge under normal and fault conditions and under device saturation. It was found that properly chosen devices could withstand the stresses under fault and successfully turn-off by interrupting the fault current. Figure 9 shows voltage and current stresses on the power electronic devices of a rectifier when operating in saturation / active region during turn-off.

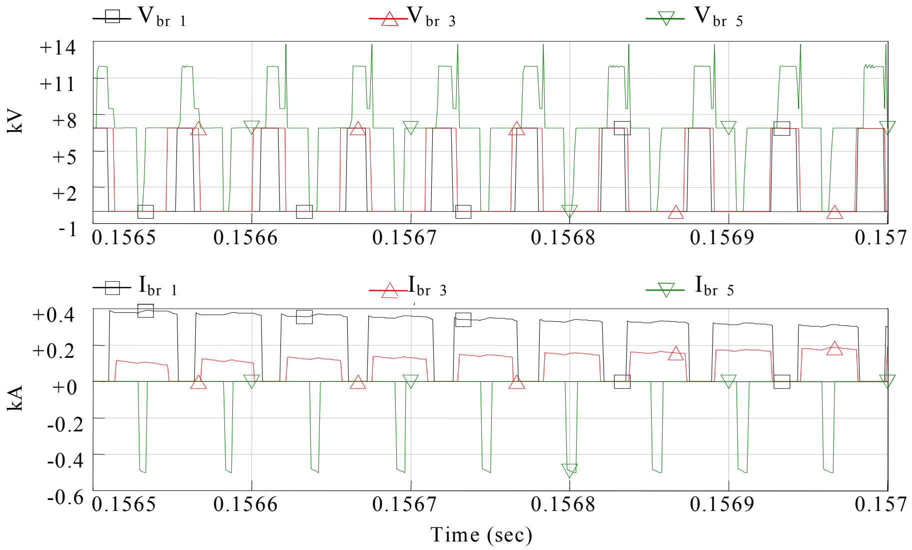


Figure 9 : Voltage and Current Stress under High Impedance Fault

By replacing the diodes by IGBTs, we have many advantages [19]. On the other hand the disadvantages of IGBT which weigh in heavily, in favor of ETOs:

(1) The IGBTs are relatively less robust as compared to ETOs. This demands that VERY fast fault detection circuits be used for IGBTs and this also requires a fast initiation of turn-off (order of few µs),

(2) Single IGBTs do not have high voltage high current withstand capability, thus requiring many series and parallel devices to achieve the required voltage and current ratings respectively and

(3) Higher numbers of isolated power supplies are necessary for IGBT gate control.

Because of these disadvantages, in addition to the higher cost of the IGBT, we considered ETO (Emitter Turn-Off) among other power electronic devices to replace the free-wheeling diode. The ETO is a relatively new device which is derived by hybrid connection of a GTO and MOSFET switches. The circuit diagram of an ETO is shown in Figure 10. Figure 11 shows the circuit symbol of an ETO [16, 26].

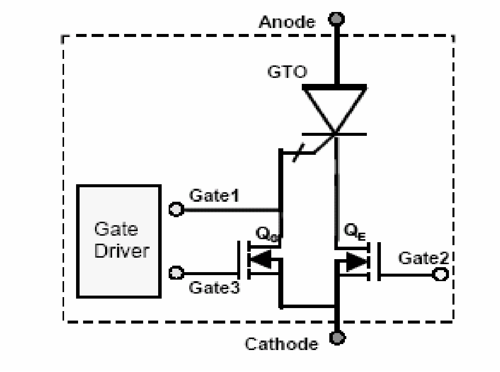


Figure 10 : Equivalent Circuit of ETO

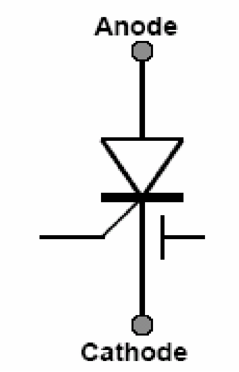


Figure 11 : ETO Circuit Symbol

The ETO has many desirable features. Theoretical analysis and experimental results suggest that the ETO has the combined advantages of both the GTO and the IGBT, namely, GTO's high voltage and current rating, low forward voltage drop, and IGBT's voltage control, high switching speed, wider RBSOA, high reliability [26]. Its ability to turn off high currents while simultaneously sustaining the high voltage, gives it a robust Reverse Biased Safe Operating Area (RBSOA). The ETO thyristor also has another important feature of having a series MOSFET in the cathode terminal (emitter terminal) which is used for current sensing through the device. This current sensing can be very effectively used for turning off the device before the maximum controllable current limit is reached. This feature is used for the Switch Level Autonomous Protection, as will be described later. The operation of the semiconductor device (ETO or IGBT) in the active region has been discussed in literature [4, 24, 25, 27] as a useful technique for handling short circuits and for dv/dt control, as shown above in Figure 8.

The ETOs with current and voltage rating and turn-off capabilities similar to that of GTOs (4kA, 6kV) have been developed and successful operation have been experimentally demonstrated [26, 28]. Figure 12 shows the turn-off waveform of the Gen-3 ETO at 4000A, 2200V DC bus without snubber [28].

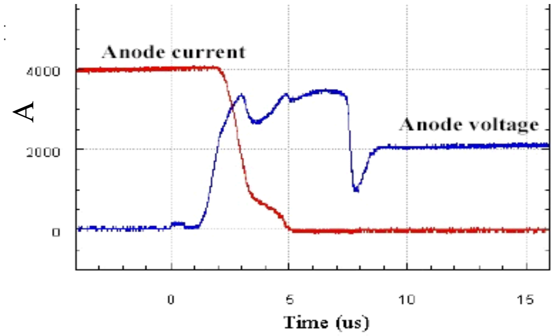


Figure 12 : ETO Snubberless Turn-Off Capability

For our application, where the ETO would replace the diode, the switching requirements on the ETO are quite lenient. Under normal operation of the VSC, the ETO is fired continuously to emulate a diode operation (i.e. when a positive voltage is applied across it, it is fired ON, and hence conducts, else not). Thus, the operating principle of the VSC is not modified. This new switch realization is shown in Figure 13.

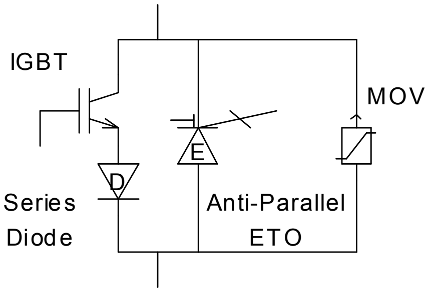


Figure 13 : Switch Realization with IGBT and Anti-Parallel ETO Device

By inserting ETOs, in place of diode we get the controlled turn-off with high surge current rating, robustness and long withstand times as required under fault conditions. Thus, after fault detection, all the IGBTs are switched OFF instantaneously while the ETO devices (which can withstand fault for much longer) are kept fired ON. This aids us by giving enough time to differentiate between transient and sustained fault. Once a sustained fault is established all the ETO devices in the bridge can be shutdown in a controlled fashion by gate voltage turn-off. Thus, this provides a method to shutdown the rectifier completely by controlling the gate terminals of the IGBTs and the ETOs.

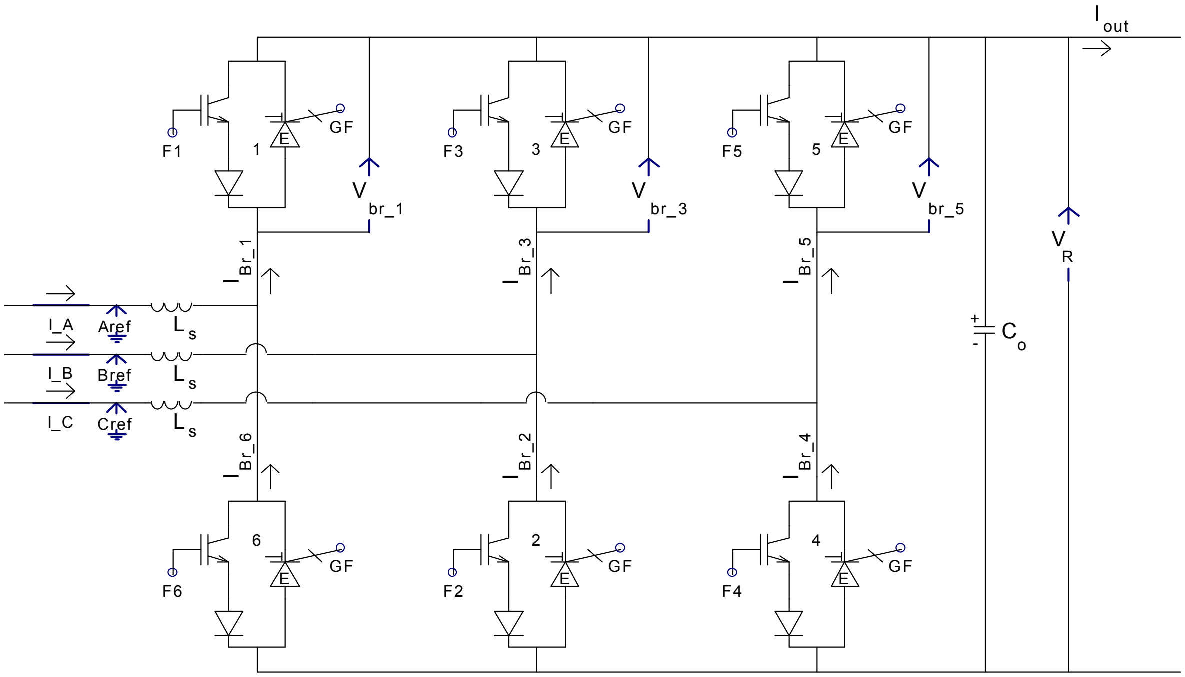


Figure 14 : Modified Rectifier PEBB Topology

Simulations were performed in PSCAD/EMTDC to demonstrate the fault interruption capability of the modified rectifier PEBB. A non-linear switching model was designed in PSCAD by the author to properly represent the current limiting and soft turn-off of the ETOs in the active region during gate controlled ETO shutdown. The simulation results demonstrating the fault current interruption by the rectifier are shown in Figure 15 and Figure 16. Figure 15(a) shows the DC Bus voltage V_R. Figure 15(b) and (c) show the six branch currents I_{Br1}, $I_{Br2,}$… I_{Br6}. Figure 15(d) shows the three branch voltages V_{Br1}, V_{Br3} and V_{Br5}. Figure 16 shows the rectifier input currents Ia, Ib and Ic.

$0.059 < t < t_{fault}$: Normal Operation : The DC bus voltage is at the normal rated value of 7kV. The branch currents under normal PWM switching are the rated value of 650A (peak). When a branch is “OFF”, V_R is applied across the branch and when a branch is “ON” the on-state voltage appears across it. This is represented by V_{Br1}, V_{Br3} and V_{Br5} in Figure 15(d).

$t_{fault} < t < t_{softoff}$: Faulted Condition : At $t_{fault} = 0.06$s, a fault occurs at the output terminals of the rectifier. V_R collapses to a very low value determined by fault impedance. Correspondingly, I_{Br3}, I_{Br4}, and I_{Br6} start to increase. The ETOs behave like diodes and carry the increasing fault current, and the VSC starts operating in a diode bridge rectifier mode.

$t_{softoff} < t < t_{shutdown}$: Soft Turn-Off : At $t_{softoff}$ =0.06095s, it is established, based on time segregation, that a sustained fault has occurred. Also, the current I_{Br3} approaches the device maximum turn-off limit of 3kA, and a “soft turn-off” or gradual ramping down of the gate voltages of all the devices is initiated. The ramping down of the gate voltages results in the ramping down of the currents I_{Br3} I_{Br4}… I_{Br6}. This current ramping causes the voltages V_{Br1}, V_{Br3} and V_{Br5} to rise. This voltage rise is limited by the MOV to 14kV. The whole soft turn-off process is finished within about 20 μsec, but the shut-down is not complete as the rectifier input current (also the generator current Figure 16) has not been interrupted. The MOVs free-wheel the current until $t_{shutdown}$.

$t_{shutdown} < t < 0.0615$: Shut down : At $t_{shutdown}$ = 0.6125 the freewheeling action of the MOVs ceases and the fault current is completely interrupted by the PEBB. The full line voltage is applied across the branches as represented by the voltages V_{Br1}, V_{Br3} and V_{Br5}. The application of the nominal voltages across the branches causes the MOVs to go back into non-conducting state.

The generator currents which constitute of the branch current (or the rectifier input current) is shown in Figure 16. At t = 0.06s, the fault causes the current to rise till the soft shutdown of the rectifier is initiated at $t_{softoff}$ = 0.06095s. The current is interrupted in a controlled manner to completely shutdown the rectifier PEBB.

In summary, we see that the PEBB can withstand the high current for about 1ms and further limit and interrupt the current without excessive over-voltages. Thus, we see that the replacement of the diode by an ETO, allows one to satisfy the requirements for a CB, which were outlined in the previous section, and allows it to perform the functions of a circuit breaker successfully.

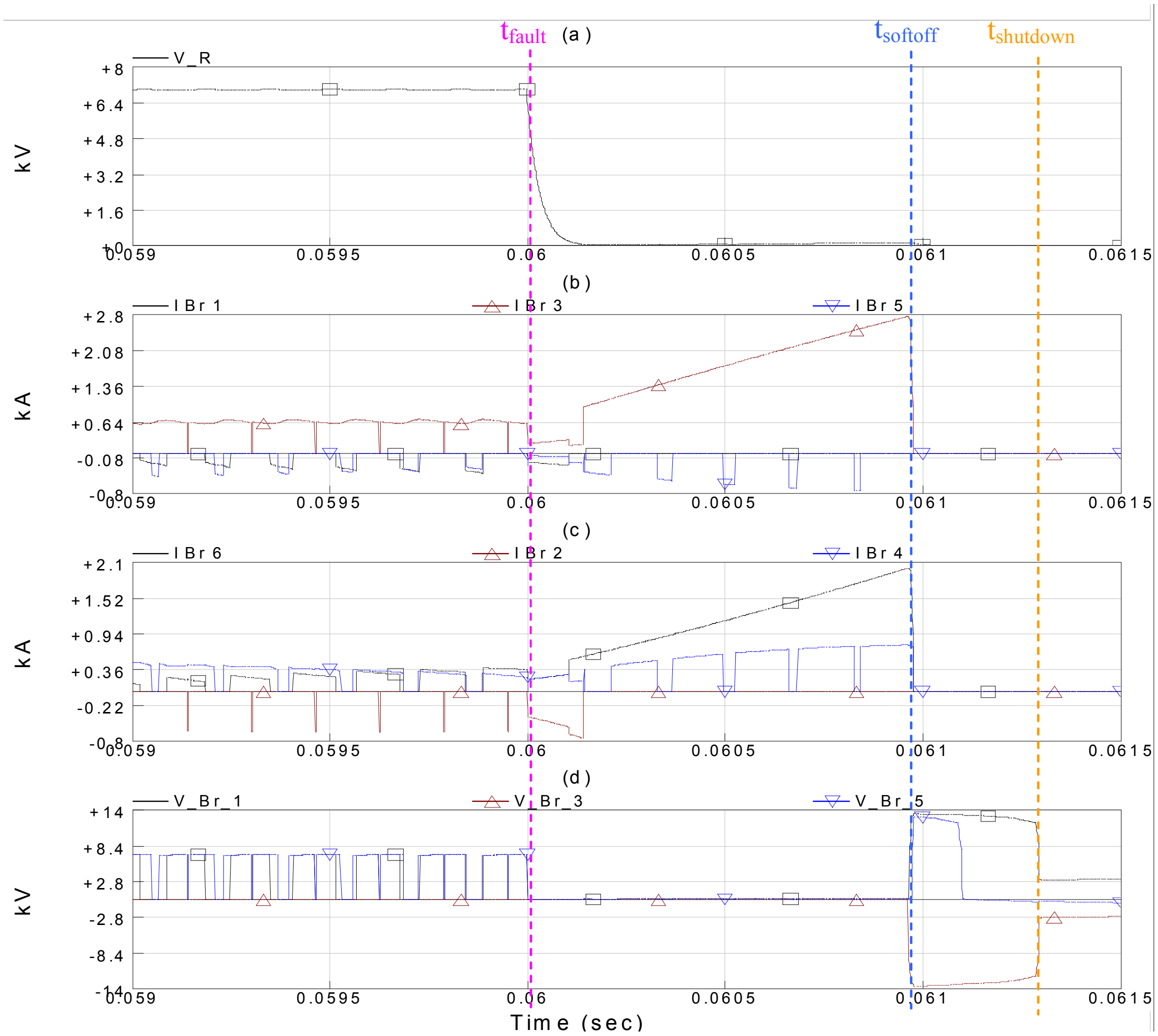
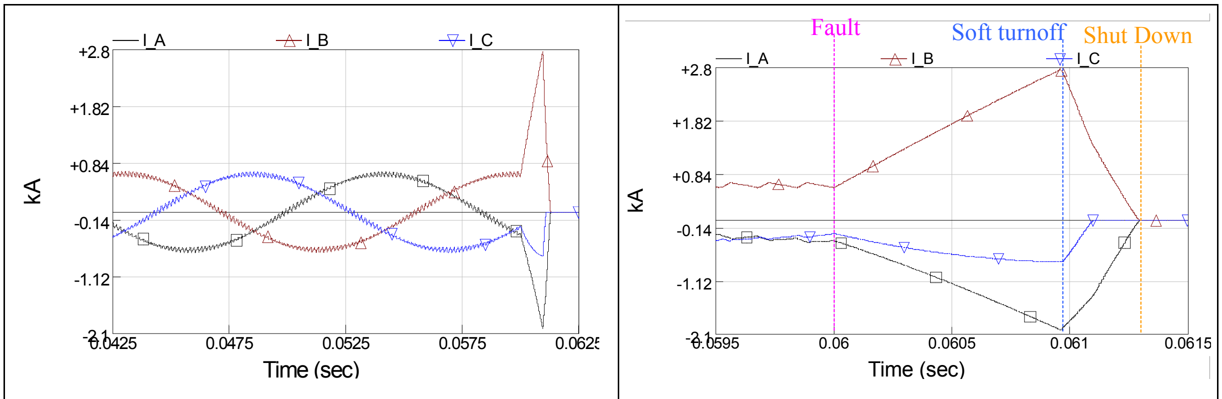


Figure 15 : Rectifier Shutdown



(a) Generator Currents

(b) Zoom-in of (a)

Figure 16 : Generator Currents

2.5 Inverter Fault Current Limiting CB

Inverters are used to feed AC motor loads and other electronic loads. They are also used in high power applications in conjunction with rectifiers for transmission purposes. Another application of inverters is in conjunction with fuel cells which give DC as output. In all these applications the inverters employ PWM. Simulations using PSCAD/EMTP were performed on a test system. A 3-phase inverter as shown in Figure 17 is connected to an ideal DC source and a 3 phase squirrel cage induction motor, is used in our simulation.

Simulation results for an inverter PEBB show that the diodes in an inverter do not free-wheel indefinitely under fault at the output terminals of the inverter. A turn-off signal to all the gate controlled devices of the inverter PEBB is effective way to interrupt the fault current and isolate the fault. This indicates that the topological modifications that were necessary in case of a rectifier PEBB for interruption of fault are not necessary for an inverter PEBB. And, therefore, a conventional inverter PEBB can be used for circuit breaking function without modification to the topology. For such an inverter to act as a circuit breaker under fault condition, it is just necessary to turn-off all the controllable devices in the bridge.

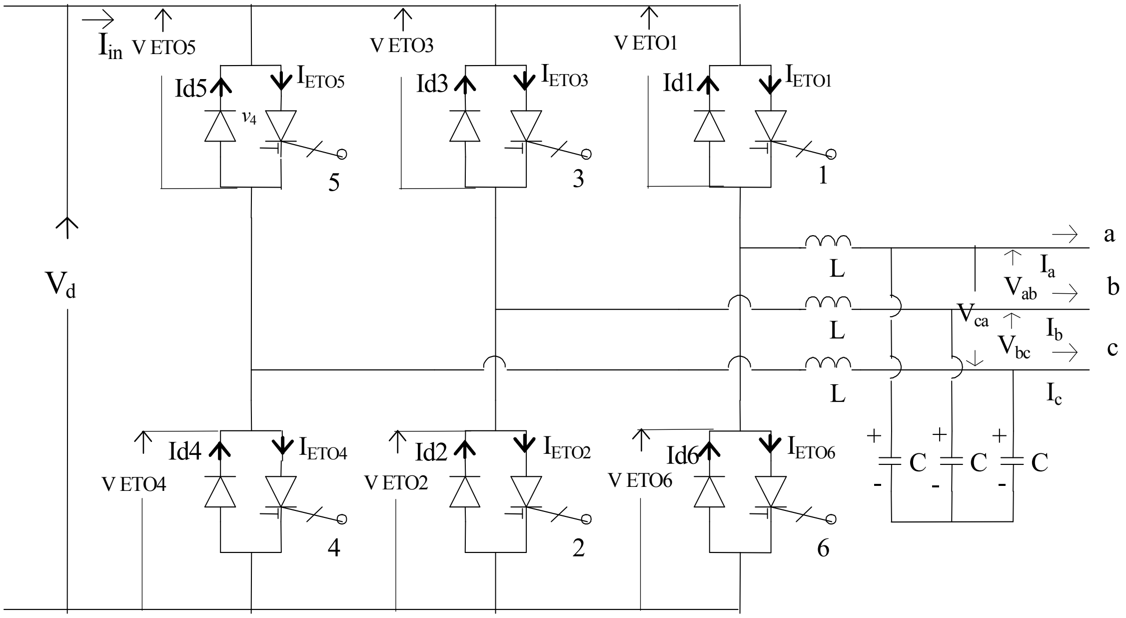


Figure 17 : PWM Inverter with Associated Filters

Modern inverters employ IGBT (for high switching frequency, medium power applications) or GTOs (for lower switching frequency, high power applications) as the controllable semiconductor devices. Although the use of any gate controllable device (GTO, IGBT, ETO etc) for switch realization, allows the inverter PEBB to be used as a circuit breaker, in our simulations ETOs have been used to allow for longer withstand times along with high switching frequency, higher breakdown voltages at high power levels. Simulation results are shown in Figure 18, Figure 19, Figure 20 and Figure 21. Figure 18(a) shows the inverter output voltages, V_{ab}, V_{bc} and V_{ca} and inverter output currents, I_a, I_b and I_c. Figure 18(b) shows the zoom-in of the Figure 18(a) around the fault occurrence. The device currents of the six branches are shown in Figure 19 and the six branch voltages are shown in Figure 20. The inverter input current I_{in} is shown in Figure 21.

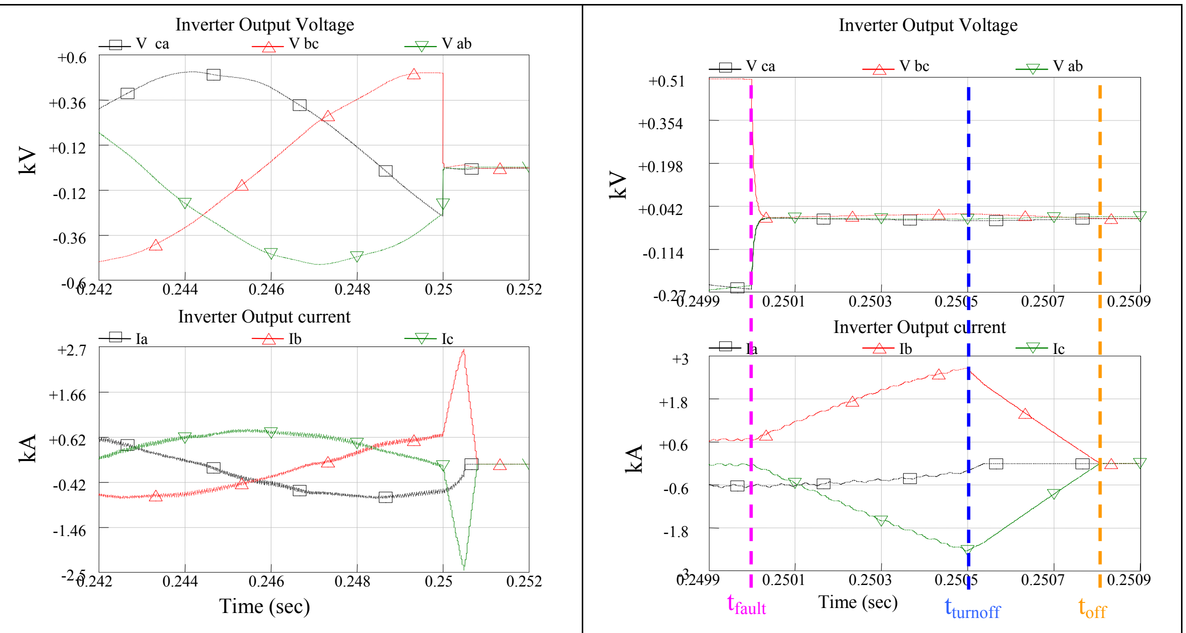
$0.2500 < t < t_{fault}$: Normal Operation : The inverter output voltage V_{ab}, V_{bc} and V_{ca} and the inverter full load output line currents I_a, I_b, and I_c are at the nominal values of 450 V (L-L peak) and 700A (peak) respectively. When a branch is “OFF”, the corresponding voltages V_{ETO1}, V_{ETO2}, …, V_{ETO6} are the normal input DC value of 800V while when the branch is “ON” the voltages V_{ETO1}, V_{ETO2}, …, V_{ETO6} are normal forward voltage drop of the CSDs. I_{in} represents the normal charging-discharging current of the inverter PEBB.

$t_{fault} < t << t_{turnoff}$: Faulted condition : A fault at $t_{fault} = 0.2500$s causes the voltage V_{ab}, V_{bc}, V_{ca} to collapse and the line currents to I_a, I_b, and I_c to rise. The fault causes only a minor change in the voltages V_{ETO1}, V_{ETO2}, …, V_{ETO6}. The I_{in} starts increasing proportional to the increase in the output current due to the inverter output 3 phase fault currents.

$t_{turnoff} < t < t_{off}$: Diode freewheeling : At $t_{turnoff} = 0.2505$s, enough time has passed to rule out a temporary transient fault establishing a sustained fault. In addition, since the currents are approaching the device limits, gating to the CSDs of the inverter PEBB is stopped. Turning off the CSDs at $t_{turnoff} = 0.2505$s limits the current from increasing further and initiates the shutdown of the PEBB. The currents I_a, I_b, and I_c are not “chopped” off, but rather decrease gradually to zero due to the presence of the output filter inductors. The energy stored in the inductors is freewheeled back to the source through the diodes as seen by the negative I_{in}. Just prior to $t_{turnoff}$, I_{in} is flowing through the ETO of branch 3, output filter inductors, and returning through the diode of branch 1 and ETO of branch 4.

At $t_{turnoff}$ = 0.2505s, when the CSDs are gated off, to maintain the continuity of the current through the output inductor of phase **b**, the current flowing through the ETO of branch 3 is commutated into the diode of branch 2. Similarly, to maintain the continuity of the current through inductor of phase **c**, the current flowing through the ETO of branch 4 is commutated into the diode of branch 5. The diode of branch 1 which was conducting prior to $t_{turnoff}$ continues to conduct till current zero of phase **a** thereby maintaining the continuity of the current through the inductor of phase **a**. The commutation of the currents from the ETOs into the diodes causes the I_{in} to reverse, that is, to reverse feed into the source as seen by the negative current in Figure 21 after $t_{turnoff}$. The energy stored in the inductor is completely fed back to the source and the shutdown of the PEBB is complete at t_{off} = 0.2508s.

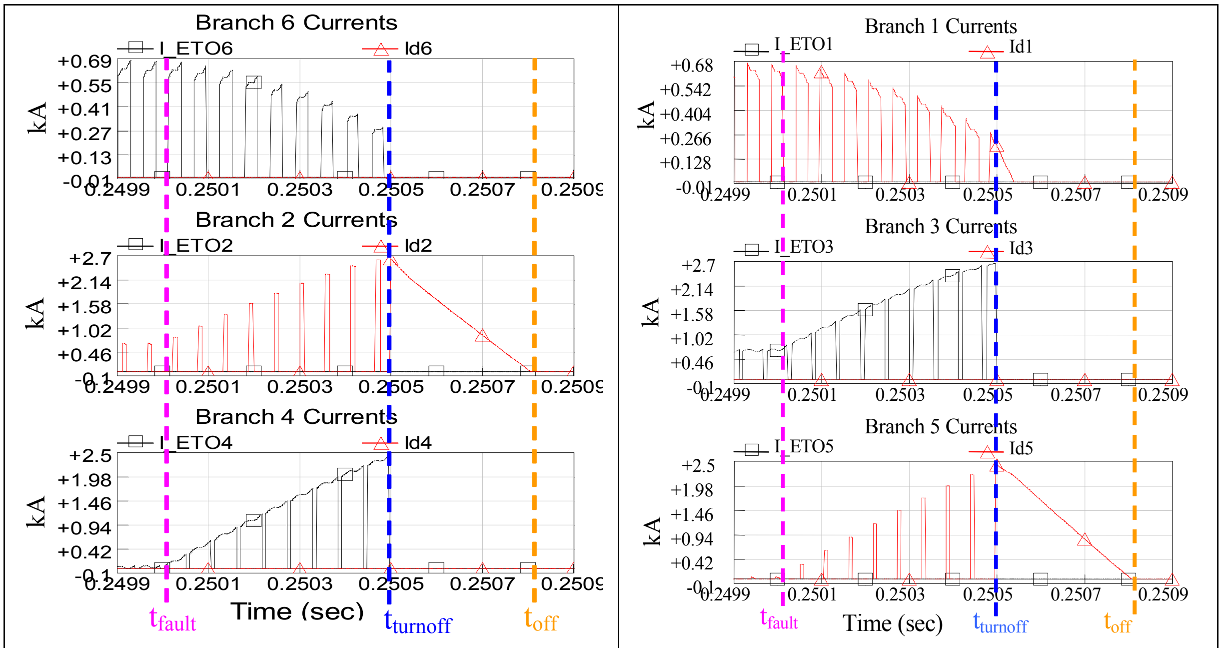
t_{off} < t < 0.2509 : At t_{off}=0.2508s the shutdown is complete. The currents I_a, I_b, and I_c are interrupted and the post fault voltage is shared equally (=0.4kV) among the top (1, 3 and 5) and bottom (6, 2 and 4) branches as seen in Figure 20. At t_{off}, the PEBB has successfully interrupted the current.



(a) Inverter Output waveforms

(b) Zoom-in of (a)

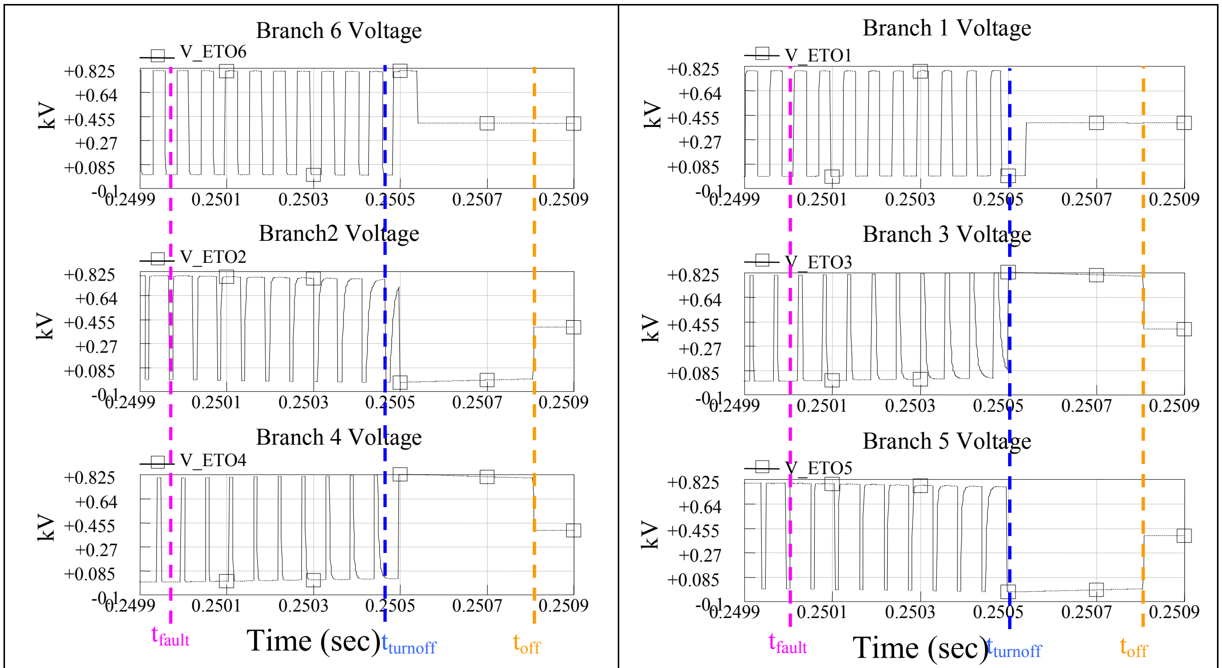
Figure 18 : Inverter PEBB Current Limiting



(a) Currents of Branches 6, 2 and 4

(b) Currents of Branches 1, 3 and 5

Figure 19 : ETO and Diode Currents



(a) Voltage across branches 6, 2 and 4

(b) Voltage across branches 1, 3 and 5

Figure 20 : Branch (Device) Voltages

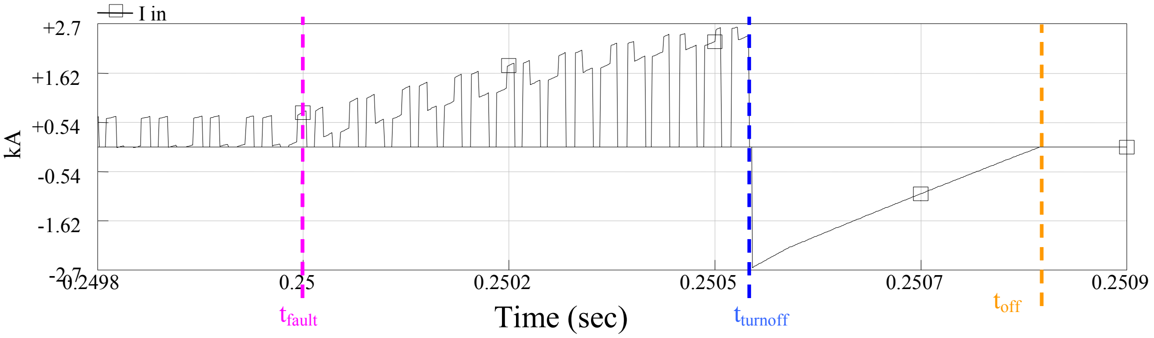


Figure 21 : Inverter Input Current

The limiting and interruption of the fault current has been achieved by turning off the controllable devices in the inverter (before they reach their limits). The freewheeling of the diodes allows the current to decay to zero and prevents any over-voltages in the PEBB. The PEBB withstands the high fault currents for 0.5ms and limits the fault current for another 0.3ms before the inverter is completely shuts down. This gives time for the overall system protection scheme to differentiate transient and sustained fault and act accordingly.

Summarizing, a conventional inverter PEBB can withstand a fault and turn off to interrupt the fault current without causing damaging over voltages, thereby functioning successfully as a current limiting circuit breaking PEBB.

2.6 Buck Converter Fault Current Limiting CB

A typical full bridge buck converter along with its associated filters is shown in Figure 22.

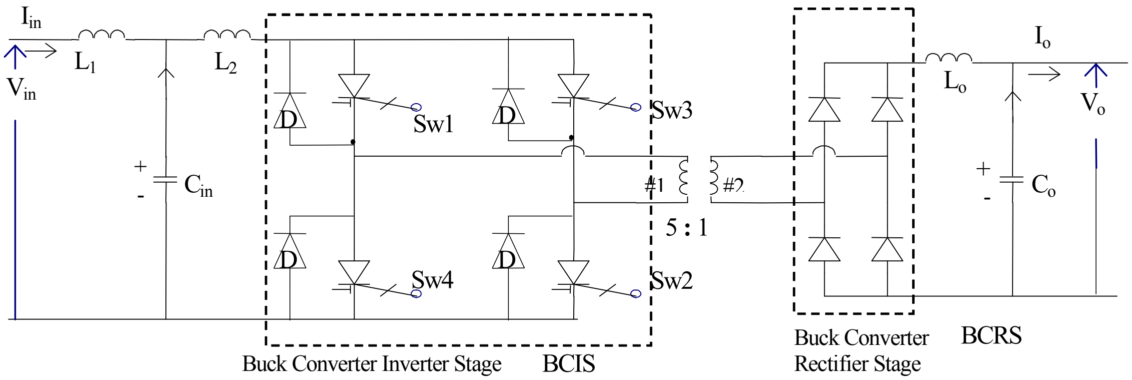


Figure 22 : Full Bridge Buck Converter

Note that the Buck converter has an inverter stage (BCIS) connected to the rectifier stage by an isolation transformer. By adopting a proper PWM, we can have the switches of this stage to carry only unidirectional currents [29]. This will allow us to realize the switches of the BCIS by ETOs without anti-parallel diodes and thus, we can turn the Buck converter completely off by turning off all the switches of BCIS. The modified topology with this switch realization is shown in Figure 23.

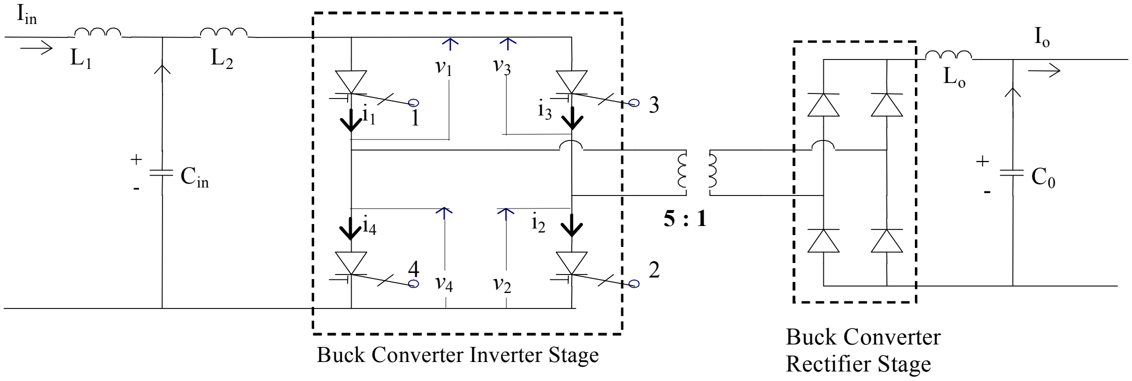


Figure 23 : Modified Full Bridge Buck Converter

With this modified switch realization, we can use the BCIS to interrupt the faults by employing the same technique (hard turn-off) as employed above for the inverter. The main concern here is the voltage stress by chopping (due to absence of freewheeling diodes) of the current through the input inductor L_2 and the transformer magnetizing current. However since the associated input inductor, L_2 is very small, less than a µH, the voltage stress is negligible, given that the device turn-off time is about 3-5µs. Also, turning off all the switches in the BCIS will force the transformer magnetizing current to flow through the secondary winding and therefore the current will not be chopped and does not result in any extra voltage stress on the devices. Therefore, the turn-off operation of a buck converter under fault can be done similar to the turn-off of the inverter PEBB.

To test the current limiting of the buck converter with the proposed scheme, the buck converter of Figure 23 was simulated, which employs ETOs as the CSDs. The converter is supplied from a DC source of 7kV and steps down the voltage to 800V DC. A short circuit at the output DC terminals is created for the simulation. The branch currents i_1, i_2, i_3 and i_4 and the branch voltages v_1, v_2, v_3 and v_4 are shown in Figure 24 and Figure 25 respectively.

$0.0492 < t < t_{fault}$: Normal Operation : Under normal operation of the buck converter, the full load rated current flows through the ON devices i_1 and i_2 or i_3 and i_4. Figure 25 shows the voltages v_1, v_2, v_3 and v_4. The voltages across an ETO are at a value of 3.5kV, when the both the ETOs of a leg are OFF, for example, when ETO1 and ETO4 are OFF, they share the voltage and v_1 and v_4 are at a value of 3.5kV. Whereas, when only one of the ETOs of the leg is OFF the voltage across it is 7kV. For example, when ETO1 is ON, ETO4 is OFF; therefore voltage across ETO1, v_1, is the low forward voltage drop, while the voltage across the OFF ETO4, v_4 is 7kV.

$t_{fault} < t < t_{off}$: Faulted Operation : A fault occurring at t = 0.05s forces the current through the CSDs to rise to ≈ 3kA in 900μs after fault. At this time, a transient fault is ruled out based on time segregation and the current approaches current limits of the CSDs.

$t_{off} < t < 0.0512$ Shutdown : At $t_{off} = 0.0509$s, the gating signals to the BCIS are stopped and the BCIS is completely turned-off. The currents i_1, i_2, i_3 and i_4 cease to flow. The un-availability of a current path for the magnetizing current on the primary side of the isolating transformer forces it through the secondary winding of the transformer. The diodes of the BCRS free-wheel the current though the output capacitor, the short circuit and load. After the turn-off, the input voltage of 7kV is shared equally (3.5kV each) among top and bottom CSDs.

Thus, we see that a properly controlled buck converter can limit and interrupt a fault in less than 1ms. In addition; it can limit and interrupt the fault current without excessive voltage stress on the switches

The pulsed capacitor currents which flow through the branches constitute the transformer input currents. Following the fault, currents 6x the rated currents flow through the transformer for a few hundred μs, this causes simultaneous high current and rated voltage in the transformer, for short period. The transformer should be properly chosen for such a duty. The considerations for selection of a proper transformer are given in Appendix B.

In summary, we see that the Buck Converter PEBB can withstand the limit the current without over-voltages. Thus, we see that the modified buck converter can successfully perform the functions of a current limiting circuit breaker.

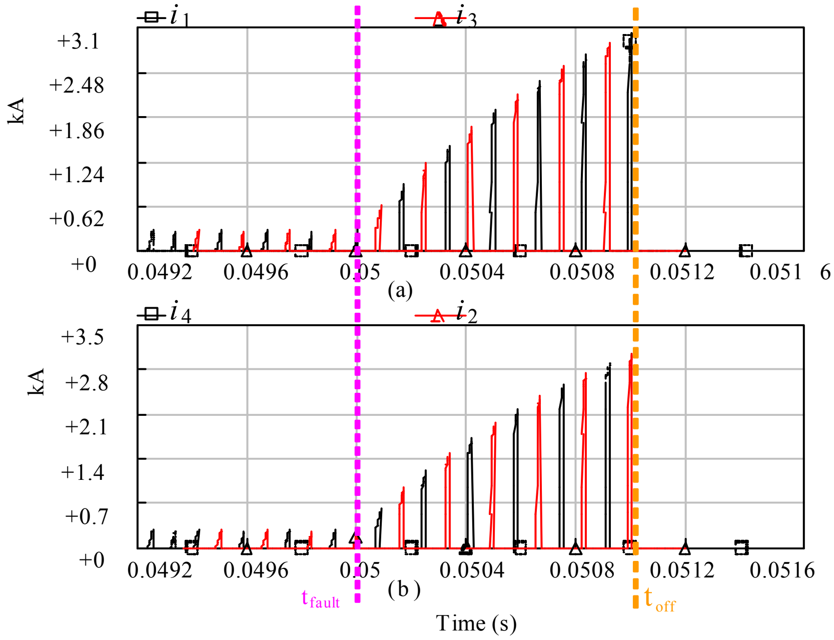


Figure 24 : Branch (ETO) Currents

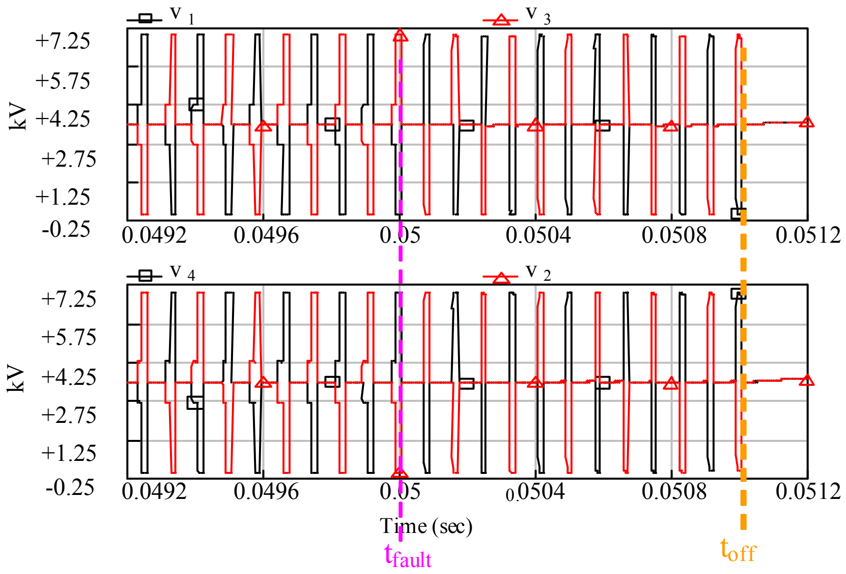


Figure 25 : Voltage across Branches (ETO)

2.7 Chapter Summary

This chapter described the fault handling methods of the various PEBBs namely the rectifier, the inverter and the buck converter. We showed that the PEBBs with the modified switch realizations can withstand the fault currents so that the protection scheme would have time to process the information at a system level and provide protection to the electrical system. We also showed that the PEBBs can limit and interrupt the fault current successfully without causing damaging over-voltages. Thus, these PEBB based circuit breakers lend themselves for application in system level protection.

3 DC DISTRIBUTION SYSTEM PROTECTION

3.1 Introduction and Overview

In AC systems, all the devices of the system (generators, transformers, lines etc) are covered by one or more protection schemes (overlapping zones). The important devices have their own protections called the unit protections, which trip if and only if the fault is in their zone of protection, namely in the device. Therefore, these protection schemes are device based, i.e., they are aimed to protect the devices etc, on a system.

In the new DC SES, the PEBBs, which are expensive devices, would also need unit protection. In the envisioned protection scheme for the SES, the PEBBs are also used as fast acting current limiting circuit breakers. With this new functionality for the PEBBs, a new challenge emerges, that the protection scheme should be also able to detect and locate the faults faster. To achieve this goal, an "agent" based system protection in contrast to the conventional protection scheme has been designed here, which consists of smart agents embedded into the PEBB. The "Protection-Agents" of this new Agent based System Protection will monitor only the local quantities to detect and isolate the disturbances. This local protective action will ensure that protection actions are very fast which aid to reduce the system downtime.

The agents will perform two primary tasks: system protection for detecting and isolating disturbances and reconfiguration management to provide service continuity to the part of the network that is undamaged. This chapter deals with the first task.

3.2 Conventional HVDC Protection: Literature Survey

Conventional terrestrial HVDC systems employ thyristors in current source converter configuration. The converters usually constitute two 12 pulse rectifiers, (one of the two 12 pulse rectifier is shown in Figure 26) [1]. The 12 pulse rectifiers are stacked to form a bipole converter station. Such converter stations are typically used in pairs to transfer power from one AC network to another via back to back connection or via HVDC transmission lines.

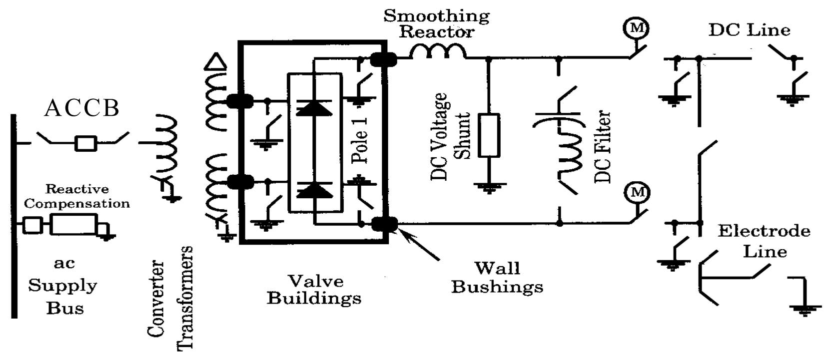


Figure 26 : Typical Configuration of a Bipole Converter Station

Different types of faults can occur on the bipole converter stations. These faults can occur on the supply line, the converter transformer, the converter or on the dc side. The protections provided to protect against these faults, are divided into AC protections and DC protections. The protective action to interrupt and isolate these AC or DC faults is to open the AC circuit breaker. Even for faults on the DC Line, due to the absence of a DC circuit breaker, the ACCB has to open to interrupt the fault current and isolate the fault.

The AC side protection is provided to the AC line which feeds the AC supply bus, the AC supply bus, and the converter transformer.

The DC protection is divided into valve protections and DC side protection. Of these, the protections that are most relevant to PEBB protections are the valve short circuit protection, converter over-current protection, valve misfire (shoot-through), voltage stress protection, converter DC differential protection, and DC over-voltage protection.

(1) Valve short circuit protection: The objective of the protection is to detect short circuits across the valves of the converter. The shorts are cleared by blocking the converter firing and tripping the AC side circuit breaker.

(2) Converter over-current protection: The objective of the protection is to detect over-currents that may cause unusual stress in the converter equipment, particularly the thyristor valves. The protective action is to block the firing to the converter and turn on bypass valves (crowbar), trip the AC circuit breaker and isolate the pole and line at both ends.

(3) Valve misfire protection: The valve misfire protection detects the failure of a valve to conduct when a control pulse has been applied, detect unintentional valve firing. It also performs two additional functions to prevent the selection of a valve as a bypass valve, if the valve has failed, and to select the valve as a bypass valve, if the valve is firing unintentionally. The protective action is to transfer control to the redundant control system, block the converter and trip the AC side circuit breaker.

(4) Voltage stress protection: The objectives of voltage stress protection are two-fold. First, it is designed to detect high commutation voltages and to prevent further increase of voltage by interlocking the converter transformer tap changers. Second, it takes the faulty converter out of service in the case of persistent AC over-voltage. On detection of a small over-voltage, the tap-changers are inhibited from further raising the voltage. On detection of a high over-voltage, the converter is blocked and the AC circuit breaker is tripped.

(5) Converter DC differential protection: The objective of this protection is to detect ground faults on the DC side of the converter between the transducer in the DC wall bushing on the low voltage terminal and the transducer in the DC reactor on the line side, Figure 26. The protective action is to block the converter, trip the AC side circuit breaker and isolate the pole and the line at both ends.

(6) DC over-voltage protection: The objective of this protection is to detect over-voltage on the DC line and equipment when starting a pole against an open-ended DC line. The protective action is to transfer control to the redundant control system, block the converter and isolate the pole and the line at both the ends.

3.3 PEBB Based DC SES Protection

The envisioned protection scheme for the PEBB based DC system borrows protection concepts from the HVDC protection described above and adds to it. The main difference is that the protection scheme for the new zonal DC distribution system uses the PEBBs as circuit breakers to limit and interrupt fault currents, as compared to the AC circuit breakers used in HVDC systems. It has been demonstrated in the previous chapter that this new functionally for PEBB can be achieved by proper selection of converter topology and by adopting a revised switch realization that uses the newly emerging robust power electronic devices such as ETO [26, 30-32].

The following sections explain the developed system protection scheme for the DC SES. The new protection scheme is designed to be hierarchical in nature so that the backup protection for the failure of the primary protection can be very fast and automatic. At the top of the hierarchy is the primary protection called the Agent Based System Protection and at the bottom level of the hierarchy is the backup protection called the Switch Level Autonomous Protection. A schematic of the protection scheme for the DC SES is shown in Figure 27.

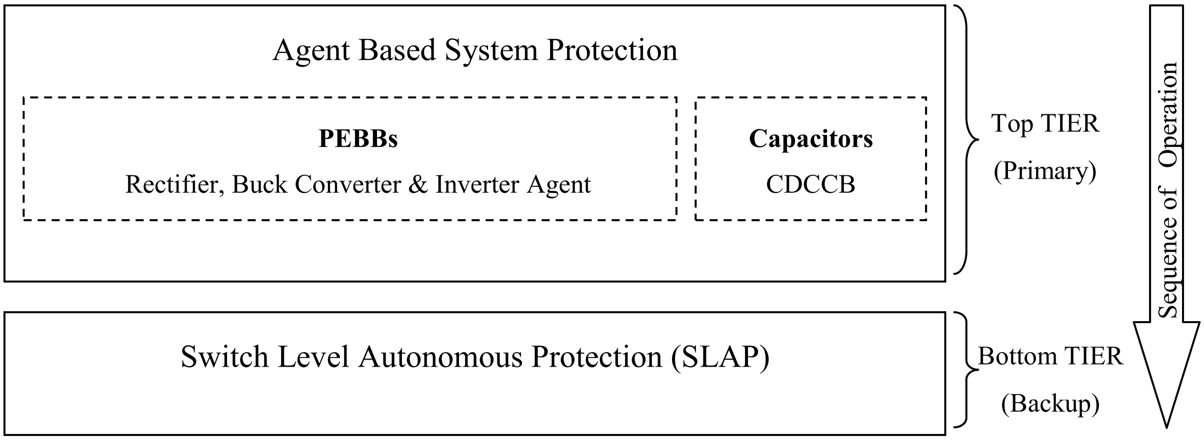


Figure 27 : Hierarchical Protection for the DC SES

3.4 Switch Level Autonomous Protection

At the lowest level of the hierarchy, the protection is provided to the basic switching element - the ETOs. Protection in this Tier is Switch Level Autonomous Protection (SLAP) which means that it does not interact with the system protection to initiate protective action. The aim of the SLAP is to work independently/autonomously and protect the individual switches from destruction. This is also the last line of protection for the CSD, and therefore defines the ultimate limits that the switch can be operated at. Therefore, the system protection must be faster than this protection and must be coordinated with it such that the system protection operates before the SLAP operates.

This type of protection (SLAP) can be either embedded into the switch (by customized manufacturing) or external means can be provided. For this study we would use embedded means (explained below) for protection of the ETO switch in the SES.

Figure 28 shows the ETO's embedded gate drive circuit which is used as Switch Level Autonomous Protection in this protection scheme [16]. The voltage across Q_E, V_{QE}, is proportional to the current through the device. This V_{QE} is first filtered by R_f and C_f and is then sent to the analog comparator to be compared with the reference voltage V_{ref}, which represents the setting current for turn-off. Once the V_{QE} is larger than V_{ref}, indicating the device current is higher than the setting current, the comparator will change its output from high logic level to low logic level. After a delay (about 3µs) dictated by R_d and C_d to prevent the false trigger, the signal V_{out} changes its state. The V_{out} is ANDed with the normal PWM firing signal of the controller and the output is appropriately connected to the gate of the ETO (gates of Q_E and Q_G as shown in Figure 28. When V_{out} goes low, the ETO device is turned off to cut off the fault current within 3µs, as experimentally shown in Figure 29.

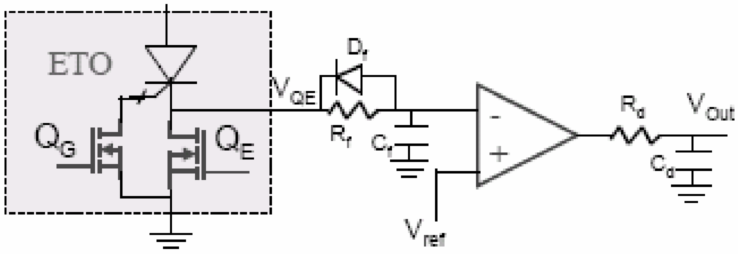


Figure 28 : ETO Gate Drive Circuit for Over-Current Protection

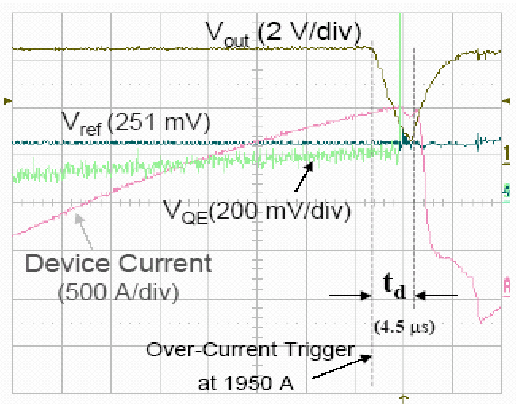


Figure 29 : Over-Current Protection Waveforms for ETO

3.5 Agent Based System Protection

At the top level of the hierarchy of the protection scheme for the DC SES is the Agent Based System protection as shown in Figure 27. The basic task is the same as any other protection scheme for a power system - locate any disturbance that can occur on the system and take appropriate action in order to minimize the effect of disturbance on the operation of the system. The aim here is to design a very effective protection scheme which is able to locate the disturbance and isolate the affected area very quickly. It should also keep the isolated area as small as possible. We plan to make use of the special features of the DC SES to achieve this goal.

The main components of a protection scheme are the protection devices, the CBs and fuses for DC distribution. These devices help to isolate the faulted part of the system and thus they divide the system into “protection zones”. In conventional protection, these CBs and fuses are placed such that there will be a protection zone for each of the major devices. This protection scheme is basically, therefore device based. Figure 30 illustrates the CBs that need to be placed for this device based protection. To protect the devices, relays are used to detect the disturbances in the associated protection zone and to operate the necessary protection devices in order to isolate the device/zone. For reliability, there is a back-up relay for each protection zone which is responsible protecting the zone if the primary protection fails to act.

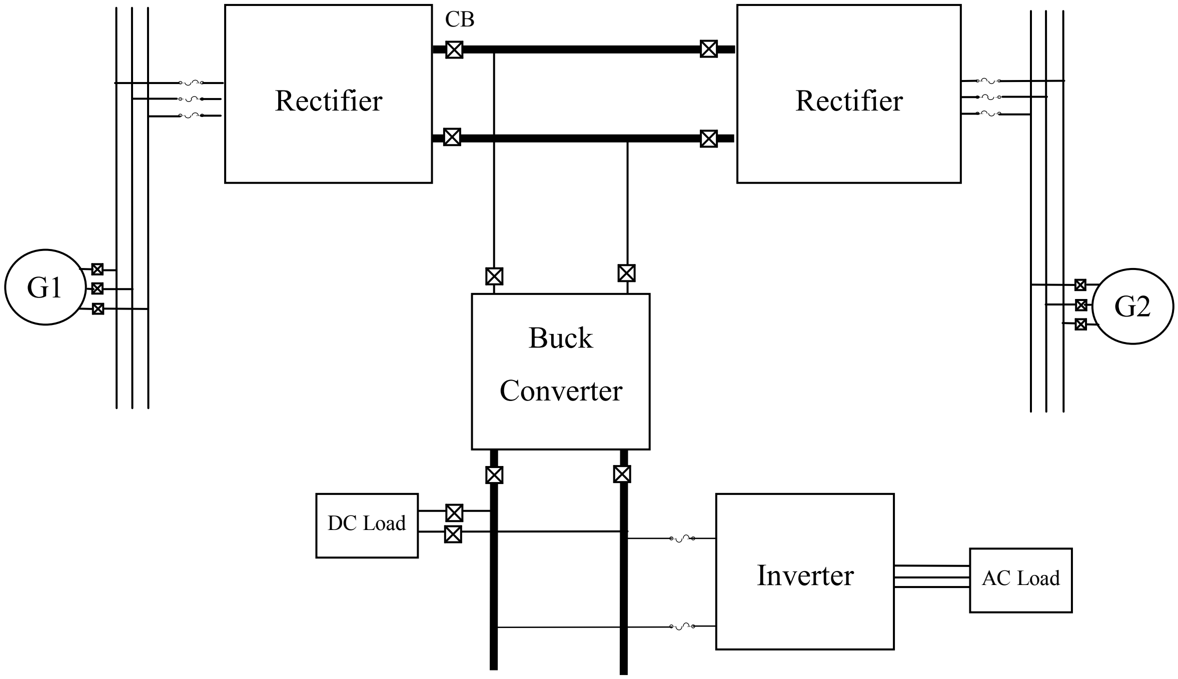


Figure 30 : DC SES with Circuit Breakers

For the new PEBB based DC distribution system, it has been shown that we can use the PEBBs themselves to perform CB duties, and thus, eliminate the need for separate CBs for protection. Therefore, the CBs will be embedded within the PEBBs and the protection zones that will be defined by them will not be device based. The SLAP, as described above will provide backup protection. Figure 31 illustrates the main zones defined by these devices on the prototype DC SES. 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. It is also the one that is exposed the most to the faults / damages. Note that since the switches in the PEBBs will be doing the fault interruption, therefore 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 30. The proposed scheme eliminates these CBs.

- ***Secondary DC Bus Zone***: The secondary DC bus supplies power to all the loads within a given 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 is localized to that zone. One load zone is illustrated in Figure 31; it is defined by the buck converter and includes the secondary DC bus, the load side buck converter rails and the source side inverter rails.

- ***Rectifier AC Zone***: As Figure 31 illustrates, the rectifiers are connected to the AC source bus supplied by generators. Note that the part of 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 source terminals of the rectifier to protect this AC source side of the rectifiers. 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 that since the system mainly uses 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, the provision of two primary busses on the system allows the protection system to transfer the loads affected by the disturbance from the faulted bus to the other alternate 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 thereby allowing for simplicity. Hence, fuses are employed for providing protection in this zone.

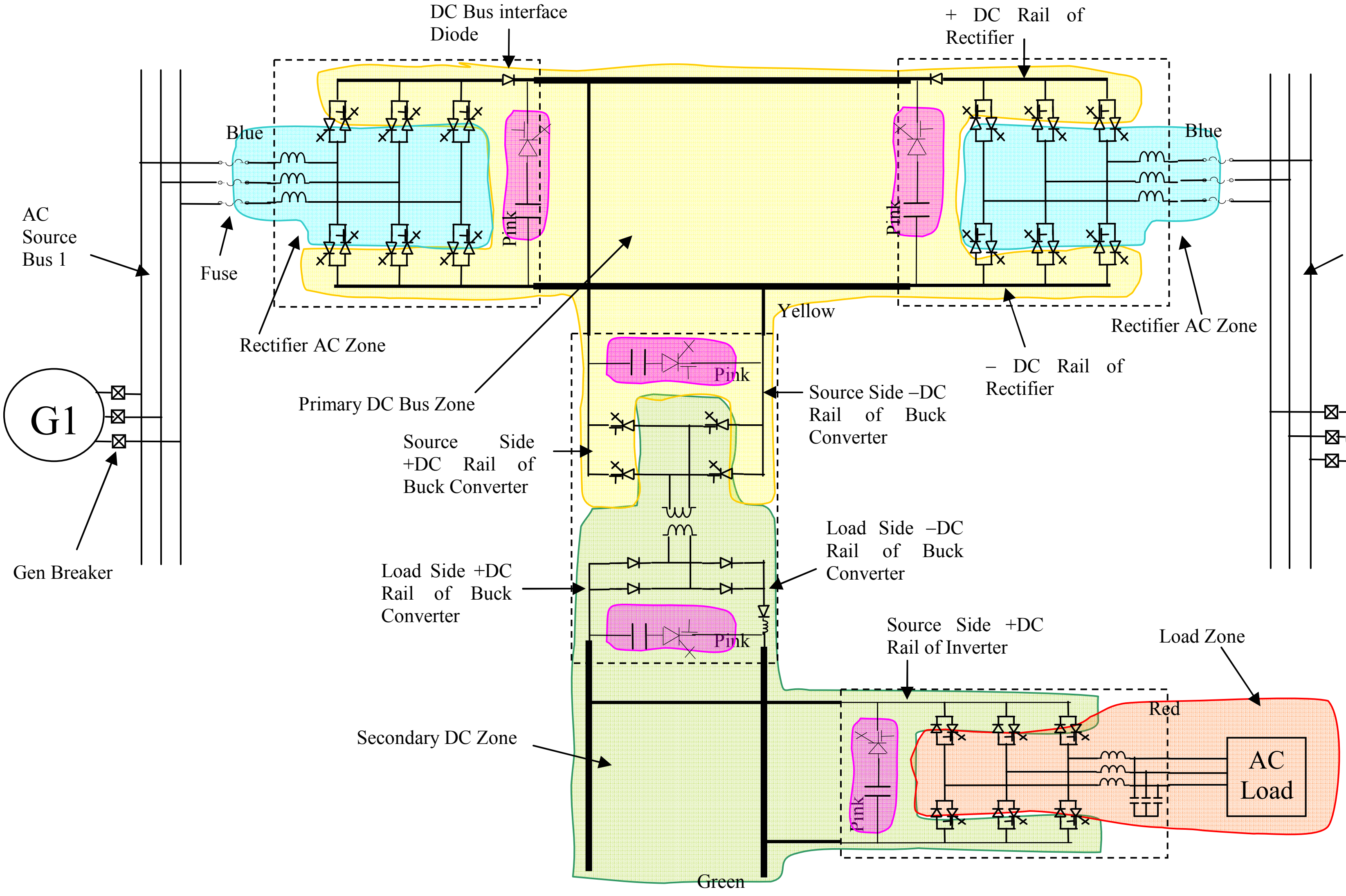


Figure 31 : Zones of a DC SES

For detecting the disturbances in these zones and operating the appropriate protective devices, again rather than using conventional relays that are assigned to each zone for this purpose, we propose to use the Agent Based System Protection scheme. This scheme will consist of agents that are associated with each PEBB. The agents will not be responsible for the protection of a particular zone, rather they will take action based on the local information that they gather. 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 system will employ three types of “Protection-Agents”, a Rectifier Agent, a Buck Converter Agent and an Inverter Agent. These agents, as it will be shown below, will provide the desired protection performance by minimizing system downtime. This will be achieved in 3 ways. First way is by using the ability of the PEBBs fast acting circuit breakers (interruption in about 1ms as shown in the previous chapter). Secondly, each Protection 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 for taking the protective action, which in turn minimizes the system downtime. Thirdly, the system downtime is minimized by reducing/eliminating the requirement of co-ordination for backup purposes. This is done by designing the protection system in a hierarchical manner so that if the agent based protection fails to isolate the fault, the switch level autonomous protection automatically provides backup protection and isolates the fault. It will be shown that by properly designing the tasks of the Protection-Agents at the system level, the time-delay based co-ordination will not be required, which will help us to minimize the system downtime.

To illustrate how this agent based system protection scheme will work on the DC distribution system; first we have a look at the main faults/disturbances that the system will be exposed to.

These faults can be listed on a zone basis as:

(A) Primary DC Zone

The primary DC zone is the yellow shaded area as shown in Figure 31. As said above, this zone includes primary DC bus, the DC rails of the rectifier and the source side DC rails of the buck converter.

***DC Bus Fault*: **Faults on the cable of the primary DC bus, i.e. DC bus faults on the DC SES are often permanent, and primarily occur due to cable insulation failure or battle damage like missile hit etc. These faults are very severe in nature which 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 it does not cause an interruption of power, since the SES is high impedance grounded. These DC bus to ground faults are therefore non-disruptive.

***Rectifier DC Rail fault*: **One of the other faults that can occur in this zone is the fault on the DC rails of the rectifier PEBB. The likelihood of these faults is less due to their physical location within the enclosed converter. These faults are 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 31.

***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 as severe. The only difference being the physical location of the fault and the lesser likelihood of its occurrence due to its physical location within the converter.

(B) Secondary DC Zone

The secondary DC zone is the green shaded area as shown in Figure 31. This zone 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.

DC Bus Fault: Similar to the primary DC bus, the secondary DC bus is also a cable. The faults occurring on the secondary DC bus are of permanent nature similar to the primary DC bus and caused by cable insulation failure or battle damage. These faults are less severe as the secondary DC bus voltage is 800 V as compared to 7kV 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 but physically occurring within the converter.

(C) Rectifier AC side zone

The rectifier AC zone is the blue shaded area as shown in Figure 31. As the name suggests, this zone includes the AC side of the rectifier until the fuses and the rectifier AC side filters. The faults that can occur in this zone are the

→ Line – Ground fault (phase A, B and C):

→ Line – Line faults (phase A-B, BC and CA):

→ Three – phase faults before and after the input inductor

(D) War Damage

War damage is a special condition wherein multiple faults occur in close physical vicinity. Typically this kind of fault occurs within a load zone comprising of a watertight bulkhead compartment requiring the shutdown of that complete load zone of a DC SES.

The following sections illustrate how the agents detect these disturbances and take the appropriate protective action. The principles used for detection of faults and the protective action initiated by the agents to isolate the fault are given. The protective action for a severe fault is to command the circuit breaking units (the ETO based switches of the PEBBs) to turn off (open) or to raise an "alarm" for a non-disruptive faults. To illustrate the proposed schemes and their effectiveness, simulation on the prototype DC SES of Figure 31 has been performed using PSCAD /EMTP.

3.5.1 Rectifier Fuse for Rectifier AC Zone

As pointed out above, we propose to use fuses at the source side of rectifiers to protect the rectifier AC zone shown in Figure 34. 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 operation (shutdown) of the rectifier PEBB does not isolate the fault. The fuse also provides backup protection to the Rectifier Agent.

The fuse chosen for our 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, similar to a typical protection, here it is required that the fuses should be slow enough so that the downstream protection gets enough time to operate. For our particular application, 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 basic principles of operation of a fuse are given in Appendix A. Based on basic fuse types, the main consideration for the choice of the fuse for the prototype system are as follows

(1) The normal rated current of the device to be protected is ~450A (RMS)

(2) The startup current (due to initial capacitor charging via rectifier PEBB) is of the order of 1.5kA (RMS) for about 5-10ms (<0.01s).

(3) The faults that are to be protected against, have fault currents of the order 9-10kA (faults after source inductor) to 30kA (faults before source inductor)

With these considerations in mind, a choice a 500E rated fuse for our application, is appropriate as the normal rated current is about 450A. An EJO-1 type 9F62 fuse from General Electric meets these requirements and has been used for this particular application.

To demonstrate the fuse operation, the rectifier of Figure 34 is used. A fuse model for PSCAD was developed by the author to represent the fuse to melting and clearing. The results of a simulation of a Line A-B fault in the Rectifier AC zone (fault B1 in Figure 35) at t = 0.05s are shown in Figure 32. Following the fault at t_{fault} = 0.05s, the current I_A and I_B increase as shown in Figure 32(a) and are limited only by the source impedance. 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 the time required for the fuse to melt and clear. At t_{melt} = 0.0507s, the energy dissipated in the fuse exceeds the energy required for melting the fuse which causes the fuse A and fuse B to melt as shown in Figure 32(b). Similarly, at t_{clear} = 0.0604s, the fuse have dissipated enough energy for clearing and therefore at t = 0.0604s the fuse of phase A and phase B clear. Consequent to this, at t = 0.062s, the first zero current crossing of I_A and I_B, the fault current due to the L-L fault is interrupted by the fuse.

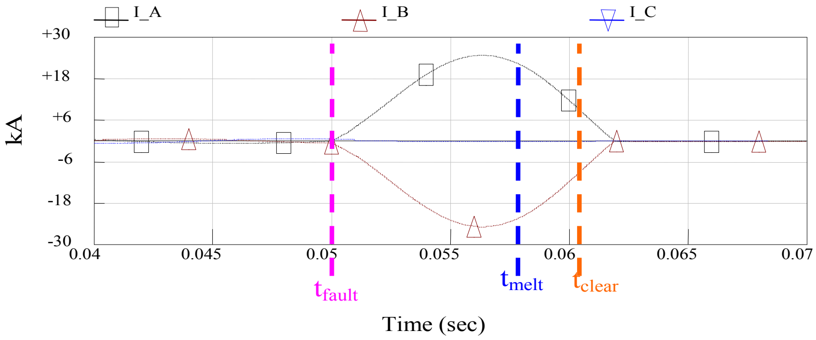


Figure 32 : Fuse Operation

3.5.2 CDCCB for Primary DC Zone

For a fault in the primary DC bus zone, the capacitors on the bus, such as the rectifier output capacitor, also contribute high fault currents which have a very short time constant. Therefore, in addition to the main zones of protection outlined above, the capacitors connected to the DC busses demand special attention in the form of their own zone of protection.

Protection to the capacitors is typically provided at a hardware level by the way of RLD snubbers [33] to limit the magnitude of the capacitor fault current contribution and the rate of discharge. The snubbers however, do not interrupt the fault current, they merely limit it.

Therefore, in contrast to the snubber approach, a capacitor DC circuit breaker (CDCCB) has been employed here, which defines the zone of protection for the capacitor. This CDCCB is employed between the energy storage capacitor and the positive DC bus rail [16] as shown in Figure 33 . The zone of protection for the capacitor is outlined by the CDCCB and it is the pink shaded area encircling the capacitors and as shown in Figure 34.

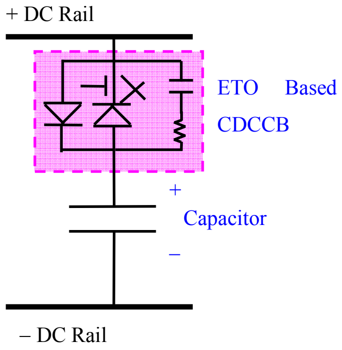


Figure 33 : CDCCB Protection

In our application to a DC SES, the CDCCB opens to protect the capacitor and other devices. The opening operation of the CDCCB prevents the capacitor from discharging and therefore preventing the capacitor voltage decay. This translates into extra advantage in terms of minimization of rise time of the load voltage following a fault and reapplication of the source. In addition, there is no overshoot of the DC voltage as the output capacitor holds un-discharged state [34]. Further in comparison to RLD snubbers, with the CDCCB approach, there is no need for power resistors and the heat dissipation is avoided, in other words thermal requirements are virtually eliminated. With these advantages in mind, a CDCCB is employed for the protection of all the capacitors connected to the DC buses of the SES.

Since here we replace the RLD snubber with a CDCCB, the time constants involved for the discharging of capacitor without RLD snubber, are extremely small of the order of 10µs. Therefore, the CDCCB should also be very fast in order to effectively protect the capacitor from extreme stresses and destruction [30, 35]. In [16, 30] it is shown that indeed an ETO based CDCCB can be used to turn off and interrupt fault current in less than 10µs, thereby meeting the requirement set forth.

The basic principle of operation of the CDCCB is based on the inherent current sensing of the ETO [30]. The measured current is compared to a 2.1kA threshold (maximum limit of the DCCB ETO= 2.5kA). A hard turn-off is initiated when the through current crosses this threshold. This hard turn-off limits the current from increasing further and interrupts the current in 3-7µs.

3.5.3 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 the part of the DC SES shown in Figure 34. The RA takes appropriate action in order to minimize the effect of disturbance on the operation of the system. The figure also shows the zones of protection.

For the part of the system shown in Figure 34, the rectifier AC zone faults and the primary DC bus zone faults are relevant. These faults are illustrated in Figure 35.

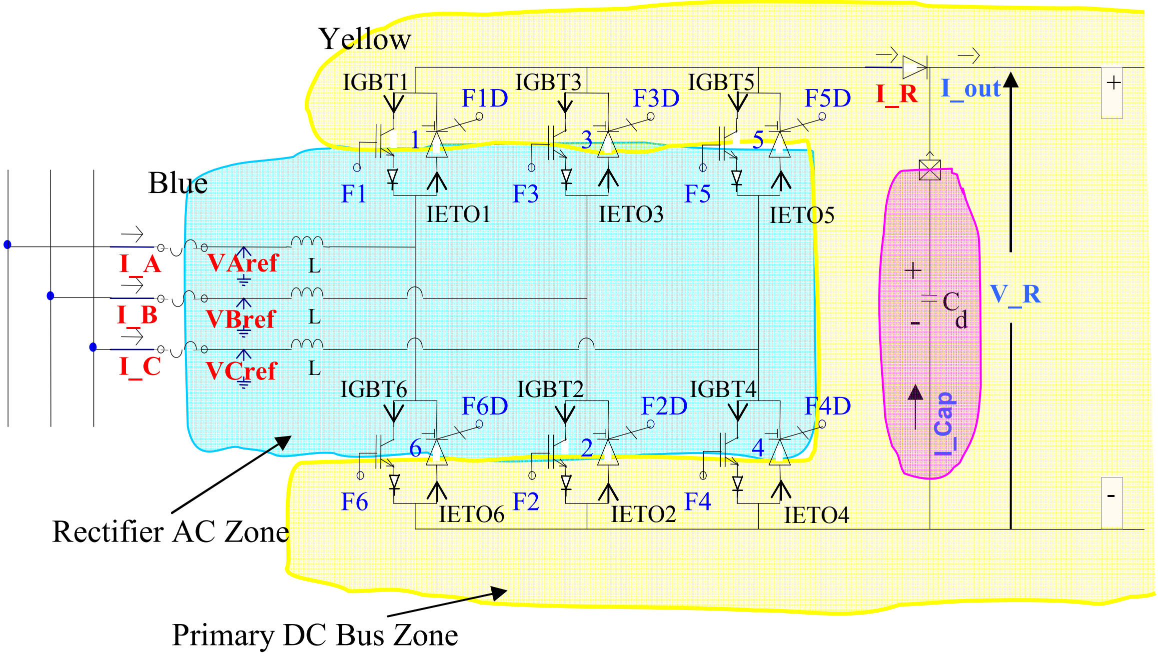


Figure 34 : Protection Zones around Rectifier PEBB

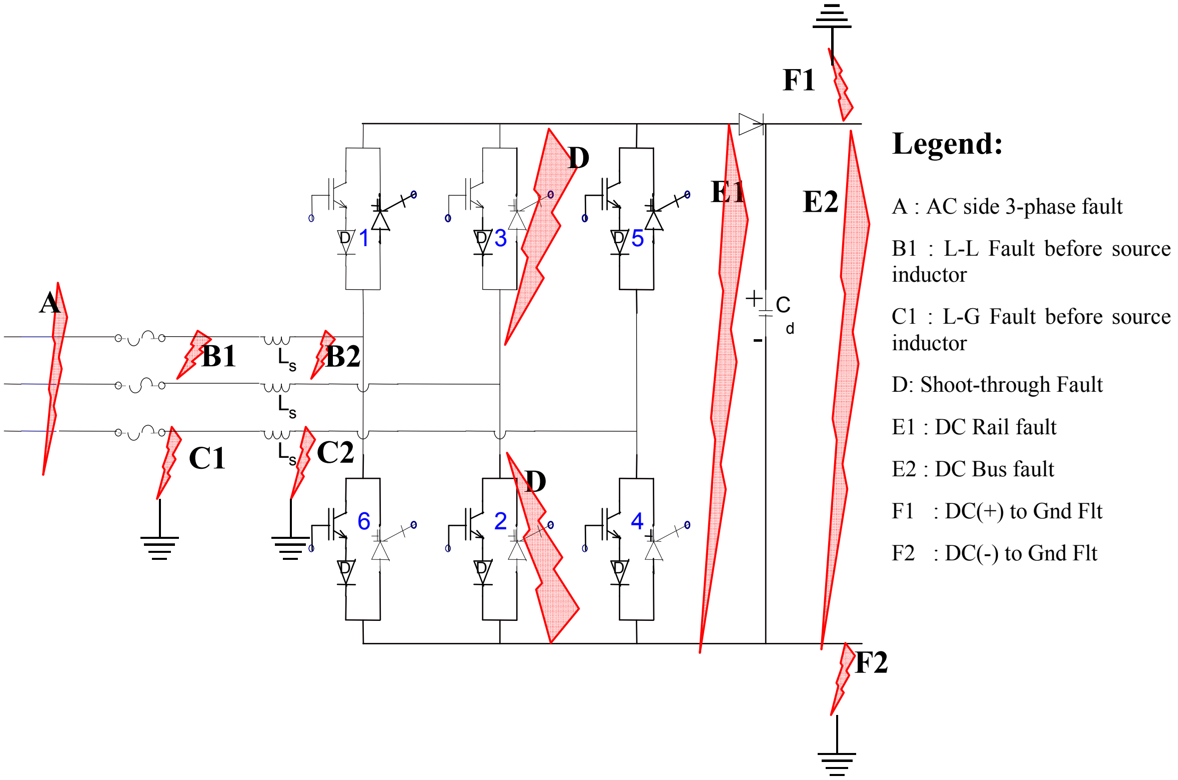


Figure 35 : AC and DC Faults close to Rectifier PEBB

Rectifier Agent for Rectifier DC Zone

To detect the various faults, the RA monitors the following local measurements (shown in red in Figure 34):

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

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

The agent uses these measurements to detect faults and take proper protective actions. The schemes developed for the agent to do this, are given below.

(a) Rectifier DC Bus fault (**E2 **in Figure 35)

The bus faults occurring in the primary DC zone are the most severe faults on the DC SES. Faults on improperly protected DC bus will cause very high currents due to discharging of all the capacitors connected to the DC bus, which includes the rectifier output DC smoothing capacitors and buck converter input capacitors. Hence, very fast detection and protective action is necessary to protect (a) the capacitor, (b) the DC cable and (c) the PEBB devices from destructive failure due to a DC bus fault.

The fault contribution for a primary DC bus fault is from 2 sources – the bus capacitor and the generator. The fault contribution by the capacitor is with an extremely short time constant while the fault contribution due to the generator is with a relatively longer time constant. Due to the extremely short time constant involved with capacitor discharge, as detailed earlier, a hardware based solution of a CDCCB is employed to limit the current and turn off and interrupt the fault current, thereby protecting the capacitor and connected devices.

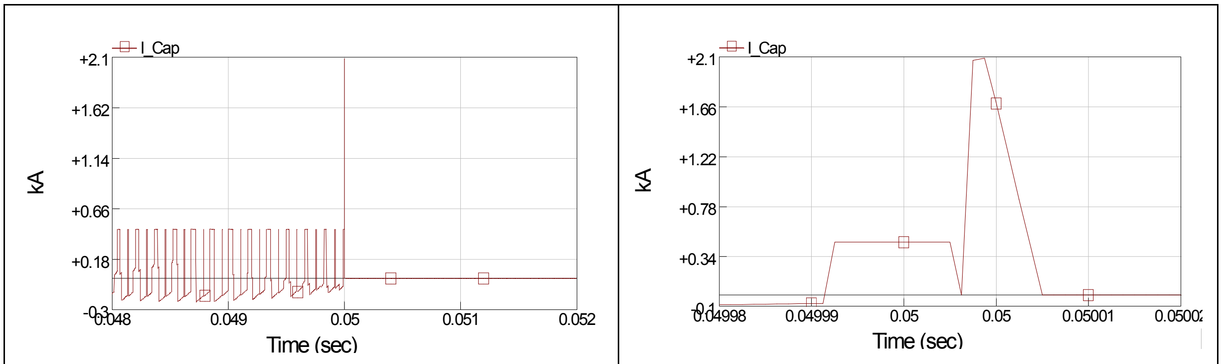
The RA provides protection against the fault contribution by the generator via the rectifier. The RA monitors the current I_R as shown in Figure 34. The RA compares this value to a preset threshold of 1.75kA. When the current I_R exceeds the threshold for 3 samples, RA identifies the condition as a DC bus fault. The RA initiates a soft-turnoff to limit the current from further increasing and interrupts the current 20μs later.

As it will be seen later, the RA must detect a DC fault before it detects an AC fault. This condition is ensured by setting the threshold for the detection of a DC fault by I_R to be 1.75kA as compared to a threshold of 3.5kA for I_A, I_B and I_C to detect an L-L fault.

When a DC bus fault occurs, the capacitor and the generator feed the fault. The CDCCB operates and open in 10μs. Therefore, the capacitor stops contributing to the fault current. The generator, however, contributes to the fault current via the rectifier and causes the currents I_R and I_A, I_B and I_C to increase simultaneously. When these currents simultaneously cross the threshold of 1.75 kA it is detected by the RA and the fault is identified as a primary DC bus fault.

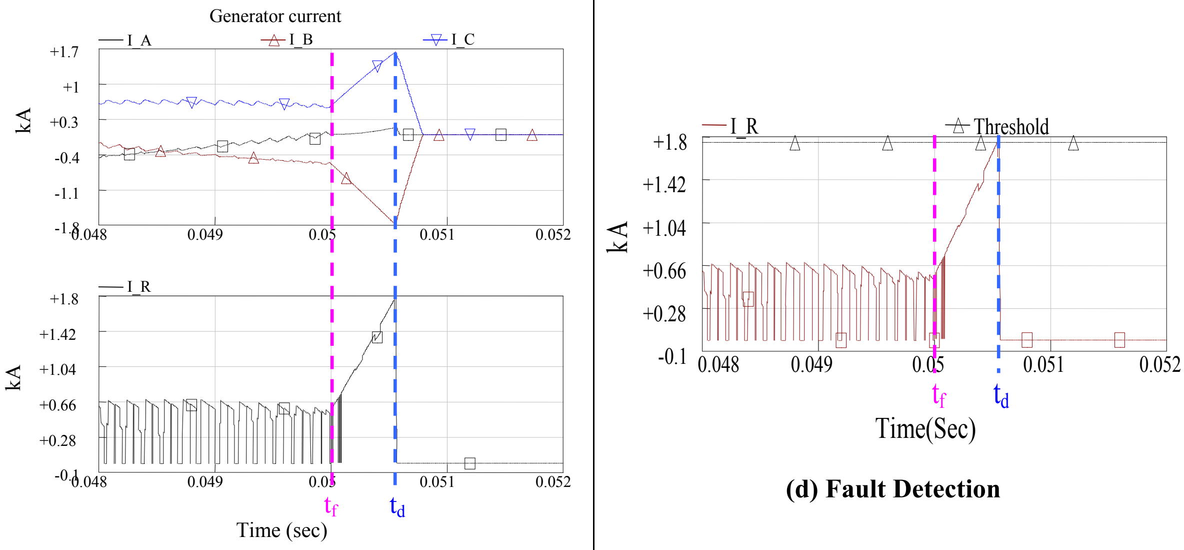
Therefore, the protective action by the RA for a rectifier DC bus fault can be explained in a sequential manner as follows. Following a DC Bus fault, the hardware based DCCB detects and opens to interrupt the fault current contributed by the capacitor. Subsequent to that, the RA detects the fault and commands soft turn-off of the Rectifier PEBB. The turn-off of the rectifier PEBB interrupts the fault contribution by the generator. These 2 actions completely isolate the faulted part of the system.

Simulation results for a primary DC Bus fault are shown in Figure 36. Following a fault at t_f = 0.05s, the bus capacitor discharges into the fault with a very short time constant as seen in Figure 36(a) and (b). The operation of the CDCCB limits and interrupts the fault current in 9μs. Following the fault, the generator also starts contributing fault current as seen by the I_A, I_B, I_C and I_R in Figure 36(c). The RA monitors the I_R and when I_R exceeds the threshold of 1.75kA at t_d = 0.0505s, it detects and identifies a primary DC bus fault as seen in Figure 36(d).



(a) Capacitor Discharge

(b) Zoom-in of (a)



(c) Generator Fault Contribution

(d) Fault Detection

Figure 36 : Simulation Results of Rectifier DC Bus fault

(b) Rectifier DC Rail fault (E1 in Figure 35)

The positive and the negative DC rails of the rectifier PEBB are electrically the same as the positive and the negative DC buses respectively, but the rails are physically a part of the Rectifier PEBB, and are enclosed within the PEBB. Therefore, a rectifier DC rail fault is less likely than a rectifier DC bus fault. The diode which connects the PEBB DC Rails to the DC Bus provides the radiality to the zonal distribution architecture. It also prevents other rectifiers from feeding into the faults that occur within this rectifier. The diode also prevents the DC bus capacitors from contributing to the DC rail faults.

Under normal operation of the PEBB, I_R is the charging current of the rectifier output capacitor. Therefore, it is at a value of capacitor charging current or at zero (when the capacitor is discharging into the load). Therefore it is fluctuating between the rated value or zero at the switching frequency.

When a DC Rail fault E1 occurs, the generator current which normally charges the capacitor is now diverted into the fault. Therefore, the current measurement I_R is very small, as long as the fault exists.

The RA, monitors I_R and I_A, I_B and I_C and detects the fault E1, when the following conditions are satisfied.

(a) $I\_R_{new} < I\_R_{old}$ (i.e. I_R "crosses" the threshold from positive to negative)

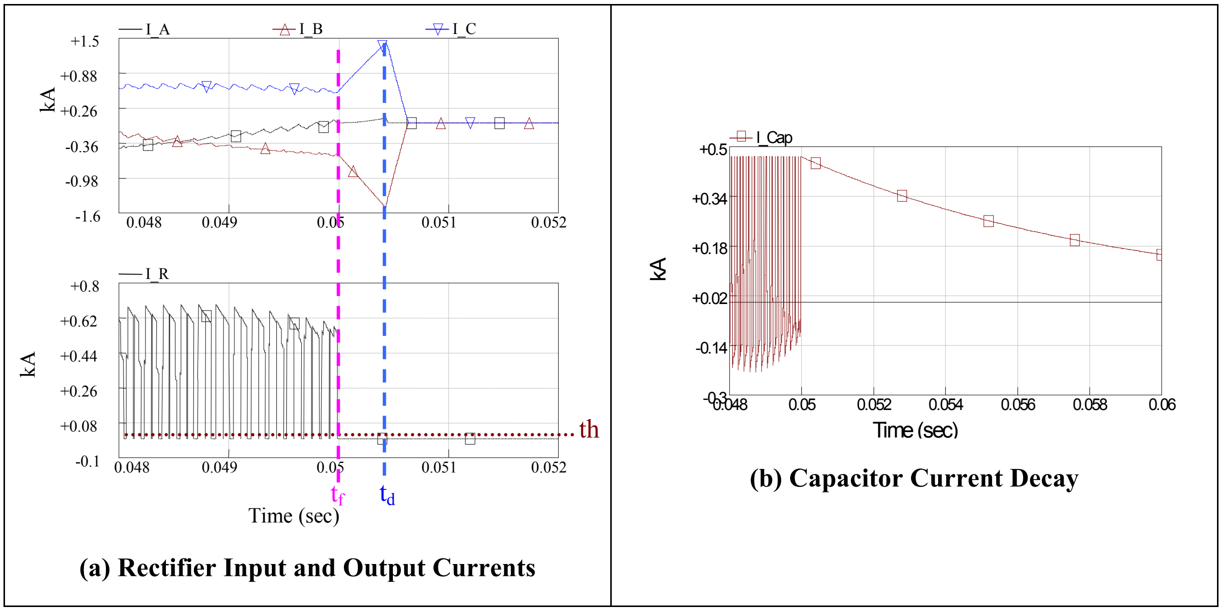
(b) I_R is less than the I_{th} (= 25A = minimum load current) continuously for > 2 T_s.

(c) I_A, I_B and I_C are > I_{th2} , and

(d) The soft turn-off of the PEBB has not initiated.

The conditions (a) and (b) identify the scenario when the generator current is diverted into the fault causing the current I_R to decrease to zero. Therefore these two conditions help in detecting the existence of a fault. The condition (c) ensures it is indeed a fault condition and not a "lull" period due to capacitor overcharging. In contrast to a fault condition, during lull period, the currents I_A, I_B and I_C are very close to zero that is I_A, I_B and I_C < I_{th2}. Condition (d) ensures that the RA does not misidentify any other fault to be a DC rail fault, during the condition when the PEBB is in the process of being turned off as a result of another fault in the system.

Figure 37 shows the simulation results of a rectifier DC+ to DC- rail fault. The results were obtained in PSCAD/EMTP. A fault occurring at t_f =0.05s causes the current I_R to drop below the threshold of 0.025kA as shown in Figure 37(a). At t = 0.0502s, the condition (c) is satisfied as the current I_B exceeds I_{th2}. This rules out that it is a lull period. The current I_R remains below the threshold for a time interval of 150µs (> 2 T_s). Therefore, at t_d =0.05042s a fault is detected. Since, no other fault condition exists; the turn-off of the PEBB has not already been initiated thus satisfying (d). At t_d = 0.050427s, the RA detects and identifies the fault as a DC Rail fault and commands the PEBB to turn off. This limits the current from increasing further and at t = 0.05064 the fault current is interrupted as shown in Figure 37(a). The reverse biasing of the diode, following the fault, prevents the capacitor from discharging into the fault E1 and the capacitor discharges into the load as shown in Figure 37(b).



(a) Rectifier Input and Output Currents

(b) Capacitor Current Decay

Figure 37 : Simulation Results of Rectifier DC Rail fault

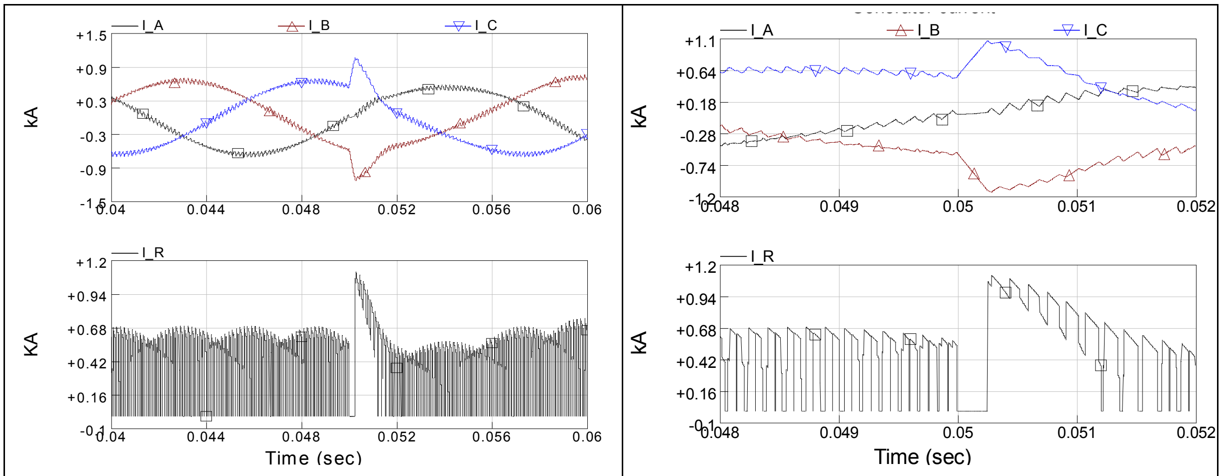
(c) Shoot-Through fault (D in Figure 35)

A shoot through fault by definition is the shorting of the DC rail by accidental misfiring of the switching devices of a given leg. In our system we employ a bus interface diode between the Rectifier Rail and DC bus. When a misfiring by the controller causes the switching devices in a given leg to turn on simultaneously, the diode becomes reverse biased. The reverse biasing of the diode therefore, prevents any high discharge current by the capacitor.

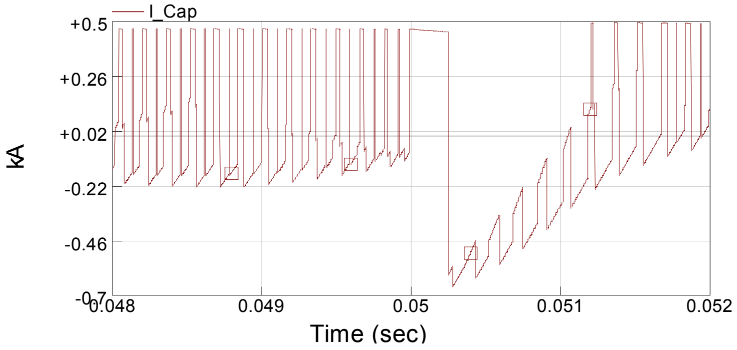
Under normal operation of the VSC, the input AC terminals are repeatedly shorted for very short intervals. When a shoot-through fault occurs in one of the converter legs, while the other legs are fired normally, it results in the shorting of the input AC terminals. Although under normal operation, the AC inputs are shorted, it is not long enough for a substantial current rise. Whereas for a shoot-through fault; the shorting is sustained for long time intervals. This sustained the input short by misfiring of the switches causes a current in increase. The input phase current is diverted from the load into the shorted switches.

Simulation results for a temporary shoot-through fault are shown in Figure 38. The mal-operation of the controller causes misfiring of the switches, resulting in shoot-through faults from $t_f = 0.05s$ to $t_n = 0.05025s$ (250µs). The shoot-through fault causes the current to rise to about 1.1kA. At $t_n = 0.05025$, the controller resumes normal operation, and the shoot through fault ceases. The generator currents I_A, I_B, and I_C go back to normal values. The IGBT and ETO currents are shown in Figure 38(d) and (e). Following the fault, IGBT3 and ETO5 currents start to increase. At $t_n = 0.5025s$, the currents start returning to their normal values.

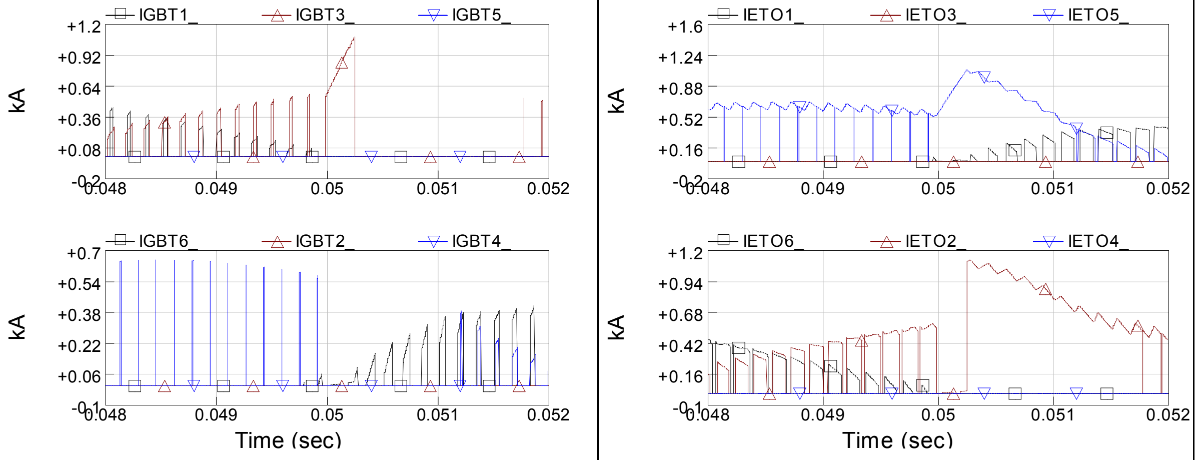
If the shoot-through fault is sustained for longer time intervals, the currents I_A, I_B and I_C increase further and exceed the threshold of 1.75kA. The RA detects this high current condition and identifies it as a fault condition. The protective action by the RA is to initiate a soft turn-off of all the switches of the PEBB. Figure 39 shows the simulation of a sustained shoot-through fault that requires the shut-down of the rectifier PEBB. A fault occurring at $t_f = 0.05s$ causes the current I_R to drop below the threshold of 0.025kA as shown in Figure 39(a). At $t_d = 0.05042s$, the I_B exceeds the threshold of 1.75kA, and the RA detects this as a fault and commands the PEBB to turn off. This stops the input current from increasing further, and at t = 0.05064 the fault current is completely interrupted as seen from Figure 39(a). The capacitor current is seen to decay into the load in Figure 39(b).



(a) Rectifier Input and Output Currents **(b) Zoom-in of (a)**

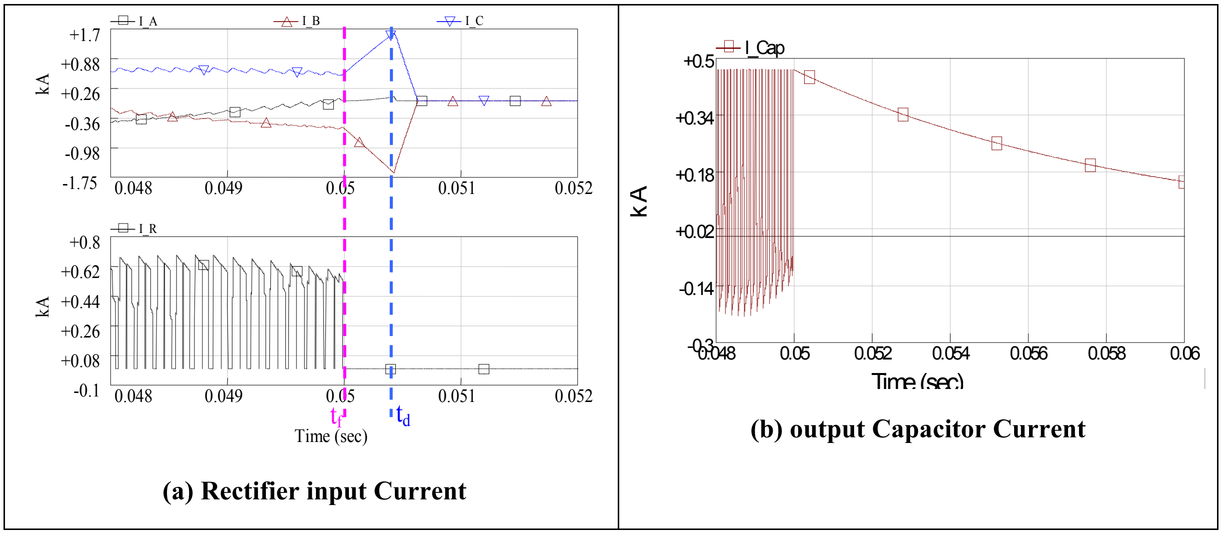


(c) Output Capacitor Current



(d) IGBT Currents **(e) ETO Currents**

Figure 38 : Shoot-Through Fault



(a) Rectifier input Current

(b) output Capacitor Current

Figure 39 : Sustained Shoot-Through Fault

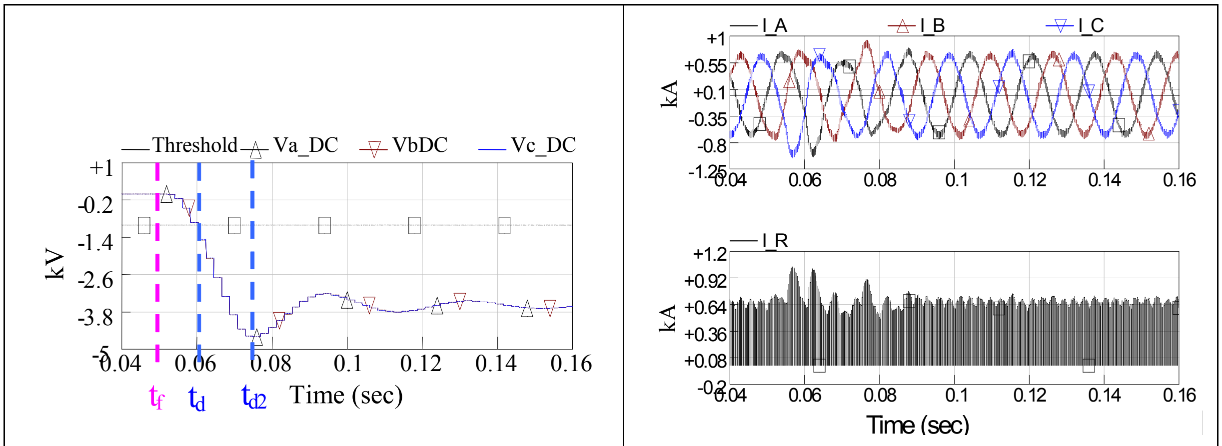
(d) Rectifier DC Bus to Ground fault (*F1 and F2* ***in Figure 35)***

When a Positive or negative DC bus to ground fault occurs, it is observed that it causes a 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. The RA extracts the DC component by an online Fast Fourier Transform of the phase voltage measurements of individual phases. The polarity of the DC offset is compared to a threshold of ±1kV. The RA detects a fault when the DC offset of the phase voltages exceeds the threshold and remains there for 1ms. The RA identifies it as a positive DC bus to ground fault if the DC component has a negative magnitude and it identifies a negative bus to ground fault if the DC component of all the three phases have a positive magnitude.

The RA avoids incorrectly detecting a 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 RA.

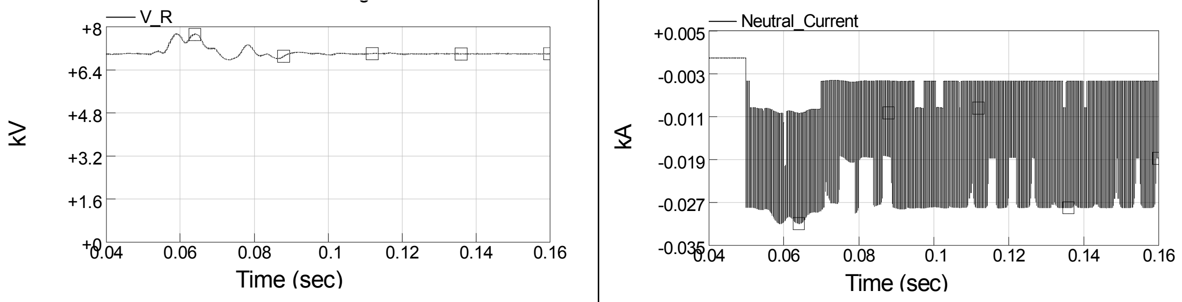
Similar to the L-G faults on the AC side discussed previously, the first DC bus to ground faults are non-disruptive, and therefore the RA only raises an alarm and the operation of the system is continued normally.

Figure 40 shows the simulation results for a positive DC bus to ground fault. A positive DC bus to ground fault occurring at $t_f = 0.05s$ causes a negative DC offset to appear in the phase voltages given by Va_DC, Vb_DC and Vc_DC in Figure 40(a). At t_d = 0.0604s, the DC components of all the three phases crosses the threshold of -1kV. This negative DC offset condition exists for 1ms and it is detected by the RA and at t_{d2} = 0.0704s the RA identifies it as a positive DC bus to ground fault, since the magnitudes of the DC component is negative. Figure 40 (b) shows the currents I_A, I_B and I_C during a positive DC Bus to Ground fault. The PCFF controller has been modified by the author to improve system performance under DC bus to ground faults. The improved performance can be seen by the sinusoidal currents and the low ripple output voltage and currents. The modification that has been introduced in the PCFF controller compensates for DC bus to ground fault by subtracting the DC offset component to the reference waveform, thereby nullifying the effect of the DC offset. As seen from the Figure 40(b), (c) and (d) that the system performance is temporarily affected and therefore with the modified controller, the fault is a non disruptive fault and the system operation is therefore continued normally without any interruption of supply during a DC bus to ground fault. Figure 40(f) shows the actual phase voltages and the DC offset. The DC Offset implies that a higher insulation level may be needed between phases and to ground in order to operate the system under such a condition.



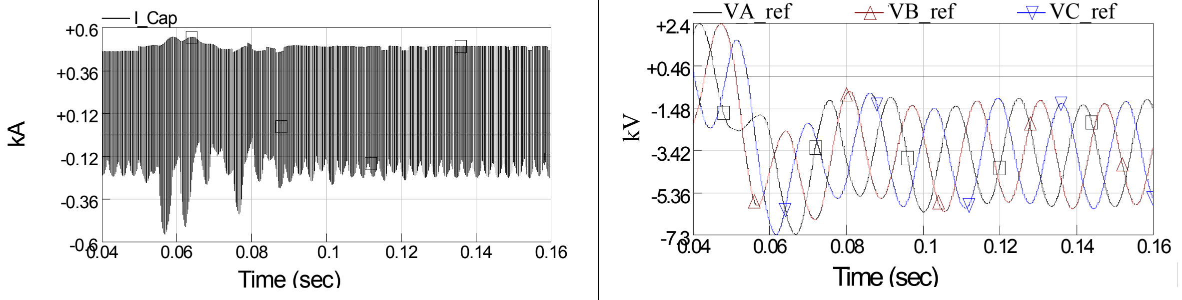
(a) Fault Detection

(b) Rectifier Currents



(c) Rectifier Output voltage

(d) Generator Neutral Current



(e) Capacitor Current

(f) Generator Phase to Ground Voltages

Figure 40 : Simulation Results of DC Bus to Ground Fault

Rectifier Agent for Rectifier AC zone

The faults in the rectifier AC zone are detected by the RA. The protection action is performed by the RA, though it does not interrupt or isolate the fault. The detection of the fault by the RA aids during reconfiguration and repairs.

(e) L-L faults,** (B1 and B2* ***Figure 35)

In conventional protection schemes, I_A, I_B and I_C are measured and the comparison of these current magnitudes with a preset threshold in an over current type of protection is used for the detection of a fault.

In an AC/DC system like ours, fault current magnitude comparison is sufficient just to detect the existence of **a** fault. But since a DC fault also causes high magnitudes of I_A, I_ and I_C, this method is therefore, insufficient to identify and locate the L-L faults.

In order to successfully segregate L-L faults from the DC faults, additional information is necessary. This additional information may be in terms of negative sequence current components from Online Fast Fourier Transformation or as additional measurements or it may be as “intelligent” system facts.

When an L-L fault occurs, the unbalance in the phase current causes the magnitude of the negative sequence component currents to be large in contrast to a DC fault, where all the phase currents have negligible negative sequence component. An online FFT can be used to calculate the negative sequence current from I_A, I_B and I_C. An L-L fault can therefore be segregated from other faults if magnitude of the negative sequence current component exceeds a preset threshold.

The other method to segregate the L-L faults involves the use of extra measurements by additional transducers. This proposition is typically much expensive and therefore is not discussed here.

The last method that has been used here to segregate an L-L fault is by the way of knowledge of additional system information. The additional information here in our case is the fact that the detection of a DC fault by the RA is faster than the detection of an L-L fault, as had been eluded earlier.

It was shown earlier that for a Rectifier DC fault (rail/bus), the RA detects the fault and commands the PEBB to turn off. Turning-off of the PEBB prevents the current through the ETOs and the currents I_A, I_B and I_C to increase beyond the threshold of 1.75kA. With this additional fact now, under the scenario when the currents I_A, I_B or I_C exceed another threshold of 3.5kA (> 1.75kA), it definitely implies that the RA and its backup protection did not detect a DC fault; therefore eliminate the possibility of the existence of a DC fault and hence implying an L-L fault.

Summarizing the protective action of the RA in a sequential manner, the RA monitors the local measurement quantities. If a DC fault exists, the RA detects it and turns the PEBB off thereby limiting the currents I_A, I_B and I_C from increasing further. If a DC fault does not exist, then the RA does not detect it and therefore does not limit the current to 1.75kA and the current increases further. When two of the three measurements of I_A, I_B or I_C exceed the preset threshold of 3.5kA an L-L fault is identified.

In response to the detection of the L-L fault, the protective action performed by the RA is to command the PEBB to turn off.

As illustrated earlier, the increased currents due to the L-L fault causes the fuses to melt and clear and therefore 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 EMTP /PSCAD simulation results for AC L-L fault are shown below. Two scenarios of L-L faults are simulated.

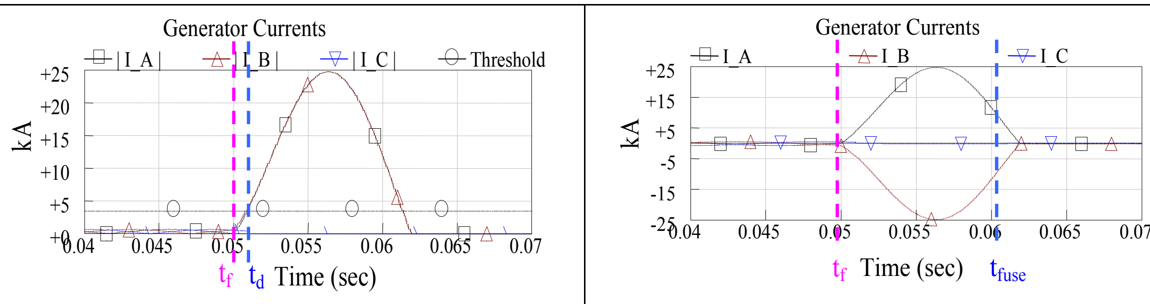
Scenario 1: AC L-L Fault before input inductor (B1 in Figure 35)

Figure 41 shows the simulation results of a fault before input inductor. An L-L fault occurs at t_f = 0.05s. The magnitudes of currents I_A, I_B and I_C, as shown Figure 41(a) rise following the fault. At t_d = 0.051s the current magnitudes exceed the threshold of 3.5kA 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_d = 0.051s as a result of the detection of the AC fault.

Figure 41(b) shows that the high currents I_A and I_B cause the fuse to melt and clear at t_{fuse} = 0.0604s and successively interrupt the fault at the following current zero at t = 0.0618s.

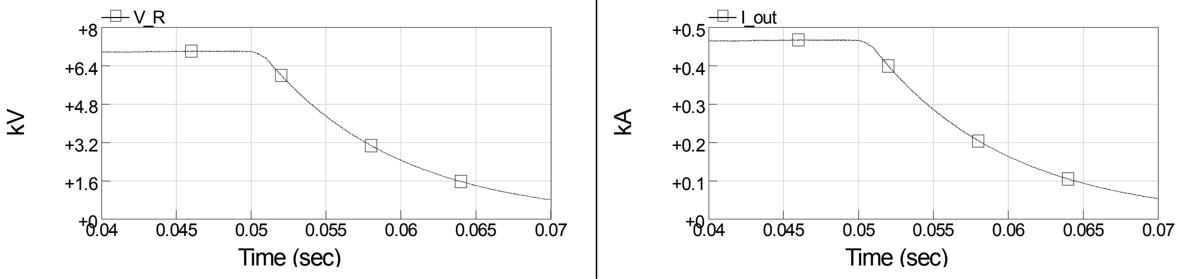
The PEBB turn-off and the blowing of the fuse isolate the faulted portion of the system.

The output DC voltage and current are shown in Figure 41(c) and (d) respectively. Following the PEBB turn-off; as a result of the discharging of the capacitor into the isolated load, the DC voltage and DC current decay to zero. Figure 41(e) shows the capacitor current, I_cap of Figure 34. Following the AC fault and the turn-off of the PEBB, any further charging of the capacitor is prevented and the energy of the capacitor only discharges into the load.



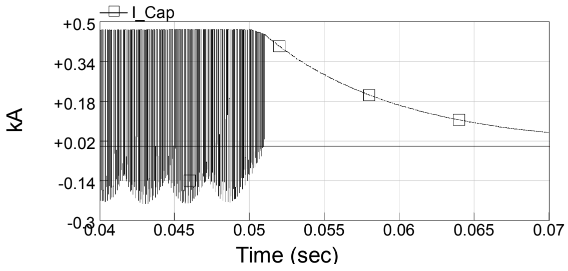
(a) Fault Detection

(b) Fuse Operation



(c) Rectifier Output Voltage Decay

(d) Rectifier Output Current Decay



(e) Output Capacitor Current Decay

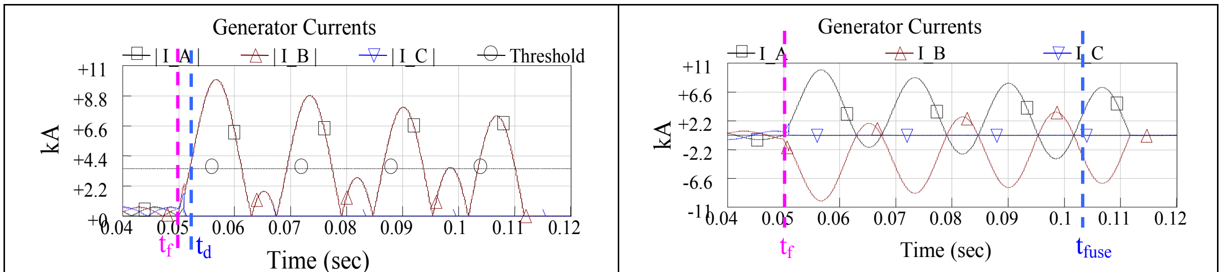
Figure 41 : Simulation Results of L-L fault before Inductor

Scenario 2: AC L-L Fault after input inductor (B2 in Figure 35)

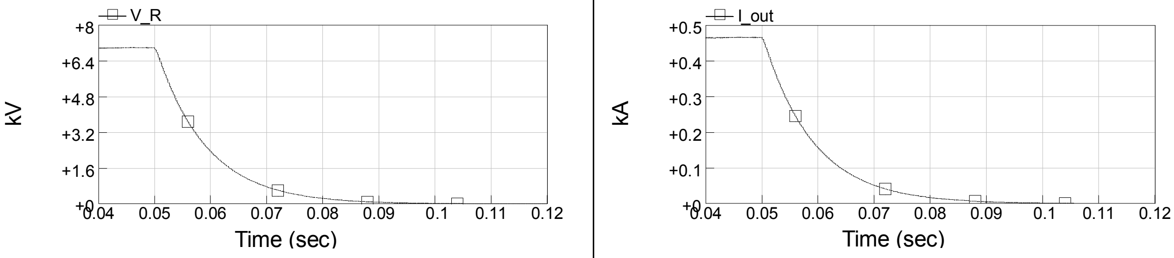
Simulation results of an L-L fault after inductor are shown in Figure 42. The results are similar to the previous scenario.

An L-L fault after the inductor occurs at $t_d = 0.05$s. The magnitudes of currents I_A, I_B and I_C, as shown Figure 42(a), rise following the fault. At t = 0.0525s the current magnitudes exceed the threshold of 3.5kA 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 = 0.0525s as a result of the detection of the AC fault. Figure 42(b) shows that the high currents I_A and I_B cause the fuse to melt and clear at $t_{fuse} = 0.1035$s and successively interrupt the fault at the following current zero at t = 0.112s. The PEBB turn-off and the blowing of the fuse isolate the faulted portion of the system.

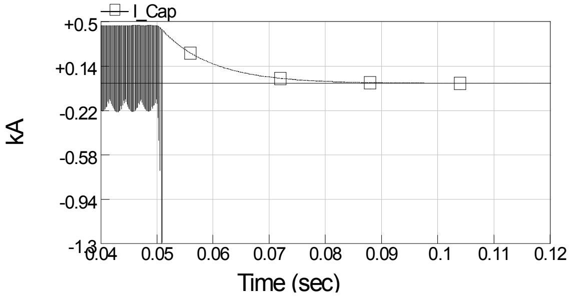
The output DC voltage and current of the rectifier PEBB are shown in Figure 42(c) and (d) respectively. Following the PEBB turn-off; as a result of the discharging of the capacitor into the isolated load, the DC voltage and DC current decay to zero. Figure 42 (e) shows the capacitor current, I_cap of Figure 34. Following the AC fault and the turn-off of the PEBB, the capacitor is not charged further, but discharges completely into the load.



(a) Fault Detection **(b) Fuse Operation**



(c) Rectifier Output Voltage Decay **(d) Rectifier Output Current Decay**



(e) Output Capacitor Current Decay

Figure 42 : Simulation Results of L-L Fault after Inductor

The stark differences of the above 2 scenarios is in the magnitudes of the currents I_A, I_B and I_C. The current magnitudes in the 2nd scenario as seen Figure 42(a) in contrast to Figure 41(a) are less. This is due to the additional impedance of the AC side filter inductor in the fault path. The increased impedance reduces the fault current and in turn it takes longer for the fuses to blow. This is seen in Figure 41(b) in contrast to Figure 42(b), where an L-L fault before input inductance is fault is interrupted at t =0.0618s as compared to t = 0.112s for an L-L fault after inductor.

(f) Three Phase faults (A in Figure 35)

In conventional systems, the three single phase relays monitor the phase currents and trip when the RMS magnitude exceeds a preset threshold. Thus they do not identify and differentiate the various faults.

In the designed protection scheme, the RA carries forward the information it obtained from the detection of the AC L-L fault. The RA refines this by applying additional condition to identify and segregate a 3 phase fault from an L-L fault.

The existing condition is that the RA has already detected the existence of an L-L fault and turned the PEBB off. Therefore the segregation of the L-L fault from a 3-phase fault is not critical but may be helpful during the reconfiguration stage of protection.

The RA refines the existing state by an additional condition, where it checks if all the three phase currents I_A, I_B and I_C exceed the 3.5kA threshold. If this is satisfied, then the RA identifies a 3-phase fault.

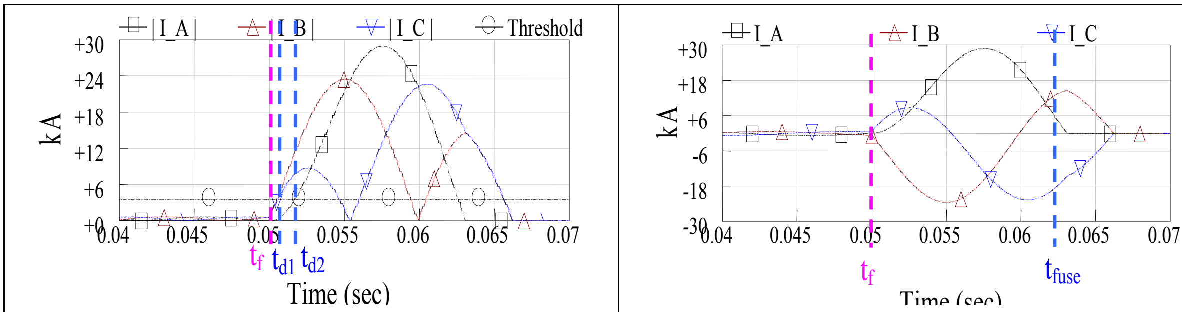
Similar to the fuse operation results shown earlier for an L-L fault, the increased currents cause the fuses to melt and clear and therefore interrupt the fault current. The shutdown of the PEBB (due to L-L fault detection) and the blowing of the fuse complete the protective action to isolate the faulted part of the system.

Simulation results of a 3-phase fault are shown in Figure 43. A 3-phase fault occurs at t_f = 0.05s. The magnitudes of currents I_A, I_B and I_C, as shown Figure 43 (a), rise following the fault. At t_{d1} = 0.0506s the current magnitudes I_A and I_C exceed the threshold of 3.5kA 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 = 0.0506s as a result of the detection of this AC fault. This is the pre-existing condition. At t_{d2} = 0.0518s, the current magnitude I_B exceeds the threshold of 3.5kA indicating a 3-phase fault rather than an L-L fault. This condition of all the three currents exceeding the threshold is detected by the RA and the RA identifies the fault as a 3-phase fault at t_{d2} =0.0518s.

Figure 43(b) shows that the high currents I_A, I_B and I_C cause the fuses to melt and clear at t_{fuse} = 0.0625s and successively interrupt the fault at the following current zero at t = 0.0661s.

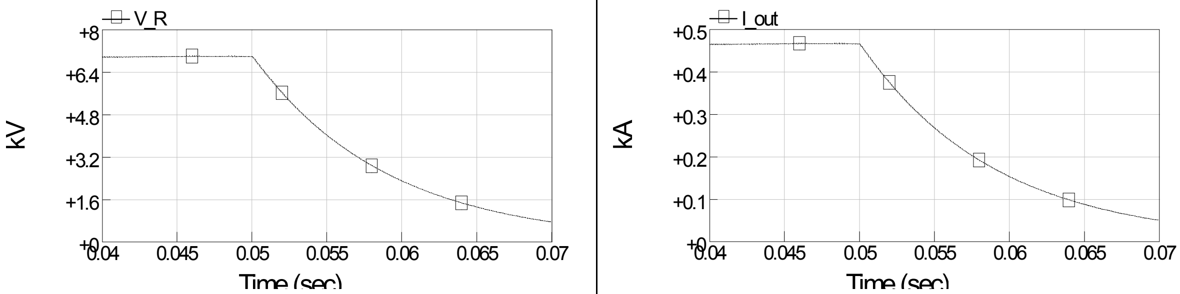
The PEBB turn-off and the blowing of the fuse isolate the faulted portion of the system. And the PEBB flags a 3-phase fault rather than an L-L fault.

The output DC voltage and current are shown in Figure 43(c) and (d) respectively. Following the PEBB turn-off; as a result of the discharging of the capacitor into the isolated load, the DC voltage and DC current decay to zero. Figure 43(e) shows the capacitor current, I_cap of Figure 34. Following the AC fault and the turn-off of the PEBB, any further charging of the capacitor is prevented and the capacitor discharges completely into the load



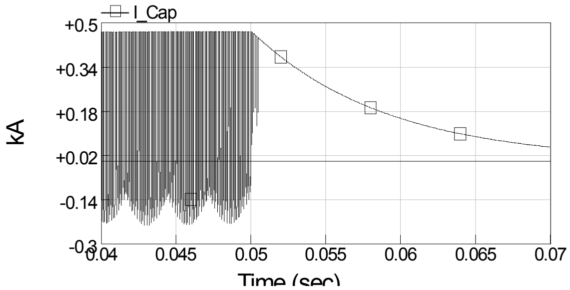
(a) Fault Detection

(b) Fuse Operation



(c) Rectifier Output Voltage Decay

(d) Rectifier Output Current Decay



(e) Output Capacitor Current Decay

Figure 43 : Simulation Results of 3-Phase Fault

(g) Rectifier AC L-G *(C1 and C2* ***in Figure 35)***

In conventional systems, the L-G faults are detected based on the zero sequence components extracted from measured 3 phase currents or the neutral currents. For a high impedance grounded system such as the DC SES, the protection scheme will have to be extremely sensitive and therefore impractical to detect a ground fault. In addition, since the neutral current divides up among the generators, it would be even harder to locate the ground fault.

On a high impedance system like the DC SES, it is observed that for an L-G fault, the fundamental component of the phase voltages collapse to near zero. Therefore, for the protection of the ground faults on the high impedance system like ours, the RA monitors the 3 phase voltages, VA_ref, VB_ref and VC_ref as shown in Figure 34 and extracts the fundamental component of the phase voltages. The RA compares this fundamental component with a preset threshold of 0.2kV. The RA detects an L-G fault when the fundamental component crosses the threshold (with a negative slope) and stays below the preset threshold (0.2kV, a small percentage of the rated voltage) for 1ms. This ensures that the L-G fault is a sustained/permanent fault. During startup, the fundamental component is below the threshold but it has a positive slope. This condition prevents the RA from falsely detecting an L-G fault during startup condition.

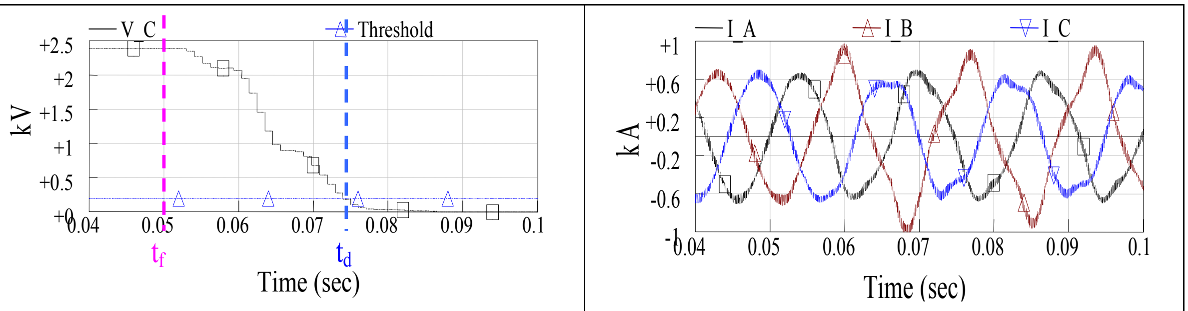
In addition to detecting the existence of an L-G fault, the RA is also able to identify the faulted phase. For example if the fundamental component of phase C falls below the threshold of 0.2kV, then the RA identifies that the phase C has a ground fault.

Another important aspect of protecting a ground fault in a high impedance system is that the protective action is unique. Since the DC SES is grounded with high impedance, the first L-G faults are not disruptive in nature, and the normal operation of the system can be continued (provided that the controller of the converter has been designed properly for such a condition). Since the first L-G faults on high impedance systems are not disruptive in nature, the RA does not provide any protective action and it only raises an alarm to notify the existence of an L-G fault. The normal operation of the system is carried on. Also, the 1ms delay associated with correctly locating the fault is tolerable and hence justified.

Simulation results for a C-G fault are shown in Figure 44. A C-G fault at $t_f = 0.05s$ causes the fundamental component to decrease from its nominal value of 2.4kV. At $t_d = 0.07396s$, the value of the fundamental component of phase C falls below the threshold. At $t_{d2} = 0.07496s$ when the fundamental component has remained below the threshold for 1ms, the RA flags a C-G fault

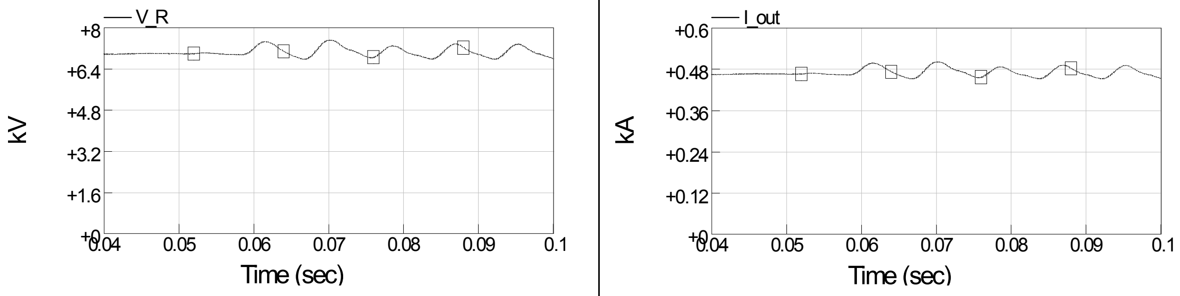
Figure 44(b) shows the harmonics introduced by the C-G fault in the converter input currents I_A, I_B and I_C with the PCFF controller. The figure also shows that the fuses do not mal-operate under the C-G fault condition, as required. This graph indicates that the modification of the PCFF may be necessary so that it may have better performance for an input L-G fault.

Figure 44(c) and (d) show the rectifier's output voltage and current. These figures show that indeed the L-G fault on a high impedance system is not disruptive in nature, but at the same time additional harmonics are introduced. The output ripple is less than 10 % under the fault condition with the PCFF controller. A modification or compensation to the controller may be implemented to obtain improved performance. Figure 44(e) shows the intermittent capacitor overload due to the L-G fault. Figure 44(f) shows the generator neutral current under the AC L-G fault is less than 16A peak.



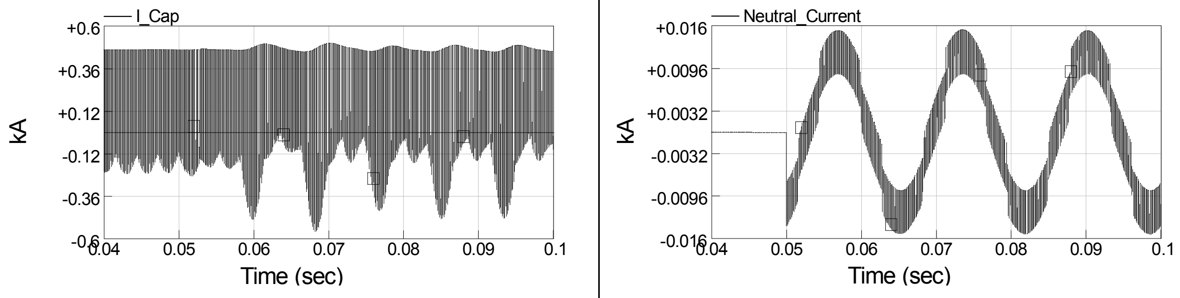
(a) Fault Detection

(b) Rectifier Input Currents



(c) Rectifier Output Voltage

(d) Rectifier Output Current



(e) Output Capacitor Current

(f) Generator Neutral Current

Figure 44 : Simulation Results of Phase C to Ground Fault

3.5.4 Buck Converter Agent

The Protection-Agent associated with the Buck Converter PEBB is called the Buck Converter Agent (BCA). The BCA monitors the local quantities of the rectifier PEBB, shown in red in Figure 45 and based on these measurements; it locates and detects the existence of any disturbance on the part of the DC SES shown in same figure. The BCA takes appropriate action in order to minimize the effect of disturbance on the operation of the system. The figure also shows the zones of protection.

The faults that can occur on the part of the system shown in Figure 45 can be divided into two categories – the Primary DC Bus Zone and the Secondary DC Bus zone. The faults are shown in Figure 46. The Buck Converter can provide protection by detecting and interrupting the faults in the secondary DC Bus zone. It can only detect and provide isolation for the faults in the primary in the Primary DC Bus Zone; it cannot interrupt any fault currents in that zone.

The isolation transformer's turn ratio, the PWM switching pattern function, the ETO device ratings, input inductor inductance are some of the important design issues that play an important role in Buck converter Agent's procedure for detection can detect of the faults shown in Figure 46.

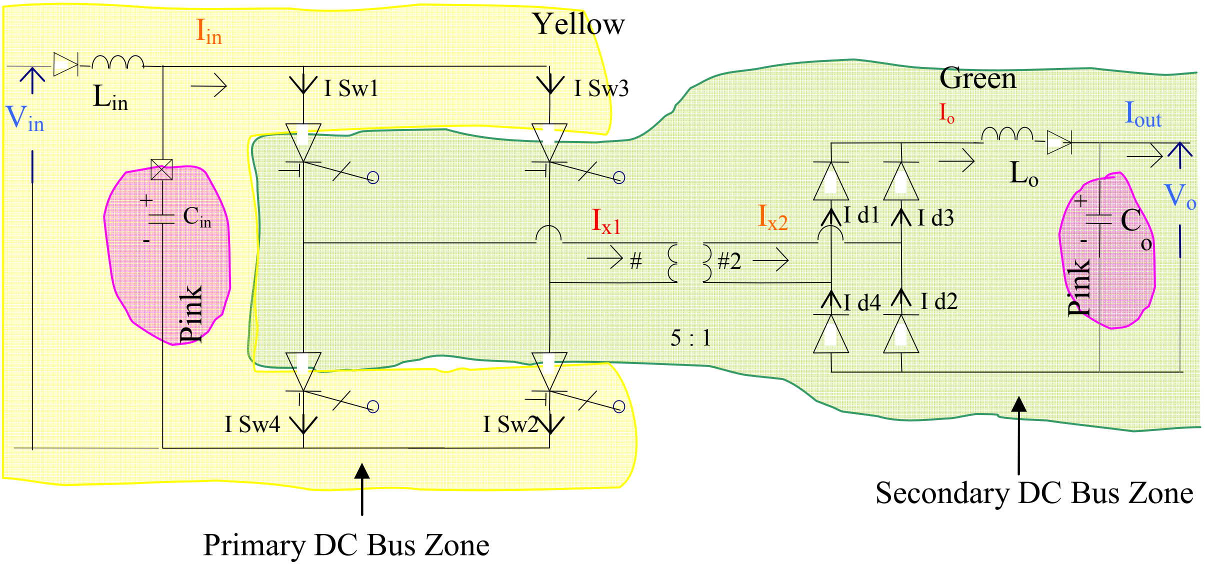


Figure 45 : Protection Zones around Buck Converter PEBB

For example, a higher turn ratio of the isolation transformer will lower the current in the CSDs of the BCIS during the normal operation. This allows us to choose ETOs with lower current ratings. But this, from a protection perspective, would result in the choice of device that can withstand much lower "maximum currents". This in turn implies that during a fault condition, the fault current will require a much shorter time to exceed the maximum current rating of the device. Therefore, the buck converter agent will have much less time to detect and identify a fault and the BCA will have to be much faster, which can make the protection task of the BCA much harder.

Another example is the choice of L_{in}. A larger L_{in} aids in limiting the rate of rise of fault current, while at the same time during turn-off of the current, a larger L_{in} will cause a higher voltage rise ($=L_{in}*di/dt$). Therefore, L_{in} should be chosen such that it provides enough time for the BCA to detect the fault and at the same time does not cause an excessive over voltage. Details for all the above issues have been provided in Appendix B.

The BCA can detect the existence of a fault by measuring the current I_{in} as shown in Figure 45. To associate the detected fault to a subsystem of the buck converter can be very useful during the physical repairs of the buck converter. Therefore, to locate the fault, 3 additional local measurement quantities, shown in red in Figure 45, are needed

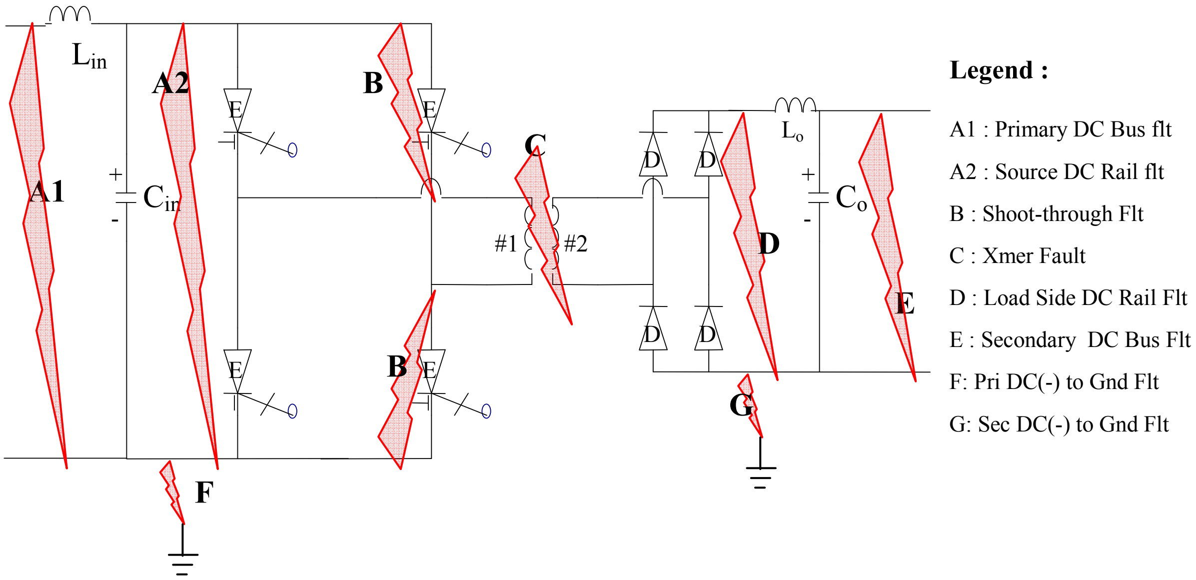


Figure 46 : Faults close to Buck Converter PEBB

The Buck Converter Input current, I_{in} is the primary measurement used for the fast detection and protection of the PEBB. I_{in} is measured through a high bandwidth current sensor (~1 MHz). The other three current measurements are: transformer input Current (I_{x1}), transformer output Current (I_{x2}) and Buck Converter Output current (I_o). These measurements are used to determine the location of the fault. The current measurements I_{x1}, I_{x2}, and I_o are the sampled at 30 kHz, 5 times switching frequency of the buck converter at 6 kHz.

Buck Converter Agent for Secondary DC zone

The detection of the faults shown in Figure 46, by the BCA is based on the high bandwidth measurement, I_{in}. Whenever the measurement I_{in} crosses certain thresholds, the BCA detects the existence of a fault. The details of the protection provided by the BCA are given in this section.

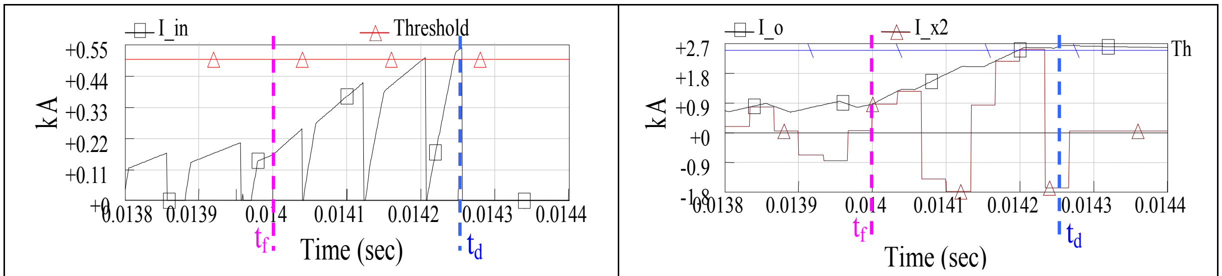
(a) Secondary DC Bus fault (E in Figure 46)

This is the main fault in the secondary DC zone. This fault causes a high current I_{in} as well as a high magnitude of I_o. The BCA detects the existence of a fault in the converter when I_{in} crosses a threshold of 0.5kA. The BCA identifies the fault as a secondary DC Bus fault when the current I_o crosses the threshold of 2.5kA along with a simultaneous increase in I_{x2}.

For this fault, the output capacitor will discharge into the fault. A DCCB similar to the rectifier output capacitor is employed for the buck converter output capacitor.

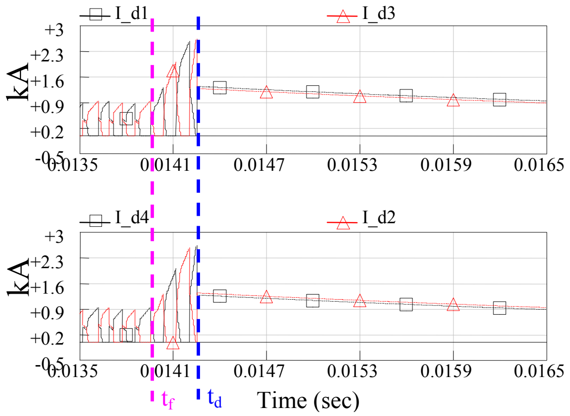
The simulation results are shown in Figure 47. For a secondary DC Bus fault occurring at t_f = 0.014s, the current I_{in} starts to increase as shown in Figure 47(a). At t_d = 0.01425s, the BCA detects a fault as I_{in} crosses the threshold of 0.5kA. Also at t_d = 0.01425s, the currents I_o and I_{x2} cross the threshold of 2.5kA as shown in Figure 47(b). The BCA therefore identifies the fault as a secondary DC bus fault. The protective action taken by the BCA is to turn-off the CSDs of the PEBB.

The protective action of hard turning off of the CSDs immediately 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. When this energy is completely dissipated the fault is completely interrupted. The freewheeling of the diodes is seen in Figure 47(c) from t_d onwards. This free-wheeling of the diodes of the BCRS prevents any excessive voltages on the downstream devices.



(a) Secondary DC Bus Fault detection

(b) Secondary DC Bus Fault Identification



(c) Diode Freewheeling

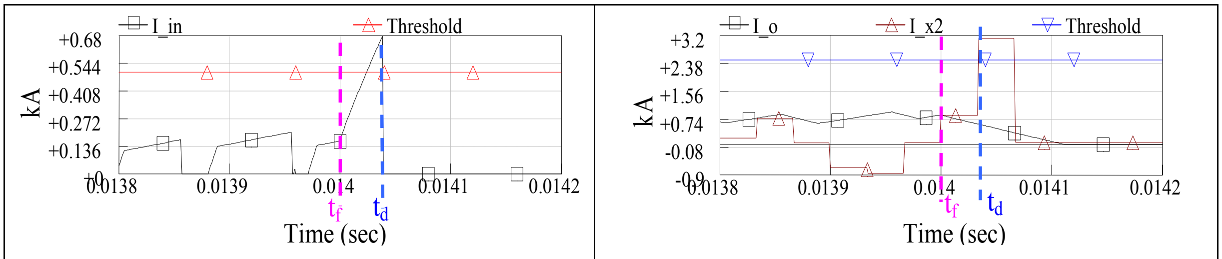
Figure 47 : Secondary DC Bus Fault Simulation Results

(b) Load side DC Rail (D in Figure 46)

The likelihood of the DC Rail fault is much less than that of the secondary Bus fault, as the DC Rails are physically enclosed within the converter. Also, an interface diode, similar to the rectifier, is connected between the secondary DC rail and the secondary DC bus. This interface diode prevents the discharge of the downstream capacitors into the secondary DC rail faults, thereby maintaining the radial nature of the system.

For the load side faults, the transformer inductance is added to the fault path and therefore this aids by increasing the current rise time following the load side rail fault. The BCA detects this fault, when the input current I_{in} exceeds the threshold I_{th1} (=0.5kA). The measurements I_{x2} and I_o help the BCA to locate the fault. When the current I_{x2} exceeds the threshold (2.5kA) without a corresponding increase in I_o, the BCA identifies the fault as a Load side DC Rail fault. This is in contrast to the DC bus fault, where both I_{x2} and I_o cross the threshold, as described before.

The simulation results are shown in Figure 48. A fault at $t_f = 0.014$s causes the input current I_{in} to increase. This is shown in Figure 48(a). At $t_d = 0.01404$s it cross the threshold of 0.5kA. The BCA detects this condition and indicates a fault in the converter. Figure 48(b) shows the currents I_o and $I_{x2,}$ Since I_{x2} increases without a corresponding increase in I_o, the BCA identifies it as a secondary DC Rail fault. The protective action for this fault is to command the CSDs of the BCIS to turn off.



(a) Buck converter DC Rail fault detection

(b)Buck converter DC Rail Fault identification

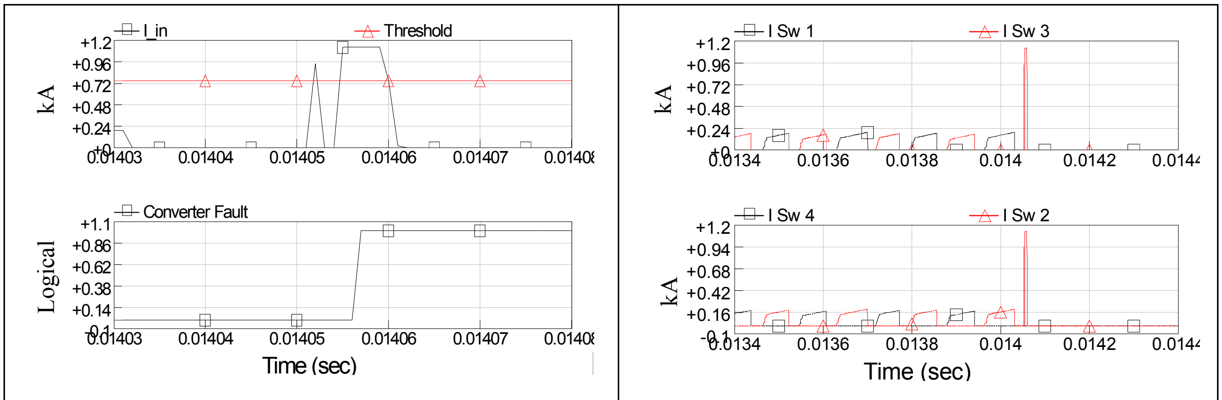
Figure 48 : Load Side DC Rail Fault simulation results

(c) Shoot-Through (B in Figure 46)

A shoot-through fault occurs when a fault in the controller causes the devices in the same leg to fire and turn ON (F1 and F4 or F3 and F2) simultaneously. Single shoot-through faults are common, but sustained shoot-through fault is very drastic and shutdown of the devices is mandatory.

Characteristics of this fault are such that it causes the input capacitor to discharge through the devices of the ON devices. Since the monitored current I_{in} will see this discharged current, the BCA detects this fault by detecting this capacitor discharge current. The protective action for sustained shoot-through fault is to command the CSDs of the Buck converter to hard turn-off.

The simulation results for a shoot-through fault are shown Figure 49. A single shoot-through fault is simulated followed by a sustained shoot-through fault. The sustained shoot-through fault causes the current to rise to ~1kA limited by the CSD. When the I_{in} crosses the threshold of 0.5kA, the BCA detects the fault. The protective action of hard-turning off the CSDs is performed to interrupt the current and thereby turning off the PEBB. Figure 49(b) shows the device currents. Under normal conditions, prior to fault, I_{sw1} and I_{sw2} or I_{sw3} and I_{sw4} conduct indicating the normal operation. During the shoot-through fault, I_{sw3} and I_{sw2} start conducting simultaneously, which is detected as high current I_{in}, indicating the shoot-through fault.



(a) Shoot-through fault detection

(b) Device currents under shoot-through fault

Figure 49 : Shoot-Through Fault Simulation Results

(d) Transformer faults (primary and secondary side) (C in Figure 46)

For a transformer fault (primary or secondary side fault), the input capacitor and the source contributes into the fault through I_{in}. The BCA detects a converter fault when the current I_{in} crosses the threshold (0.5kA). The BCA turns off the PEBB to interrupt the fault current and isolate the fault. The BCA also monitors the transformer primary current I_{x1} and I_{x2} at 30 kHz, and uses a current differential scheme to identify the fault as a transformer fault.

An important point to note here is that for transformer faults, the reverse biasing of the diodes in the BCRS prevents the output capacitor from discharging into these faults, simplifying the protection.

The simulation results for the transformer primary side faults are shown in Figure 50. Prior to the fault, the current differential is about 2A indicating normal operation. Following the fault on the primary of the transformer, at t_f = 0.014s, the current I_{x1} and I_{in} increase. The BCA detects the over current condition of I_{in} and indicates a fault. Due to the transformer fault the current differential increases to 112A and exceeds the threshold of 20A. At t_d = 0.01412s, the BCA identifies the fault as a transformer fault.

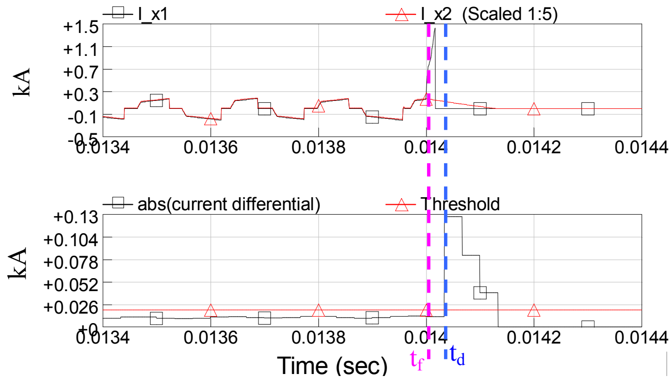


Figure 50 : Transformer Primary Side Fault Identification

Simulation results for a transformer secondary side fault on the buck converter (of Figure 45) are given in Figure 51. Similar to the above scenario, prior to a fault, the current differential is less than 2A. Following the fault on the secondary of the transformer, at t_f = 0.014s, the current I_{in} increases. The BCA detects this over-current condition and detects a fault. Following the fault, the current differential increases to 61A, exceeding the threshold of 20A. At t_d = 0.01404s the BCA, therefore identifies the fault as a transformer fault.

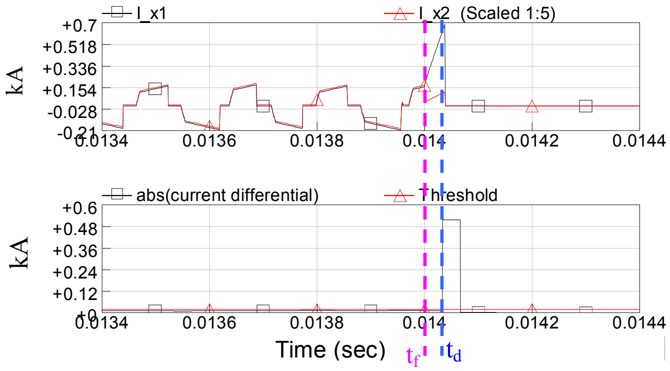


Figure 51 : Transformer Secondary Side Fault Detection

Buck Converter Agent for Primary DC zone

(e) Primary DC Bus Fault (A1 in Figure 46)

Primary DC Faults occur in the primary DC bus zone, upstream of the buck converter. These faults are therefore, interrupted by the upstream rectifiers. The BCA however needs to detect this fault so that it can isolate the fault by turning off the CSDs of the buck converter.

A DCCB similar to the rectifier output capacitor, but with lower ratings, is installed for the buck converter input capacitor. Also, similar to the rectifier, an interface diode is connected between the primary DC Bus and the Buck Converter source side DC rail. This interface diode prevents the discharge of the input capacitor into the faults on the DC Bus.

The detection of this fault is based on the fact that under such a fault, the current I_{in} drops to a very low value, as the current is diverted from the buck converter into the fault. The BCA detects a primary DC Bus fault when the current I_{in} crosses and remains below a threshold (10A). When this low current condition is detected and persists for a certain time interval (=300μs), a source side DC fault is detected. A startup restraint is provided to allow the buck converter to startup from zero current condition. Another restraint is also provided which prevents the BCA from falsely identifying other faults as DC Bus fault, when the BCA has been turned off in response to other faults.

The simulation results for this fault are shown in Figure 52. A Primary DC bus fault occurs at $t_f = 0.0140$s. The current I_{in} to drop to about 1A (leakage current of diode) at t = 0.01403s. At $t_d = 0.1433$s, the BCA detects that I_{in} has remained below the threshold of 10A for 300μs and therefore identifies it as a DC Bus fault.

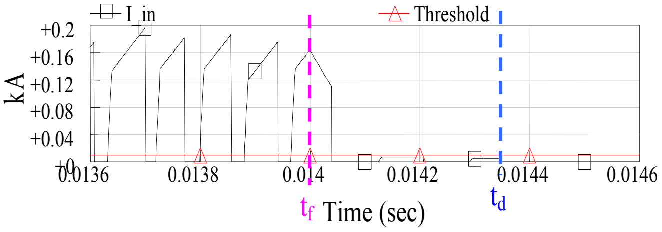


Figure 52 : Source Fault Detection

(f) Source side DC Rail fault (A2 in Figure 46)

The source side DC Rail fault A2, as shown in Figure 46 is a fault on the source side DC rails of the buck converter. The detection of this fault by the BCA is based on the measurement of the capacitor (rectifier DC capacitor and Buck input capacitor) discharge current, reflected through the monitored current I_{in}. The BCA detects a fault when the current I_{in}, crosses a threshold, I_{th1} (=0.5kA) and persists for 10 samples. This ensures the prevention of any nuisance tripping. Unlike the shoot-though fault or the transformer fault, the turn-off of the buck converter does not limit the fault current from increasing beyond 1kA. Therefore, when the current I_{in} continues to increase even after the BCA has turned off the buck converter, the BCA identifies it as a buck converter source side DC rail fault. The fault interruption is provided by the upstream rectifiers. The buck converter turn-off provides isolation.

The simulation results for the buck converter source side DC rail fault are shown in Figure 53. A buck converter DC rail fault at t_f = 0.014s causes the current I_{in} to increase. Immediately following the fault, at t_{d1} =0.014002, the current exceeds the threshold of 0.5kA and persists for 10µs. Therefore, at t = 0.01401s existence of a fault is detected by the BCA. When the current I_{in} exceeds the threshold I_{th2} = 1.5kA at 0.01402s, a DC rail fault in identified by the BCA.

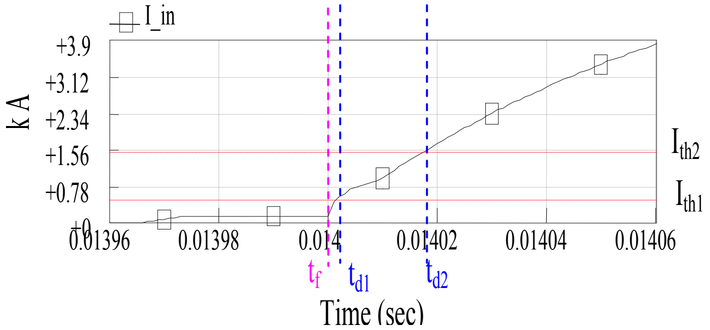


Figure 53 : Buck Converter Input Fault after Capacitor Detection

(g) Ground Faults (F and G in Figure 46)

Ground faults can occur on the source side (transformer primary side) of the buck converter, Fault F in Figure 46 i.e. buck converter source DC Rail fault. These ground faults on the source side of the buck converter are detected by the upstream Rectifier Agents, as illustrated in section 3.5.3(d).

Ground faults on the load side fault G in Figure 46 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.

3.5.5 Inverter Agent

Many schemes have been developed for the protection of AC inverter drive systems [33, 36-43] and even schemes for so-called fault tolerant drives [38, 40, 42, 44] which enable operation of the drive in a "degraded" mode under fault condition. This section reviews the literature and then describes how the existing protection schemes may be adapted for the agent based system protection scheme developed in this dissertation.

The Protection agent associated with the Inverter PEBB, called the Inverter Agent (IA), measures the local quantities and based on the detection principles that will be adopted; it will detect the existence of any disturbance on the part of the DC SES shown in Figure 54. The figure also shows the zones of protection associated with the inverter PEBB.

The interruption and isolation of the faults on the source side i.e., the secondary DC zone fault (A1) and the inverter DC rail faults (A2), is provided by the upstream buck converter. The IA is therefore responsible for the faults in the load zone which are three phase short circuits, line-line fault (C) and line to ground fault (D). These are illustrated in Figure 55.

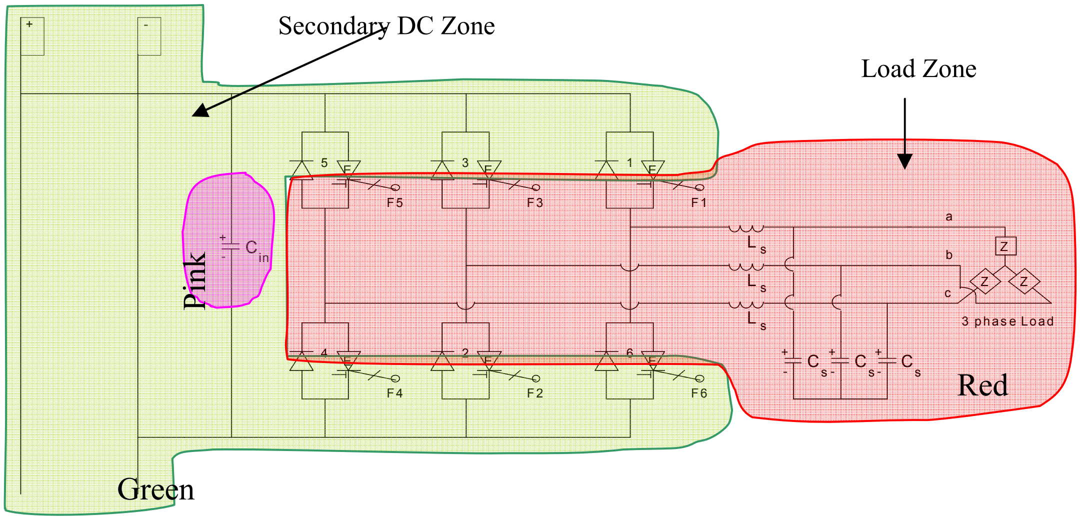


Figure 54 : Protection Zones around Inverter PEBB

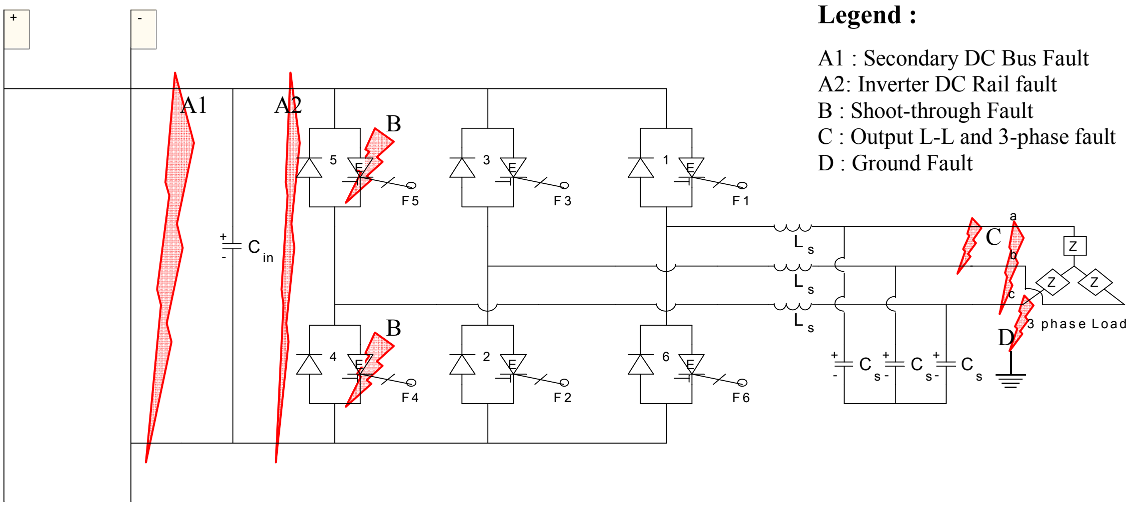


Figure 55 : Faults close to Inverter PEBB

To detect the faults shown in Figure 55 many methods have been proposed in literature [33, 36-39]. Typically, a combined solution is provided for the control and protection of the inverter [33, 39, 40]. The protection scheme in a commercial drive is usually designed conservatively so as to prevent damage in the converter system.

A typical protection system for voltage source inverter drive is shown in Figure 56 [40]. For the inverter and the load side faults, the transistor switches are opened and the magnetic contactor at the input is opened. The CB trips for steady over-current to the converter. The inverter input fuse protects the filter capacitor against shoot-through fault in the inverter. The machine’s over-temperature is protected by a breaker activated by thermal relay.

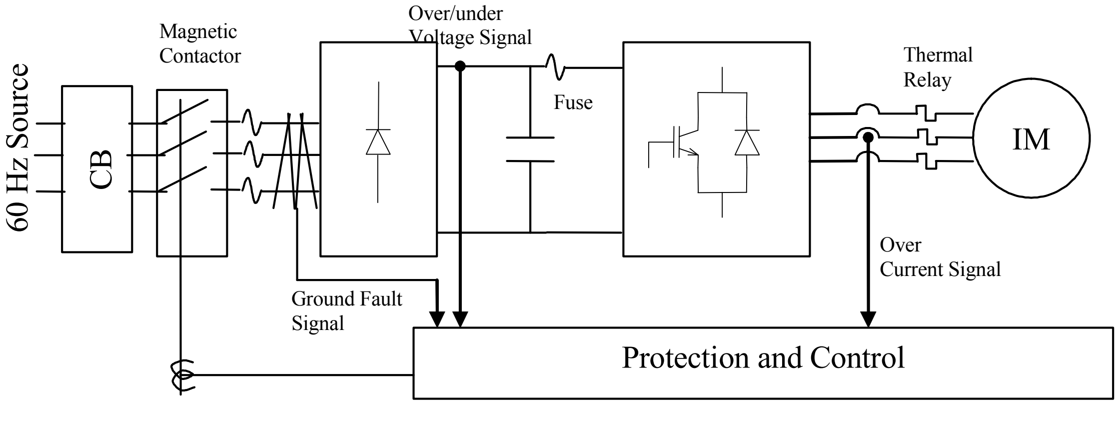


Figure 56 : Typical Protection for Voltage-fed Inverter

Another conventional scheme that provides total inverter protection is shown in Figure 57. The three-phase current sensors (I_a, I_b and I_c) at the output are used to detect over-current and earth faults and a DC link current sensor is used to detect shoot-through in the DC link. Elements R_s, C_s, and D_s act as snubber while L_s is a stray inductance or an intentional inductance which limits di/dt during shoot-though and short circuit on the DC rails. This provides complete protection for all the faults illustrated in Figure 55.

The Inverter Agent can adopt the scheme illustrated in Figure 57 to provide full protection to the voltage source inverter. The IA will monitor the four local quantities – I_{dc}, I_a, I_b and I_c. When these currents cross the appropriate thresholds, the IA detects the faults. One important point to note here is that since the SES is high impedance grounded/ floating, therefore the first ground faults are not disruptive.

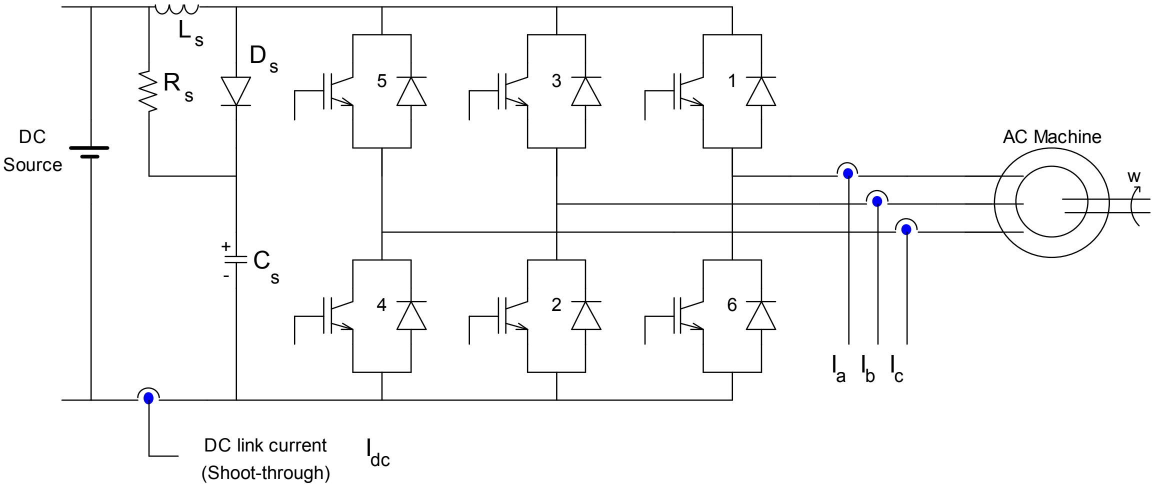


Figure 57 : Fully Protected PWM-VSI Inverter with 4 Current Sensors and One Snubber

Once the fault has been detected by the IA, the typical protective action is either (i) to inhibit firing pulses to the CSDs of only the faulted leg or (ii) to inhibit the firing pulses to all the CSDs of the PEBB, which is the preferable option [33, 40].

The simulations for such a protective action have been demonstrated earlier in section 2.5. Again, the switch level autonomous protection provides backup protection for failure in IA. In addition, ultra fast-action fuses which blow and clear the fault current in a few ms [41] may also be employed for backup.

3.6 Agent Based System Protection: Co-ordination & Backup

For the proposed Agent Based Protection scheme to provide complete system protection, the protection-agents should be able to provide (1) proper coordination among various protection devices/agents, and (2) backup protection if a protection device/agent fails.

(1) Coordination

Coordination between protection agents is needed to provide selectivity. Selectivity refers to the protective strategy wherein only those protective devices closest to a fault will operate to isolate the faulted part of the system [1]. Selectivity can be achieved by grading of protective device-thresholds, timing or operating characteristics. The coordination is the determination of these graded settings to achieve selectivity.

This sub-section shows, for the DC SES, how the proper co-ordination is achieved by choosing the correct thresholds for the various protection devices.

(a) Coordination between Rectifier Agent and fuses

As shown earlier, the coordination between the RA and the fuses is achieved by the proper selection of fuse. The fast action fuse selected for the rectifiers takes few ms to 100ms to interrupt and isolate the AC zone faults (depending on fault current), whereas the RA detects and interrupts the DC zone faults fault in about 0.5ms. Therefore, the Rectifier-Agents that are associated with the PEBB current limiting circuit breaker detect and interrupt the faults much earlier than the upstream fuses or the generator breakers. Thus, based on timing, coordination is achieved.

Another coordination issue that needs to be considered here is the coordination between the SLAP of the rectifier PEBB and the fuses. The threshold of the SLAP is set at a value of 2kA. The time to detect and interrupt the fault for the SLAP is of the order of 0.6ms (as compared to 0.5ms for the RA). Therefore, its coordination with the fuse carries a similar explanation. The wide difference in the operation times takes care of the coordination requirement between the RA and the upstream protection devices.

(b) Coordination between Rectifier-Agents

The coordination among various RAs (associated with the rectifier PEBB) which are connected to the primary DC bus is also needed. This coordination will assure that for a fault in the Rectifier AC Zone, only the fuses protecting the rectifier AC zone should blow and the RA of only the corresponding rectifier should detect the fault. The RAs of the other rectifiers should not detect this fault and should not take any protective action for the fault. The bus-rail interface diode which is employed prevents the other rectifiers, which are connected to the DC bus, from feeding into the fault and their RAs from detecting this fault. This bus-rail interface diode therefore altogether eliminates the coordination requirements between the various RAs.

(c) Coordination between Rectifier-Agent and the Buck Converter-Agents

Since the Rectifiers supply power to many (typically 6-10) buck converters, the RA has to coordinate with all the Buck Converter-Agents. The normal current of each buck converter is only a fraction of the normal current of the rectifier. Therefore, this can be used for coordination. For the prototype SES, the normal current of the buck converter is 200A and therefore the threshold for the BCA is set to 500A (2.5x). The threshold of the RA is set to 1.75kA providing sufficient margin for coordination between the RA and a BCA.

The coordination among buck converters of different zones is also needed because for a fault occurring in one of the buck converters, the input capacitors of the other buck converters will discharge into the fault. Here again, similar to the rectifier, a bus-rail interface diode is employed at the input, (as shown previously in Figure 45) to prevent the reverse feeding of the buck converter into the primary DC bus zone faults or the faults in the buck converters of other zones. Therefore, the bus-rail interface diode provides the coordination between the buck converters.

(2) Backup Requirements

Another important requirement for the overall system protection is the backup protection.

Backup protection provides protection when the primary protection fails. The Protection scheme is designed in a hierarchical manner to facilitate backup protection.

The local backup protection proposed for the new SES is such that if the primary protection provided by the agents fails, the SLAP provides backup protection. The backup protection operates to isolate the fault and prevent the devices from failure. In the event that the backup protection provided by SLAP fails to interrupt and isolate the fault, the upstream agent provides remote backup protection to interrupt and isolate the fault.

For example, if a fault occurs on the secondary DC Bus zone, the BCA provides the primary protection. If the BCA fails, the SLAP of the buck converter provides local backup protection. And, if the SLAP fails to isolate the fault, the rectifier agents of R1 and R2 provide remote backup protection and isolate the fault.

The application of this backup protection on the prototype SES is illustrated below.

(a) Local Backup protection for Rectifier Agent

To provide backup protection for the RA (which has a threshold of 1.75kA), the threshold for the SLAP is chosen to be higher (2kA) than the RA's threshold. This ensures enough time for the RA to operate but not too high as otherwise it would require larger CSDs. This higher threshold ensures that the SLAP, which is the backup protection for the RA, operates only after the RA has failed to limit and interrupt the fault current.

(b) Local Backup protection for Buck Converter Agent

Similar to the local backup of the RA, the SLAP, which is implemented on the CSDs of the buck converter devices, provides backup to the buck converter agent. The primary protection for the BCA is set to a threshold of 0.5kA; hence, the threshold for the SLAP of the buck converter devices is set to a value of 1kA. Again, it is chosen to be high enough to make sure that the SLAP, operates only after the BCA has failed to limit and interrupt the fault current. Too high a setting is not chosen because it would require CSDs of correspondingly higher ratings.

(c) Remote Backup protection for Buck Converter Agent

The remote backup is the next line of defense if the local backup fails to limit and interrupt the fault current. This kind of backup is provided by upstream devices that are remote from the fault.

For a fault occurring in the secondary bus zone, as described earlier, the buck converter provides primary protection, the SLAP provides backup protection. When the backup protection also fails to limit and interrupt the fault, the fault current increases. The immediate upstream Protection Device - the Rectifier Agents - sense this increase in current and when the current I_R, which is monitored by the Rectifier-Agents exceed the threshold of 1.75kA, the RA identifies it as a fault and take protective action to limit and interrupt the fault current.

The issue that is of concern is the coordination between the remote backup and the local backup. The remote backup should operate only after the local backup has failed as otherwise selectivity would not be achieved.

The threshold of the SLAP is set to 1kA and the threshold of the RA is set to 1.75kA. This provides enough margins for the SLAP to operate before the RA, thereby satisfying the selectivity requirement.

(d) Remote Backup protection for Rectifier Agent

The remote backup for the RA is provided by the upstream protection device – the fuse. The coordination of the SLAP and the fuse has been discussed previously. Therefore, here it is just re-iterated that the fuse provides remote backup protection for the failure of the RA and the SLAP of the rectifier.

The remaining part of this section demonstrates the above points, by the way of simulations. The prototype system developed for system level simulations is shown in Figure 58. The prototype system's PSCAD circuit diagram is shown in Figure 59. The prototype System has two AC generators, G1 and G2, at 4.16kV, 60Hz supplying power to the primary DC Bus via their respective rectifiers, R1 and R2. The primary DC bus distributes power at 7kV DC to three zones, Zone1, Zone2 and Zone3. The buck converters, B1, B2 and B3 supply power to the zones through the 800V DC secondary Bus.

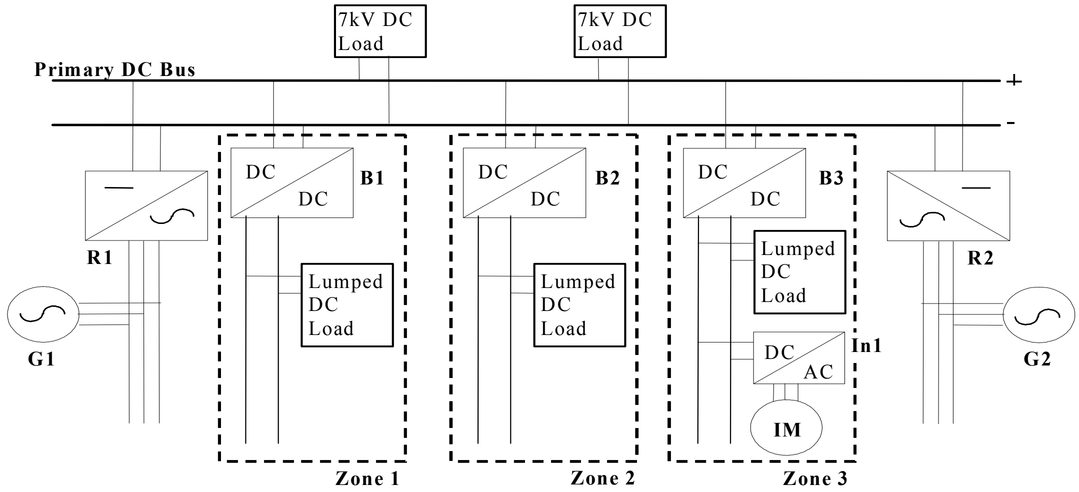


Figure 58 : Prototype DC SES for Protection System Co-ordination

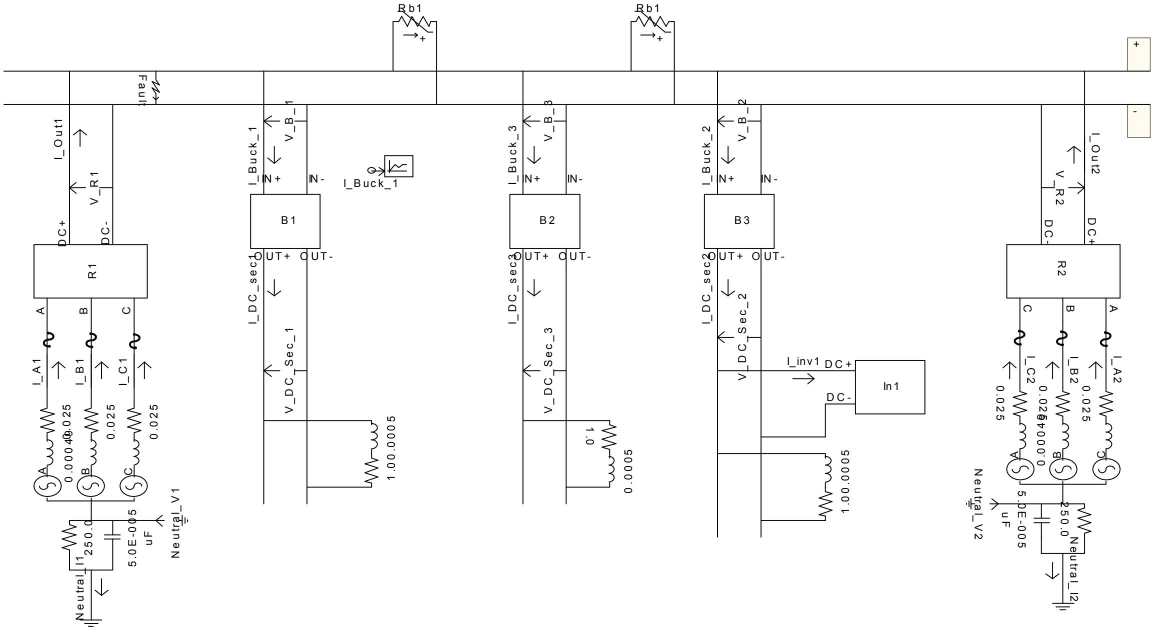


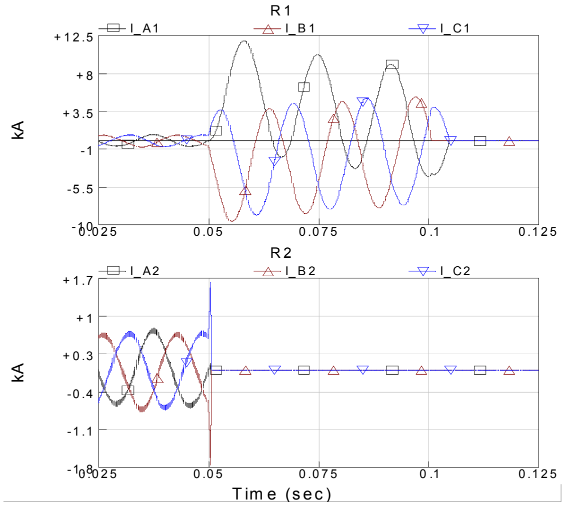
Figure 59: Prototype System Circuit Diagram in PSCAD

(a) Fault in the Primary DC Bus zone

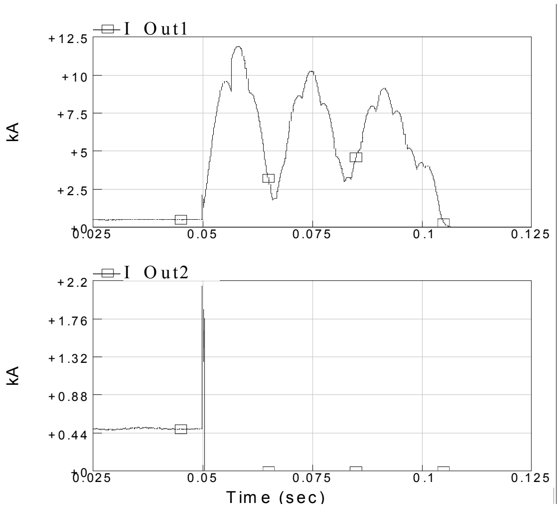
The first fault considered here is a fault in the primary DC bus zone, which is the most severe fault on the DC SES. For such a fault, as described on page 47 in section 3.5.3, the RA detects the fault and soft turns off the switches of the Rectifier PEBB. For the DC SES shown in Figure 58, the primary DC bus is connected to the rectifiers R1 and R2. Therefore, for a fault on the DC bus, the RAs associated with R1 and R2 detect, interrupt and shutdown their respective PEBBs to isolate the fault.

In addition, the buck converter agents that are associated with the buck converters B1, B2 and B3 detect the existence of a primary DC bus fault. The simulation results for the operation of the primary protection for a primary DC bus zone fault has already been shown in Figure 36. When the primary protection provided by R1 fails to interrupt the fault, the SLAP provides backup protection as illustrated previously in section 2.4. The fuses operate to provide remote backup in case of the failure of the local backup protection by SLAP.

The simulation results for this scenario are shown in Figure 60. A failure of the RA and the SLAP of R1 is simulated here. A fault occurs at t = 0.05s. Due to this fault, the current rises to 1.75kA. The RA of R2 identifies the fault and interrupts the fault current. Correspondingly, the currents I_2A, I_2B, I_2C and I_Out2 are interrupted as shown in Figure 60 (a) and (b) respectively. Since the SLAP and the RA of R1 fail to interrupt the fault, the current I_Out1 (and also I_R1) continues to rise following the failure. The figures show that the high currents I_1A, I_1B and I_1C cause the fuses to melt and clear at t = 0.1035s and successively interrupt the fault at the following current zero at t = 0.112s.



(a) Rectifier 1 & 2 Input Currents



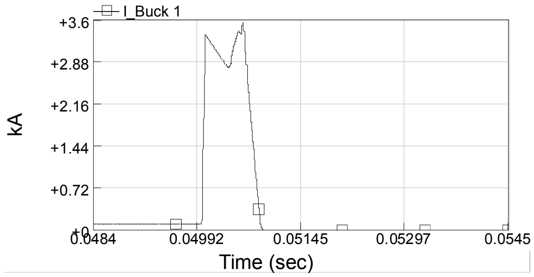
(b) Rectifier 1 & 2 Output Currents

Figure 60 : Remote Backup Protection by Fuses

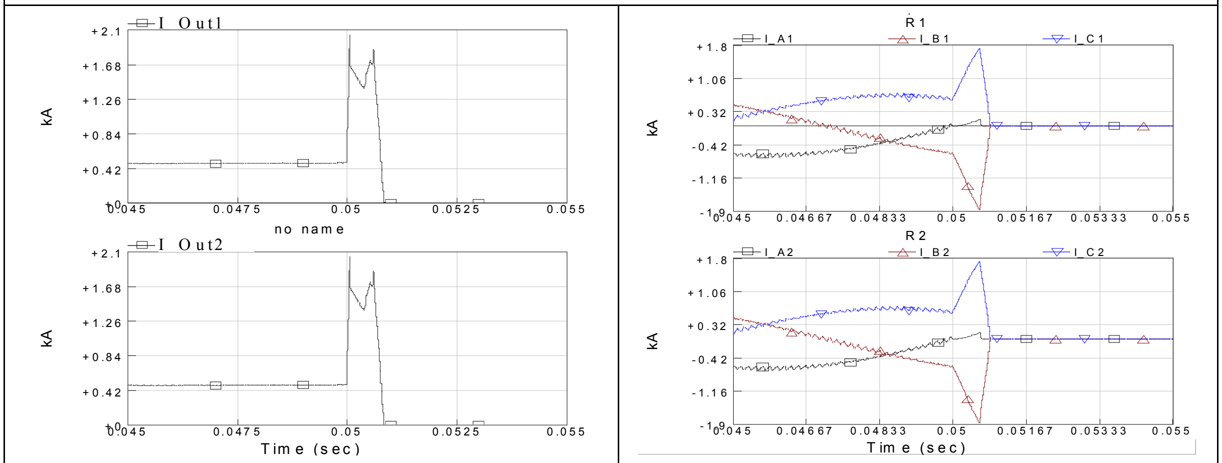
(b) Buck Converter Transformer fault

The BCA associated with the buck converter detects and locates the fault on the buck converter isolation transformer. The protective action is to hard turn-off the switches of the buck converter inverting stage. The results for the operation of the primary protection provided by the BCA have been demonstrated in Figure 53 and Figure 50 of section 2.4.

The backup protection to the BCA is provided by the SLAP of the buck converter as illustrated in Figure 23, Figure 24 and Figure 25 of section 2.6. The remote backup for the failure of the SLAP of the Buck converter is provided by the Rectifier Agents associated with the upstream rectifiers R1 and R2. The simulation results for a fault on the primary side of the transformer are shown in Figure 61. A primary side fault causes the current I_Buck1 to increase. Since the BCA and SLAP fail to detect and interrupt the fault current, the current I_Buck1 exceeds 1kA (threshold of SLAP).



(a) Buck Converter Input Current



(b) Rectifier 1 & 2 Output Currents

(c) Rectifier 1 & 2 Input Currents

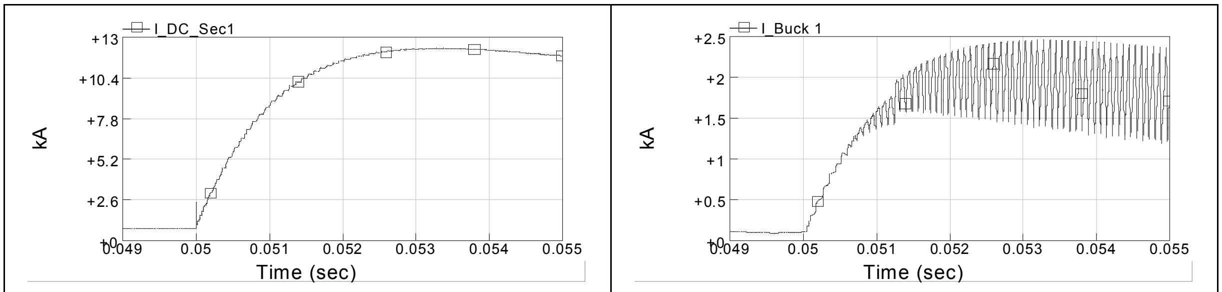
Figure 61 : Remote Backup by RAs for a Transformer Primary Fault

Directly following the fault, the output capacitors of the rectifiers discharge into the fault as seen by currents I_Out1 and I_Out2 in Figure 61(b) and successively turn off. The fault is now fed by the generators via the rectifiers. The increasing generators are shown in Figure 61(c). At t=0.0504s when the current I_Out1 and I_Out2 exceeds the RAs threshold, it detects the fault and turns off to interrupt the fault current.

(c) Fault in the Secondary DC Bus Zone

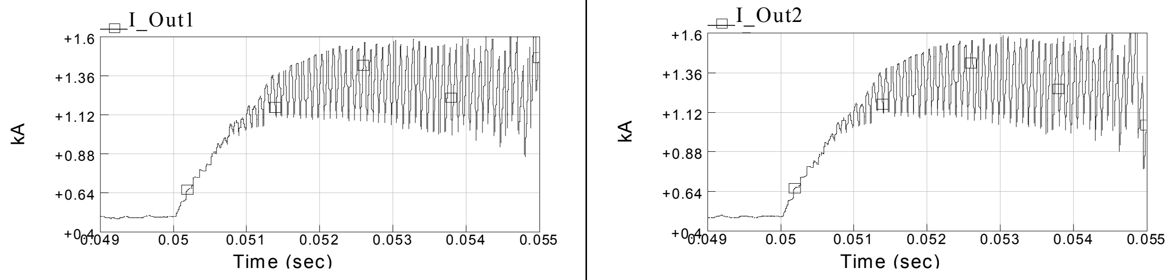
The primary protection for a fault in the secondary DC bus zone is provided by the BCA and the local backup is provided by the SLAP. A Remote backup is provided by the upstream rectifiers R1 and R2.

The simulation results are shown in Figure 62. As shown in Figure 62(a), the Buck converter output (fault) current, I_DC_Sec1 is about 12.5kA and the input side is about 2.5kA, as shown in Figure 62(b) (with a transformer ratio 5:1). Further, this current is divided equally among the two supplying rectifiers. Therefore, the current sensed by the RAs is below their threshold of 1.75kA, shown in Figure 62(c) and (d) and hence the RAs do not detect a fault condition and do not provide backup protection for SLAP failure of buck converter.



(a) Buck Converter 1 Output Current

(b) Buck Converter 1 Input Current



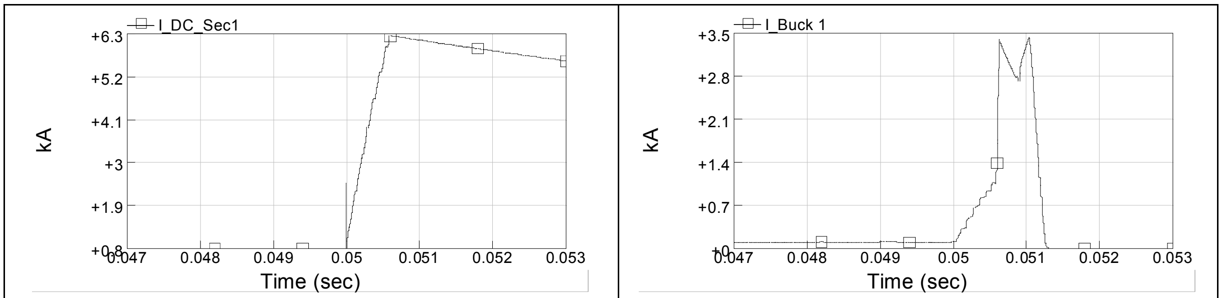
(c) Rectifier 1 Output Current

(d) Rectifier 2 Output Current

Figure 62 : Buck converter SLAP Failure during a Secondary DC bus zone fault

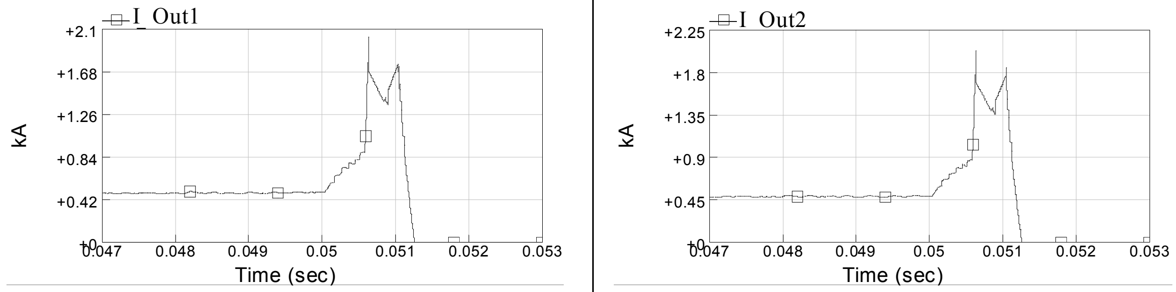
A remedy for this problem is to provide a crowbar device at the input of the buck converter ensures this. The crowbar however should be turned on only when the SLAP failure occurs. This is done by noting that the threshold of the SLAP is 1kA, therefore, when the input current, I_{in} (Figure 45) of the buck converter exceeds a threshold of 1.25kA, it implies that the SLAP and the devices have failed to interrupt the fault. Therefore, the crowbar device is turned on when the current I_{in}, exceeds the threshold of 1.25kA. This creates a low impedance path and causes the causes the current I_Out1 and I_Out2 to increase rapidly. This increased current is then sensed by the RAs and they detect a fault and turn-off the Rectifiers, thereby providing backup protection.

The simulation results are shown in Figure 63. A fault occurring at t = 0.05s causes the buck converter output current, I_DC_Sec1 and the buck converter input current, I_Buck1 to increase as seen in Figure 63(a) and (b) respectively. This causes only a marginal increase in the rectifier output currents, I_R1, I_R2. At t = 0.0505s, the buck converter input current, I_Buck1 crosses the threshold of 1.25kA. This indicates that the SLAP has failed to interrupt the fault and therefore the crowbar device is turned on. This causes the buck converter current I_Buck1, and the rectifier currents, I_R1 and I_R2 to increase sharply. At t = 0.0513s, I_R1 and I_R2 exceed 1.75kA. The RA detects this and turns the PEBB off, thus providing backup protection for SLAP failure.



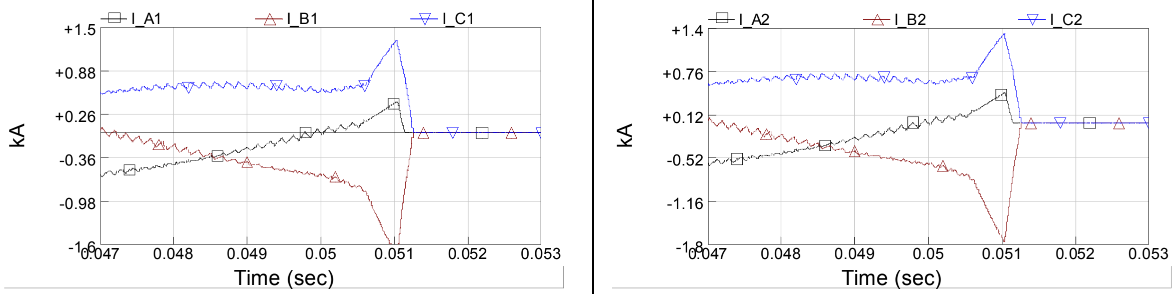
(a) Buck converter Output Current

(b) Buck converter input current



(c) Rectifier 1 Output Current

(d) Rectifier 2 Output Current



(e) Rectifier 1 Input Currents

(f) Rectifier 1 Input Currents

Figure 63 : Remote Backup by RAs for a Secondary DC Zone Fault

3.7 Chapter Summary

This chapter described the design of protection agents that are associated with the various PEBBs in a zonal electrical DC distribution system. We showed that the protection-agents can detect and locate the faults in less than 1ms and further these protection-agents interrupt the faults using the PEBB based current limiting circuit breakers described in the previous chapter. This chapter also showed the scalability of the proposed agent based protection approach. The protection agents, when employed in a SES type prototype system, also detect and locate the faults successfully. The same protection agents are also easy to coordinate and provide backup protection as well.

4 RECONFIGURATION MANAGEMENT

4.1 Introduction and Overview

The Protection-Agents of the new Agent based System Protection scheme monitor the local quantities to detect and isolate the disturbances. In response to the disturbances, the same agents then collaborate with each other to reconfigure the system. The protective action (based solely on the local variables) ensures that the protection is very fast, whereas the reconfiguration, which is a collaborative action, ensures that the re-configuration is achieved globally at a system level. Thus, it provides shorter system downtime and minimum number of components outage.

The first primary task of system protection was detailed in the previous chapter. This chapter deals with the second task of reconfiguration management which ensures service continuity to the unfaulted part of the system.

Reconfiguration is the action performed, typically the opening or closing of switches, sectionalizers and/or CBs, subsequent to the isolation of faults, to maximize power delivery to the unfaulted sections of the system, without exceeding the rated limits [45] of the system components (generators, lines etc).

4.2 Agent Based Collaborative Reconfiguration

4.2.1 Objectives and Requirements

The main objective of performing reconfiguration on a system is to maintain the availability of power to all connected loads in order to keep all the system and equipment operational. Under abnormal conditions, the power to only the smallest affected /faulted portion of the system should be interrupted [46]. The main goal, therefore, of an **automated** reconfiguration such as the one designed here for the SES, is to increase the survivability of the SES under faults and battle conditions, eliminate human errors, make reconfiguration decisions more quickly and provide optimal electric power service through the surviving electrical system [46].

For a SES like zonal electrical distribution system, it is further desired that the reconfiguration system can seamlessly transfer power to an alternate source since a small interruption in power to equipment like weapons system may have catastrophic results [6]. The zonal architecture of the SES further aids in achieving this.

4.2.2 Contingencies

The faults on the SES could be due to material casualty of individual loads or widespread damage due to battle damage. In addition to load faults, casualty can occur to cables, power generating equipment or power distribution buses. Some equipment failures and battle damages may lead to large over-current conditions. Battle damage may also generate multiple faults in contiguous areas.

For the prototype system shown in Figure 58, the contingencies for which the agent based protection scheme has detected and isolated the fault and the for which reconfiguration is desired are : generator fault /damage, Primary DC Bus damage, Rectifier fault / damage, Zone flooding, Secondary DC bus fault / damage, Buck Converter fault / damage and load damage.

These contingencies can lead to conditions of having inadequate power generation capacity to all attached loads. Therefore, connecting additional backup generators may be necessary. Load shedding is another option when backup generation is not available. A load priority list, with the critical loads having high priority and the non-critical loads with low priority is available for a SES. Load shedding is performed by disconnecting the low-priority loads followed by disconnecting the medium priority and then the high priority loads, in that order. This is done until the generation matches or exceeds the connected loads.

4.2.3 Agent Based Reconfiguration

As discussed earlier, the zonal architecture of the SES is unique and a proper design and choice of some of the design issues can considerably enhance the reconfigurability of the SES under faults and battle damages. These design consideration include the choice of number of the sectionalizers, the location of the sectionalizers, the normal state of the sectionalizers, choice of number of generators, and the secondary DC bus configuration.

Normally closed and normally open sectionalizers are provided selectively in the designed prototype SES as shown in Figure 64. Normally closed sectionalizers are provided for each zone. They can be opened during reconfiguration when a DC bus zone 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 system components without power. The normally open sectionalizers are provided to improve system survivability under the condition of multiple DC bus fault due to war damage like conditions.

The intra zonal configuration of the secondary DC buses is shown in Figure 65. The Buck converters interface the primary DC bus to the secondary DC bus. The vital or the critical loads are fed by auctioneering diodes as illustrated in Figure 65. 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 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 appear 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 scenarios of faults and battle damage are considered in this section. It is shown that the power is transferred seamlessly from the main DC bus to the alternate DC bus following a fault and that the agents reconfigure the system to improve the survivability of the SES. The steps/procedures involved in reconfiguration for the main faults are described below.

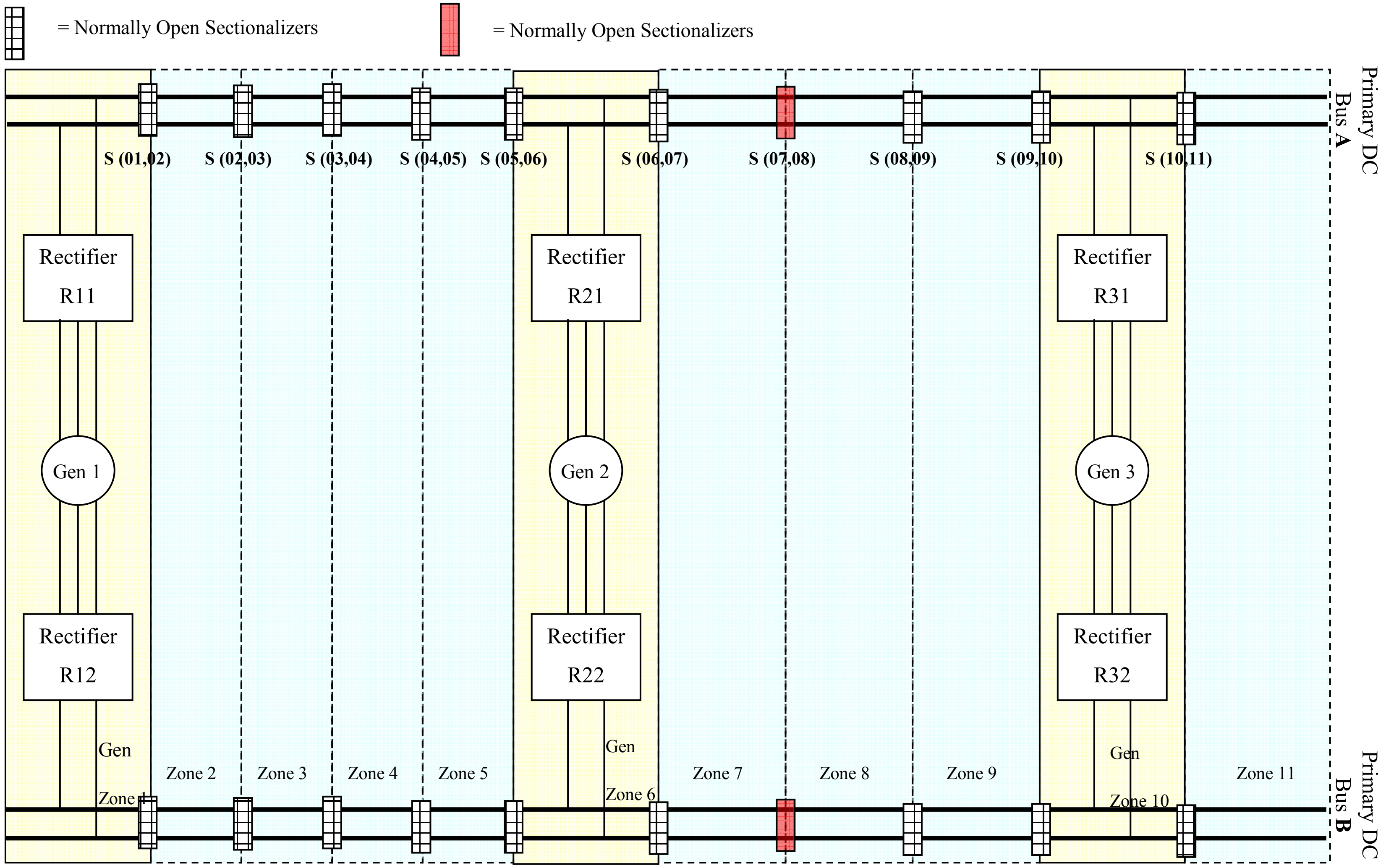


Figure 64: SES with Three Generator Configuration

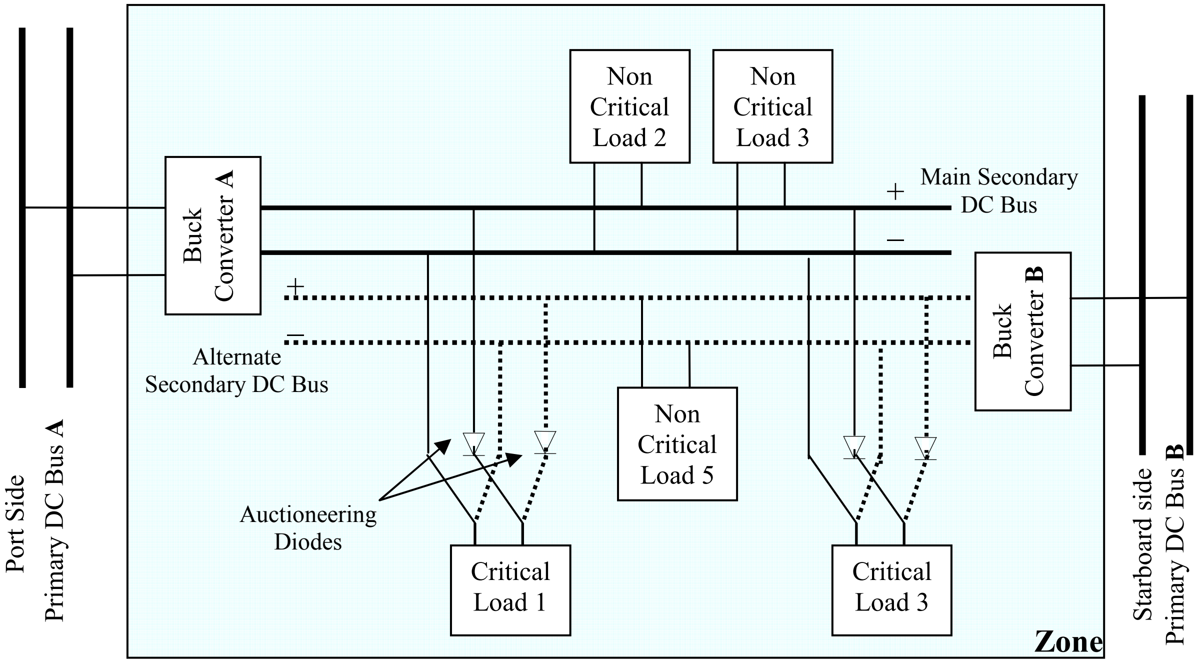


Figure 65 : Intra Zonal Bus Configuration

Primary DC Bus Zone Fault

Under normal operation, the load is supplied from the Port Side Primary DC Bus **A** via the Buck Converter **A** and the auctioneering diode, as shown in Figure 65. The voltage reference to the alternate (Buck Converter **B**'s) controller is 750V and therefore the output voltage is 750 ± 15V (ripple).

When a fault in the primary DC bus zone occurs, such as a Primary DC bus **A** of Figure 65, the upstream RAs detect and interrupt this fault. The BCAs also detect the fault and identify it as a source fault. This has been demonstrated in the previous chapter. As long as the voltage of the secondary DC bus of Buck Converter **A** is above 750V, it continues to supply the critical loads. When the voltage of the Main Secondary Bus falls below 750V, the power is automatically transferred to the Alternate Secondary DC bus. When the BCA of Buck converter **A** detects the fault, it sends a request message to the BCA of Buck converter **B** to increase the reference voltage from 750V to 800V. This completes the transfer of power from the main bus to alternate bus thereby completing the reconfiguration procedure for a primary DC bus fault. The only communication that is required is within the given zone and is between the two BCAs.

Secondary DC Bus Zone Fault

A fault on the main secondary DC bus will cause its voltage to collapse. This fault is detected by the BCA Buck converter **A** and similar to the previous scenario, the BCA **A** sends a request message to the BCA **B** to increase the reference voltage from 750 to 800V. Similar to the previous scenario, the supply of power is transferred from the main bus to the alternate bus automatically and seamlessly, when the voltage of the main secondary DC Bus **A** falls below 750V. The secondary DC bus zone fault in one zone does not affect the loads in the other zone at all.

Buck Converter Source Side DC Rail Fault

A Buck Converter source side DC Rail fault is a fault in the Primary DC Bus zone and the normally closed (NC) sectionalizers employed on the primary DC Bus can be effectively used to isolate the only affected zone. The reconfiguration for this fault in the primary DC bus zone is, therefore, different from the configuration performed for a fault on the Primary DC bus.

The Buck Converter source side DC rail fault is detected and interrupted by the RAs of the upstream Rectifiers. The BCA of the buck converter locates this fault to its input DC rails. This additional information is used advantageously for reconfiguration of the system under multiple fault condition.

The reconfiguration action performed for a single fault -a Buck converter source side DC Rail fault, is similar to the DC bus fault described above. The interruption of the fault by the RAs and the shutdown of the Buck converter cause the output voltage of the Buck converter to decay. Therefore the voltage of Buck converter **A** falls below 750V and the supply of power is transferred from the port side primary DC Bus **A** to the starboard primary DC bus **B**, thereby completing the reconfiguration for the single fault.

Another important scenario which adds challenge to the Buck converter source side DC rail fault is the occurrence of a second successive fault on the alternate primary DC bus **B**. Under such a scenario of two successive faults, one fault on the buck converter source side DC rail fault of the port side primary DC bus **A** and another bus fault on the starboard primary DC bus **B**, the whole system would need to be shutdown. The additional information gathered previously is used to avoid such a catastrophic failure. For this scenario of multiple fault condition, a solution is proposed so that the selective NO sectionalizers are opened to sectionalize the first fault (buck converter source side DC rail fault). Therefore for a successive second fault on the primary DC bus **B**, the power can be re-transferred back to the primary DC bus **A**, avoiding a total shut-down or collapse of the system. This considerably improves the system survivability under multiple fault conditions.

This is explained by an illustration. Let us consider that a Buck input DC rail fault in zone 5 occurs for the system shown in Figure 64. The RAs of Rectifier R11 and R21 detect and interrupt this fault. The BCA **A** of zone 5 also detects this fault and identifies it as a buck converter source side DC rail fault. The BCA **A** then sends a request message for to the BCA **B** to increase the reference voltage to 800V. The power is thus transferred to the alternate bus **B** and the primary DC bus **A** is de-energized. Now, for a subsequent fault on the DC bus **B** of Figure 64, the complete system will be shutdown by the Rectifiers R11, R12, R21 and R22. To avoid such a system shutdown, following the detection and location of the buck converter source side DC rail fault (of the primary DC bus **A)**, the BCA **A**, sends a request to open the sectionalizers S(04,05) and S(05,06), as soon as the R11 and R21 have interrupted the fault and de-energized the bus **A**. The opening of the sectionalizers isolates the faulted zone.

For a subsequent fault on the primary DC bus **B,** power can be re-transferred back to the healthy part of the primary DC bus **A**, since the opening the sectionalizers has isolated the faulted part of the system. Hence, the agent based reconfiguration scheme prevents a total system collapse and improves the system survivability under war damage conditions such as multiple faults.

The opening of the above mentioned sectionalizers may also create another challenge of generation-load mismatch. In the reconfigured system, the Gen1 supplies power to the zones 1 through 4 while the Gen2 supplies power to zones 6 and 7. It may be possible that the generation of Gen1 or Gen2 is not sufficient to meet all the loads of zones 1-4 or 6-7 respectively. Therefore, when a BCA requests the opening of sectionalizers, it also initiates a load flow to match the load with the generation and if necessary a load shedding algorithm is initiated, as explained previously. This ensures that the generators of the reconfigured system are not overloaded.

Fault in Zone 9

Similar to the scenario of successive faults discussed above, another challenging fault is a fault in the Zone 9 of Figure 64. Under the normal operation of the system, Gen3 supplies power to zones 8-11 as S(07,08) is normally open, while, Gen1 and Gen2 supply power to Zones 1-7.

Let us assume that primary DC Bus B has been de-energized due to a pre-existing fault. When a successive Buck converter source side DC rail fault occurs in Zone 9, the upstream rectifiers detect and interrupt the fault current and the BCA of Zone 9 identifies this fault as a source fault. The BCA also sends a request to open the sectionalizers S(08,09) and S(09,10). The opening of these sectionalizers isolates the faulted zone. But, in addition, opening of these 2 sectionalizers also unnecessarily interrupts power to zone 8. Therefore additional actions are needed to avoid the unnecessary interruption of power to Zone 8.

The sequence of actions that the BCA should take when a buck converter source side DC rail fault occurs in Zone 9, in order to avoid interruption of power to the zone 8 are:

(1) Send a request message to the alternate BCA of the same zone to increase the reference voltage from 750 to 800V,

(2) Send a request message to open the NC sectionalizers S(08,09) and

(3) Send a message to the BCA of the adjacent zones (zone 9 and zone 10) to ensure that at least one of the sectionalizers connected to those zones are closed. For this particular example, both the sectionalizers of Zone 8 are open. Therefore, in addition to these actions taken by the BCA of Zone 9, the BCA of zone 8 requests the NO sectionalizer S(07,08) to be closed. This ensures that power is supplied to Zone 8 via Gen1 and Gen2, thus maintaining the continuity of supply to all but the faulted zone.

(4) Lastly, due to the closing of the NO sectionalizer S(07,08) it may be possible that the generation capacity of Gen1 and Gen2 is insufficient to meet all the loads of Zone 1 through Zone 8. Therefore, load shedding may be required.

Generation Failure

The last fault condition that is addressed here is a fault or damage in one of the generators. The RAs of the rectifiers detect a zero input current condition and identify it as a generator fault. When such a generator fault is detected, the RAs request the closing of the NO sectionalizer S(07,08), and initiate load shedding to match the load demand with the generation (Gen2 and Gen3). This completes the reconfiguration for a generation failure.

The following part of this section illustrates the system reconfiguration procedures described above. Simulation results are shown for two of the most common faults – Primary DC Bus fault and Secondary DC Bus fault. The prototype system for reconfiguration is shown in Figure 66. It has a main primary DC bus **A** and alternate primary DC Bus **B**. Every critical load within a zone is fed by both the intra-zonal secondary DC Buses **A** and **B**, while the non-critical loads are supplied power by only either of the secondary DC buses.

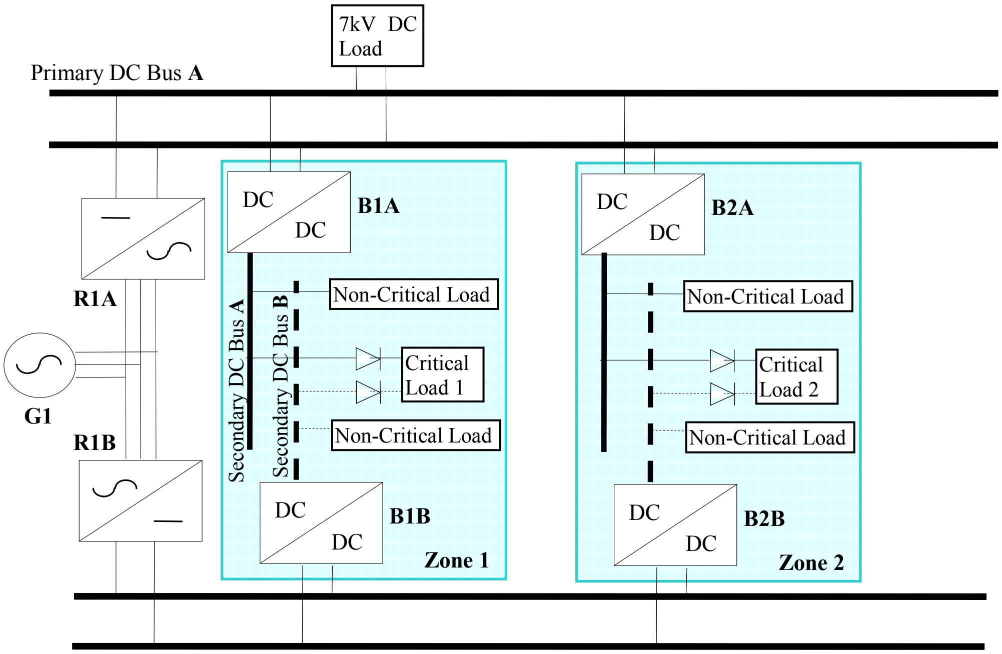
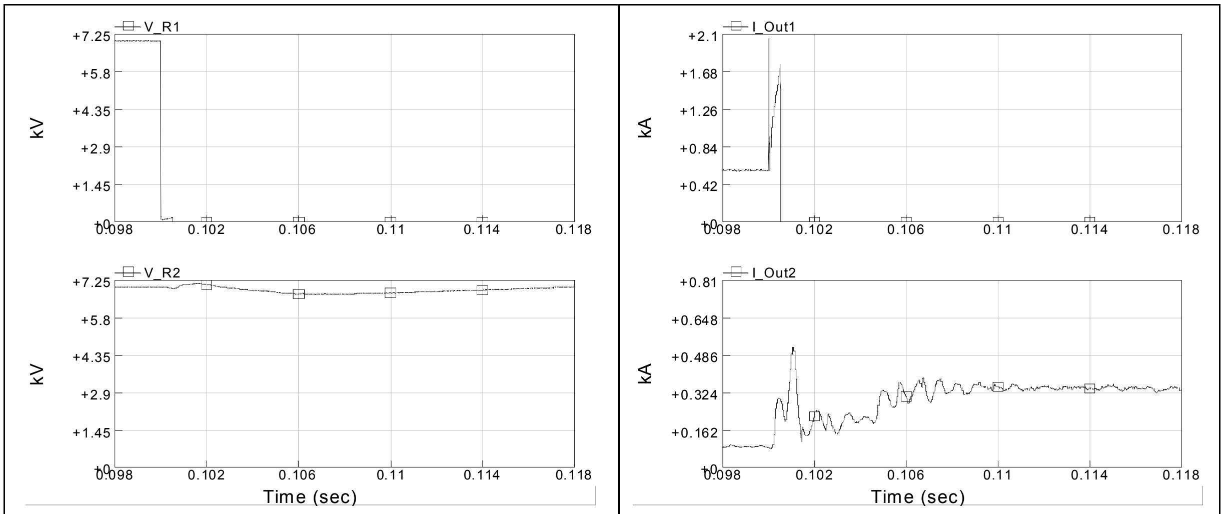


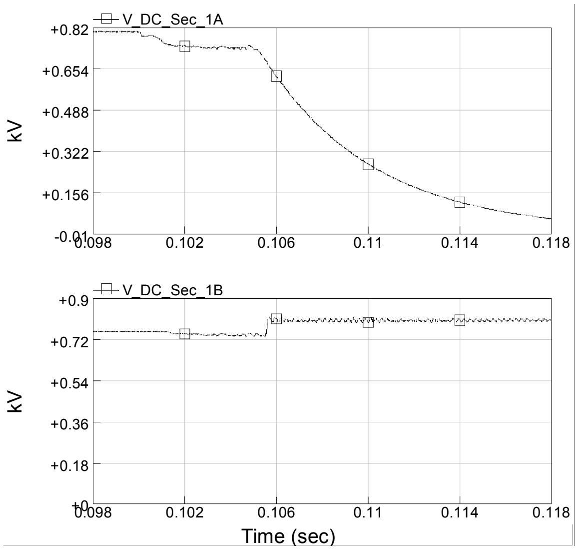
Figure 66 : Prototype System for Reconfiguration

Scenario 1: Primary DC Bus Fault

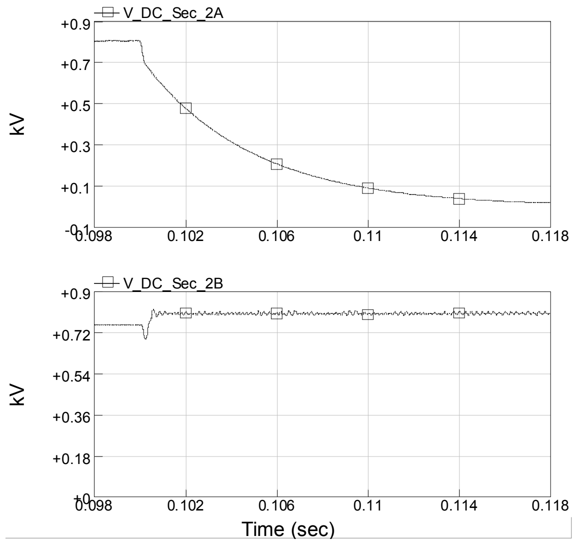
Simulation results for a fault on the primary DC bus **A** at t = 0.1s are shown in Figure 67. Following the fault, the output voltage of R1A, V_R1 (Figure 59) collapses, as shown in Figure 67(a). Correspondingly, the current, I_R1 (Figure 59) rises as shown in Figure 67(b). The fault is detected by the RA of R1A and it shuts down the Rectifier R1A of Figure 66. Following the shutdown, the voltages of the secondary DC Bus **A** of both zones 1 and 2 **(V_DC_Sec_1A and V_DC_Sec_2A**) start decaying. This is seen in Figure 67(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 67(c) and (d). The BCA of B1A detects the fault at t = 0.01055s, therefore, it is seen that the loads of 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** as seen in Figure 67(e) and (f). The voltage across the loads of the zone 1 and zone 2 are shown in Figure 67(g) and (h) and the load currents of zone 1 and 2 are shown in Figure 67(i) and (j) respectively.



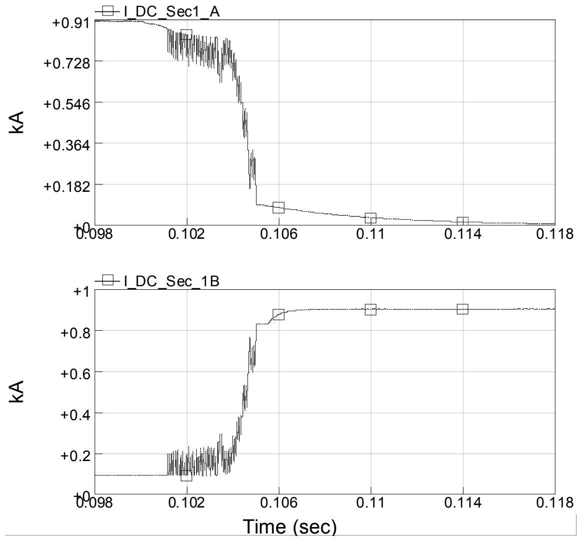
(a) Rectifier 1 & 2 Output DC Voltages **(b) Rectifier 1 &2 Output Currents**



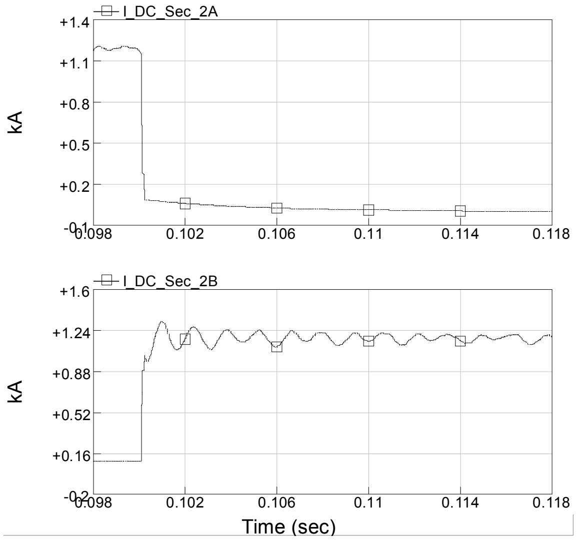
(c) Buck Converter 1 & 2 Output Voltage (Zone 1)



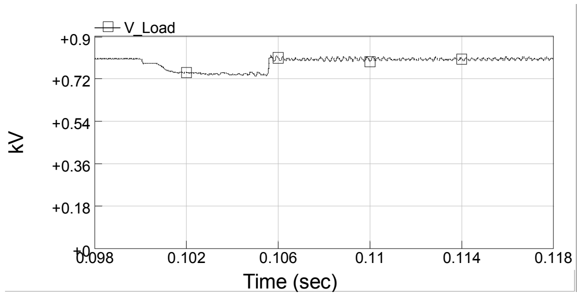
(d) Buck Converter 1 & 2 Output Voltage (Zone 2)



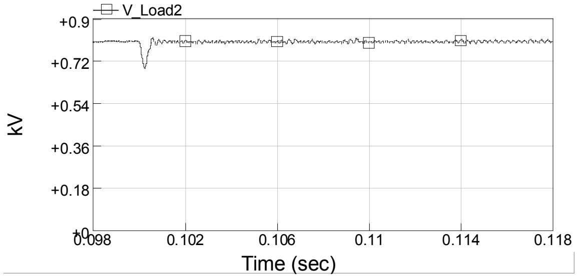
(e) Buck Converter 1 & 2 Output Current (Zone 1)



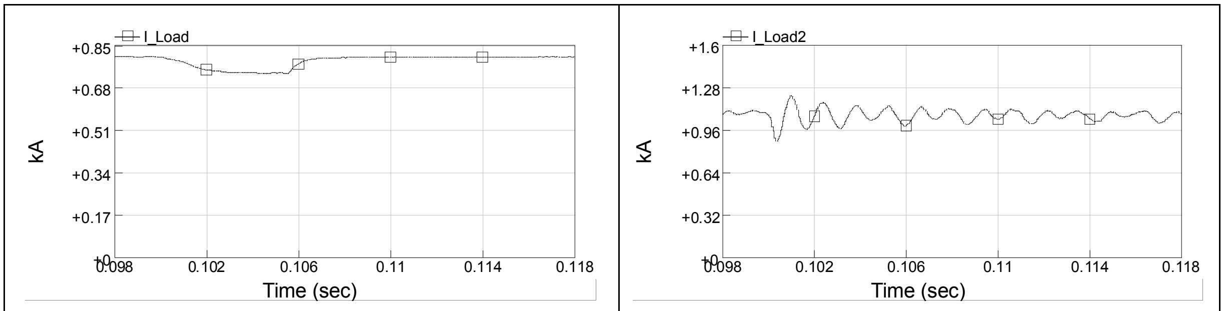
(f) Buck Converter 1 & 2 Output Current (Zone 2)



(g) Voltage Across Critical Load (Zone 1)



(h) Voltage Across Critical Load (Zone 2)



(i) Critical Load Current (Zone 1)

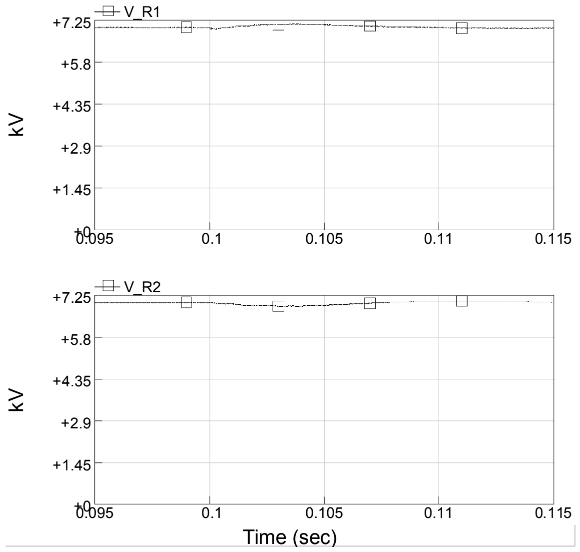
(j) Critical Load Current (Zone 2)

Figure 67 : Reconfiguration Results for Primary DC Bus Fault

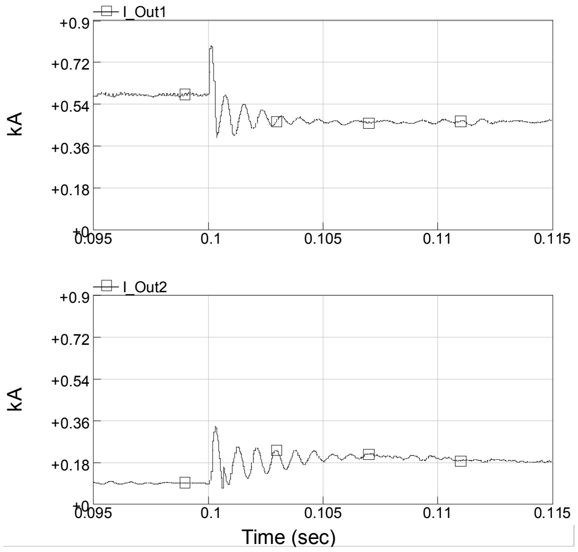
Scenario 2: Secondary DC Bus Fault

A fault on the secondary DC bus **A** of zone 1 has been simulated here. The results are shown in Figure 68. The voltages of the primary DC bus **A** and bus **B** are shown in Figure 68(a). Prior to the fault at t = 0.01s, the loads of Zone 1 are fed via **G1->R1A**->**B1A**-> Critical Load1 (Figure 65). Following the fault, the loads of zone 1 are transferred from primary DC Bus **A** to primary DC Bus **B**. Therefore the loads are now supplied via **G1**->**R1B**-> **B1B**-> **Critical Load1**. The loads of zone 2 are continuously supplied from primary DC bus **A**, via **R2A**-> **B2A -> Critical Load2**. This causes a decrease in current supplied by **R1A** (I_Out1, Figure 34) and the corresponding increase in current (I_Out2, Figure 34) supplied by **R1B.** It is seen in Figure 68(b). Subsequent to the fault on the secondary DC bus **A** of Zone 1; the voltage **V_DC_Sec_1A** collapses and the current **I_DC_Sec_1A** increases. This is shown in Figure 68(c) and (d) respectively. The BCA of **B1A** detects the DC bus fault and sends a message to the BCA of **B1B** in about 0.0004s to increase the voltage **V_DC_Sec_1B**, from 750V to 800V. Therefore, load experiences a voltage and current dip as seen in Figure 68(e) and (f) respectively for 0.0004s. Figure 68(g), (h), (i) and (j) show the voltages and currents profiles for zone 2. These figures indicate that the state of the second zone is not affected in any way, due to the fault in the Zone 1, and therefore does not require any reconfiguration.

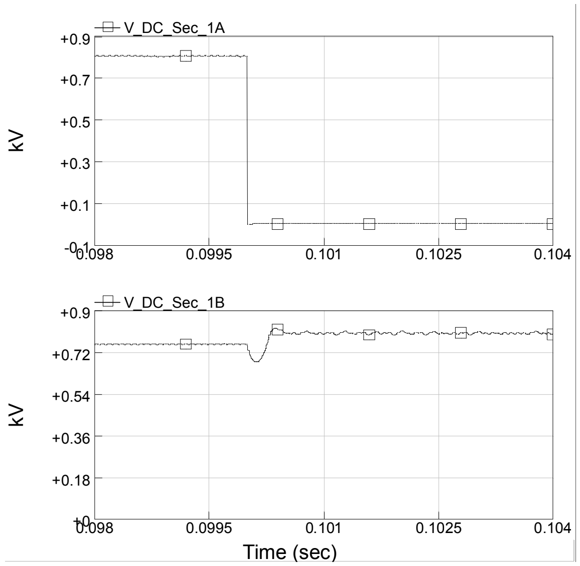
These simulation results demonstrate the effectiveness of a reconfiguration scheme under 2 of the most commons faults –the primary and the secondary DC bus fault. The reconfiguration scheme is able to seamlessly transfer power from the main bus to an alternate bus.



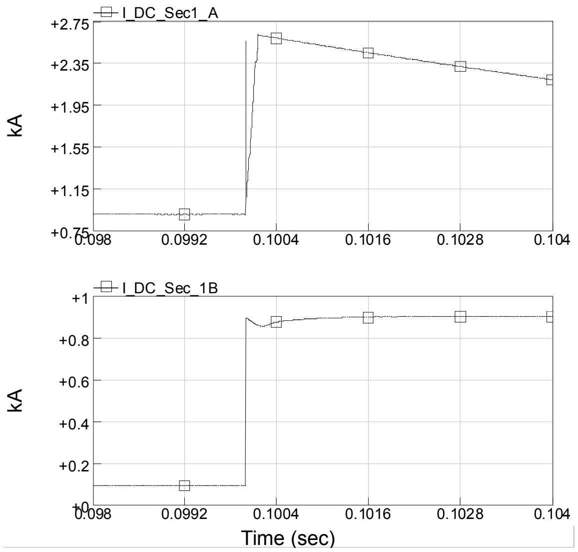
(a) Rectifier 1 & 2 Output DC Voltages



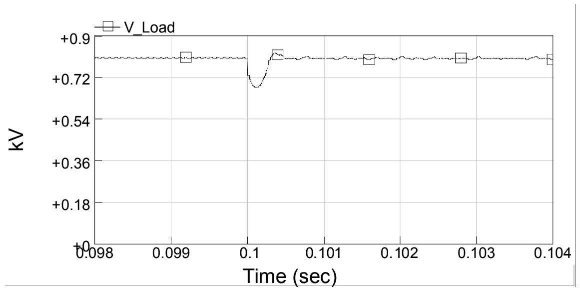
(b) Rectifier 1 & 2 Output Currents



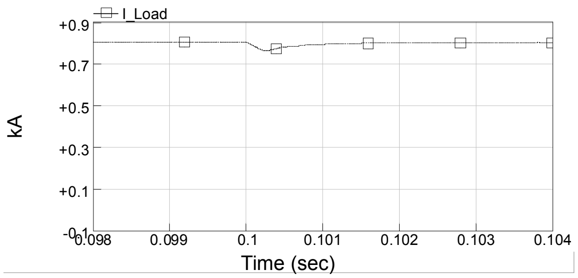
(c) Buck Converter 1 & 2 Output Voltage (Zone 1)



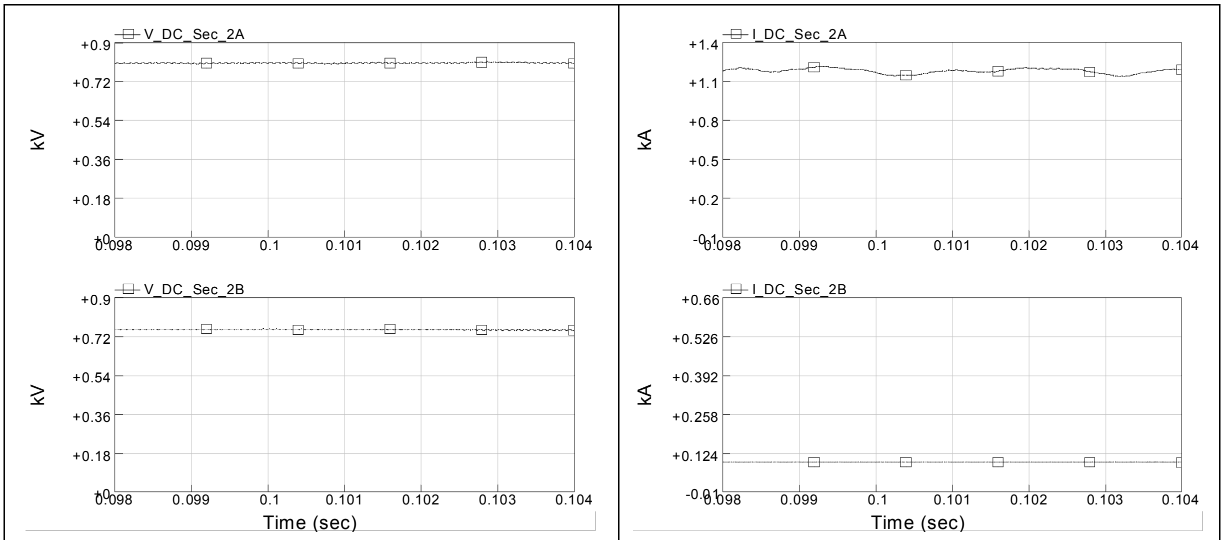
(d) Converter 1 & 2 Output Current (Zone 1)



(e) Voltage Across Critical Load (Zone 1)

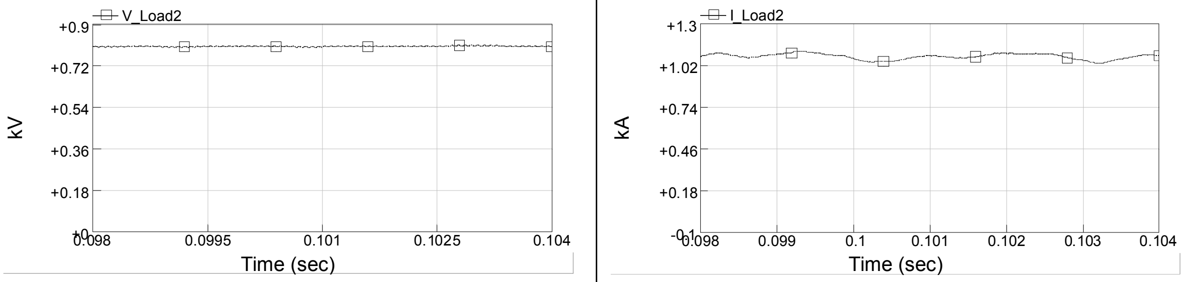


(f) Critical Load Current (Zone 1)



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

(h) Converter 1 & 2 Output Current (Zone 2)



(i) Voltage Across Critical Load (Zone 2)

(j) Critical Load Current (Zone 2)

Figure 68 : Reconfiguration Results for Secondary DC Bus Fault

4.3 Chapter Summary

This chapter described the reconfiguration procedures for some of the important faults on a zonal electrical distribution system. Reconfiguration simulation results were shown for two of the most important faults. The simulation results show that for the faults, power can be seamlessly transferred from main bus **A** to an alternate bus **B.** The protection agents also initiate opening / closing of appropriate sectionalizers to improve system survivability under multiple faults. The protection-agents detect, locate, isolate the faults and collaborate to reconfigure the system to maintain the continuity of supply to the loads under battle damage condition. In addition, the agents initiate load balance to ensure that generation capacity matches the loads of the reconfigured system. If load exceeds the generation, then load shedding is performed.

5 CONCLUSIONS

A PEBB based DC distribution system like the SES can be comprehensively protected by the agent based protection scheme. The time for detection and interruption of faults by the protection-agents is less than 1ms. The reconfiguration management ensures the continuity of power supply to the connected loads subsequent to faults and action by the protection-agents.

5.1 Contributions

Previous work [11, 47] by the author showed that it is feasible to develop a distribution system simulator using a general purpose EMTP program, and the development of such a simulator was essential in investigation of the issues associated with the new systems that use power-electronic devices.

Some of the main contributions made in this study involve the following:

1. **Investigation of System Design Issues:**

   Many design issues were investigated. These included the generator grounding, the modified switch realization for the rectifier and the buck converter, buck converter design issues for protection, intra-zonal secondary DC bus architecture, and design issues such as use of auctioneering and bus-rail interface diodes. Other design issues were also investigated, which allow for proper coordination among various PEBBs such as number and placement of sectionalizers, number of generators.

   For the investigations, the prototype simulator was used. The simulator was enhanced by adding new models to the PSCAD library. One important model that has been added during this research is an interpolating model for representing the operation of the ETO during soft turn-off. The ETO is modeled as a non-linear resistor which is changed piece-wise linearly (interpolated) based on the current through the device and the voltage across it. Another model that has been developed is the fuse model. The fuse is modeled as a resistor and the energy dissipated in the fuse is calculated and compared with the energy required to melt and clear the fuse to open a CB.

2. **PEBB based Current limiting CBs:**

   The work shows the feasibility of PEBB based current limiting circuit breaker. The switch realization of the Rectifier and the buck converter were modified so that the PEBBs are able to perform the current limiting and fault interruption. These PEBB based current limiting circuit breakers are very fast and can interrupt the fault currents in less than 1 ms. These PEBB based current limiting CBs replace conventional mechanical CBs on the DC SES and reduce the system down-time and provide better continuity of service.

3. **Design and development of Protection-Agents:**

   Protection agents, which are associated with the PEBB based current limiting Circuit breakers, were designed. The design included the assessment of minimum number of required measurement points, and the principles for the fault detection. It further included methods to identify and locate the faults, which helps during reconfiguration and repair operations.

4. **Design of Agent based Reconfiguration Management scheme:**

   A new reconfiguration management scheme has been designed. This scheme ensures the continuity of the supply to all the loads, especially the critical loads following a fault or war-damage (multiple faults etc). Different issues were investigated and a prototype design was proposed. It is shown that the scheme enhances the system survivability and reduces the system downtime under multiple fault conditions.

5.2 Future Research

The course of the research has brought up many avenues for further research into the protection of the new DC distribution systems. Some of them are:

- Addition of other power electronic building blocks including, but not limited to, AC-AC matrix converters, single phase inverters, multi-level converters etc, towards the making of a library of such PEBB converters. This would greatly enhance and simplify further developments in the area of protection.

- Simulations (based on either hardware or software) of the complete PEBB based shipboard electrical system with typical 8-10 zones would verify the scalability of the three zone system developed here. It would contribute substantially towards verifying of the protection concepts.
- More research in the direction of implementing the reconfiguration management on an actual system would be interesting. Implementation of the agents on a real-life distributed environment would be helpful for the study of timings required for the collaboration.
- New methods for detection of faults on short length cables like the primary DC bus. This would allow sectionalizing of only the smallest part of the faulted primary DC bus, thereby increasing the system survivability even further.

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APPENDICES

Appendix A Fuse Selection For Rectifier Protection

This appendix deals with the selection of fuse for its application to the protection of the rectifier AC zone.

Before giving details about the choice of the fuse for our specific application, let us have a look at the basics of a fuse - principle of operation and typical performance data available from fuse specification sheets available from manufacturers.

Fuses, by definition, are devices that open a circuit with a fusible part, which is heated and severed by current flowing through it. This fusible part is called the “element.” When current flows through a fuse, heat is generated and the element temperature rises. For a current less than or equal to its rated continuous current, temperatures rises until a steady-state condition is reached, when the heat generated equals the heat dissipated. At the rated continuous current, fuses will have temperature rises within the limits. When a current, higher than rated continuous current, flows through the fuse, the temperature of the element will rise. For some higher currents, steady-state conditions may again be achieved, but at a higher temperature. Whether such a condition is acceptable or must be avoided will depend on the fuse type and the application.

For a given fuse, the relationship between the magnitude of the current that causes melting and the time needed for it to melt is given by the fuse’s melting time-current-characteristics (TCC). Usually a TCC curve is plotted on log-log graph paper. The curve is produced from time-current tests. They are performed with constant current applied to the fuse, in an ambient temperature between 20 °C and 30 °C, with the fuse carrying no initial current. The typical shape of a fuse’s melting TCC is shown in Figure 69(a). A single graph, such as the one shown in Figure 69(a) represents curves for many different fuse elements (10E-450E in the graph). The severing of a fuse element is caused by predominantly thermal, rather than mechanical means, so there is virtually no limit on how short the melting time can be. This very fast operation (melting) of a fuse at very high currents tends to be a distinguishing characteristic of fuses compared to most other protective devices.

After the fuse element melts, the fuse must interrupt the current (which continues to flow through an arc). After interruption, the fuse must withstand any immediate TRV condition and the subsequent steady-state recovery voltage. When a fuse melts, there will always be some period of arcing before the current is interrupted. The melting time is added to this arcing period to obtain the total-clearing time. Total-clearing TCC curves are drawn to present this information.

Typical performance data that is available from a manufacturer given in terms of 3 graphs.

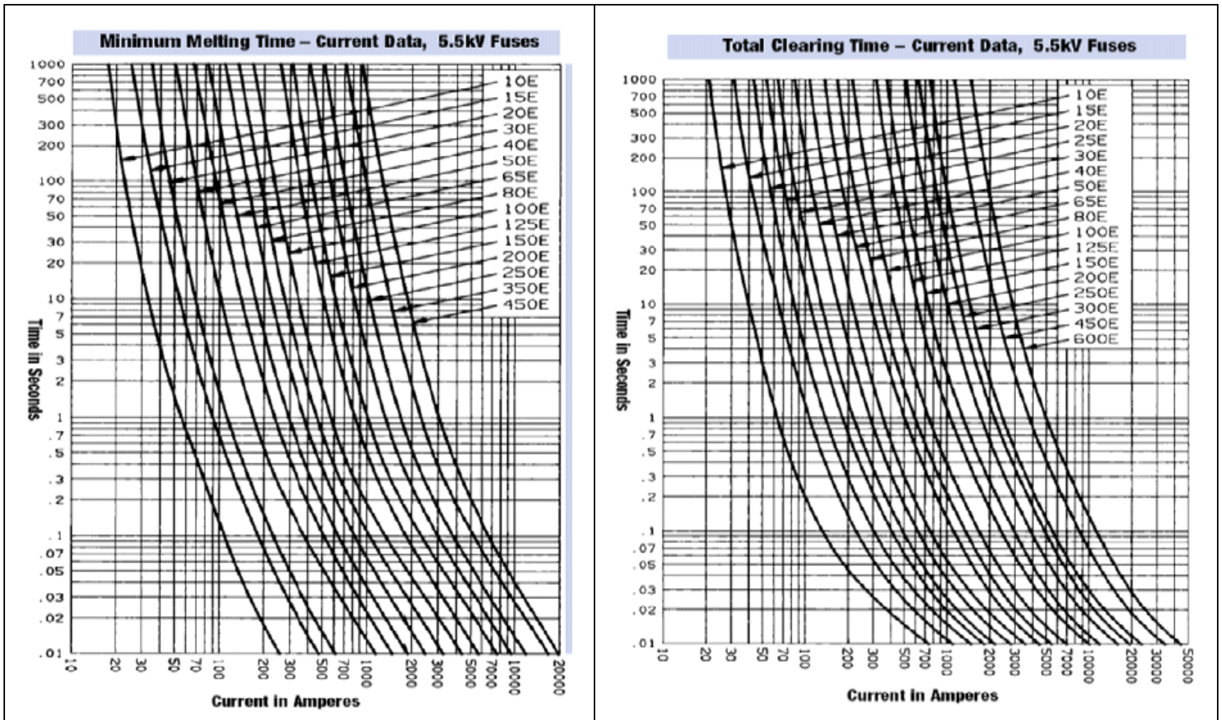
TC characteristics: The TC curves are available in 2 forms: minimum melting curve and total (or maximum) clearing time curve. These 2 curves represent the clearing times that might be expected for a given current. Typical TC curves are shown in Figure 69(a) and Figure 69(b).

The minimum melting curve is an average melting time measured in low voltage tests where arcing does not occur. Thus, for a given current value, the time for the fuse to open the circuit represents the melting time, which must fall within the tolerance given by the standards.

The second curve provides a measure of the total time to clear the circuit at a given current, including the melting time and the arcing time.

The total clearing curve should be used in coordinating against the minimum melting characteristics of a larger fuse, located towards the power source. Similarly, the minimum melting curve should be used in coordinating with the total clearing of smaller fuses, located on the load side.

Cut-Off current characteristics: Figure 70, which plots the peak let through, or cut off current, kA (peak) versus prospective fault current, kA (RMS symmetrical), under the worst case conditions of asymmetry that would normally be encountered. The point where the individual characteristics depart from the line of peak symmetry would approximate to 10ms time current point, i.e. the point where the fuse link starts to limit current (cut off) which would be ½ cycle at 50 Hz.



(a) Minimum Melting TC Curve

(b) Total Clearing TC Curve

Figure 69 : Fuse Characteristics

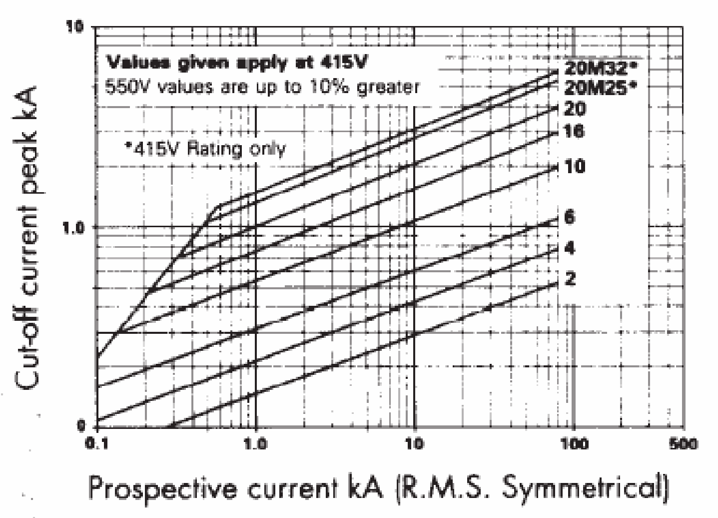
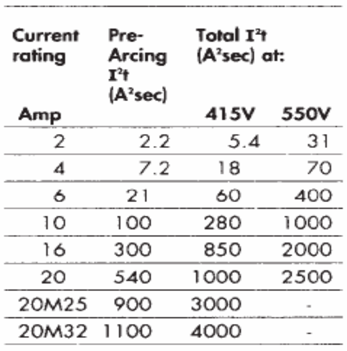


Figure 70 : Cut Off Current Characteristics

I^2t characteristics: Figure 71, expresses the 2 most important quantities representative of energy of fuse link. Firstly, the absolute minimum value of pre-arcing energy (min I^2t), which indicates the minimum energy in A^2s that will result in the melting of the fuse element. If this is exceeded then the fuse link element may be damaged thus altering the characteristics. Secondly the total energy let-through (total I^2t) which is a measure of the maximum energy in A^2s that the fuse link will let through at a particular voltage. It is important to note that the operation of the fuse links under short circuit is dependent upon the applied voltage and a significant reduction of total I^2t can be seen with lower values of applied voltages. Under no circumstance should fuse links be applied on systems above their rated voltage.



Current rating	Pre-Arcing I^2t (A^2sec)	Total I^2t (A^2sec) at:	
Amp		415V	550V
2	2.2	5.4	31
4	7.2	18	70
6	21	60	400
10	100	280	1000
16	300	850	2000
20	540	1000	2500
20M25	900	3000	-
20M32	1100	4000	-

Figure 71 : I^2t Values

Now, with this basic understanding of the fuse, let us see how we can apply this for our purpose.

In our application, the fuses are placed between after the generator breaker and the source side of the rectifier PEBB. The main purpose of the fuse in out application is to provide primary protection for the L-L faults and the 3-phase faults on the source side of the Rectifier PEBB. These are the faults for which the RA cannot interrupt the fault current. The fuse also provides backup protection for the RA.

The fuse we choose, therefore, should be fast enough so that it operates before the generator protection. That is the fuse should properly coordinate with the upstream breaker –the generator breaker. This ensures that the generator is tripped only to provide backup protection for the fuses.

The fuse also provides short circuit backup protection to the RA. If the RA does not mal-operate, it detects and interrupts faults in about 0.5ms. A typical fast action fuse, on the other hand, takes few ms to 100ms to interrupt and isolate the faults (depending on fault current). Therefore, if the RA mal-operates, a fast action fuse would automatically provide backup protection. The choice of the fuse for providing backup protection to the RA, is therefore, not critical and any fast action fuse can be chosen to provide backup protection.

Most high voltage fuse links are not designed to operate under extremely low over current fault conditions, i.e. below the fuse links minimum breaking current. This is typically 2-3 times rated current. Fuse links of this type are normally equipped with a striker pin mechanisms which are used to provide 3-phase tripping of the fuse switch.

The “E” rated fuses are general purpose current limiting fuses. They are capable of interrupting currents that cause the fusible element to melt in 1 hour to the fuse links rated interrupting current. The E rated fuses melt in 60mins at 220 to 264% of E rating, for example a 200 E rated fuse must melt in 60mins for an applied current of 440 to 528 A. These general purpose current limiting fuses are not applied as overload protection devices. This type of fuse provides reliable protection above approximately 2.2 times the continuous rated full load current. Transient currents of duration approaching fuse melting time may physically damage the fuse element and cause a change in the melting characteristics. Therefore when selecting such “E” rated fuse unit, we should allow proper allowance for such expected short term transient conditions.

For our application, the current rating considerations for the choice of a fuse are

1. The normal rated current of the device to be protected is ~450A (RMS)
2. The startup current (due to initial capacitor charging via rectifier PEBB) is of the order of 1kA (RMS) for about 5-10 milliseconds (<0.0ms).
3. The fault currents level is of the order 9-10kA for faults after source inductor and it is of the order of to 30kA for faults before source inductor. The fuse is required to operate for both these faults.

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 employ a fuse in the prototype system simulation, a fuse model was developed by the author in PSCAD. Time-current fuse characteristics of the chosen fuse were entered into the simulation as interpolated lookup tables. The energy required to melt and to clear at different current level is also calculated and entered as interpolated lookup table. During the time domain simulation, for a given value of current through the fuse, the energy dissipated in the fuse is calculated at every instant. If this calculated energy (to melt and clear) exceeds the energy required (to melt and clear) obtained from the lookup tables, then it implies that the fuse has melted and cleared. As a confirmation, the time of operation of the simulated fuse is matched with the time current curves from the specification sheets. Note that the developed model does not include arcing, as modeling the arc would not enhance the simulations under consideration.

Simulation results for one of the faults have been shown in “Rectifier Fuse for Rectifier AC Zone” on page 42.

Appendix B Buck Converter Design Considerations

For the Buck Converter Agent to provide effective and comprehensive protection for the faults shown in Figure 46, some important design choices have to be made. The main issues that need attention are (i) Isolation transformer turn ratio, (ii) Device ratings, (iii) Switching pattern function, (iv) Topology based on the switching pattern chosen, (v) Input inductor values and (vi) Crowbar selections.

The most important issue, from protection perspective, is the turn ratio of the isolation transformer. The main function of the isolation transformer is to provide isolation between primary and the secondary sides of the buck converter. For the buck converter, therefore, the typical turn ratio is 1:1. For achieving higher level of bucking action, a higher turn ratio can be used. A higher turn ratio will lower the current in the CSDs of the source side or the BCIS devices during the normal operation of the buck converter. At rated values of output current, we can choose ETOs of the BCIS to be of a lower current rating. Therefore, a higher turn ratio provides an advantage, as under normal operation, the I^2R losses will be lower in the BCIS devices.

Choosing devices with lower "normal current rating" will also lower the "maximum current ratings". This implies that for a given fault condition, the fault current will require a much shorter time to exceed the maximum current rating of the low rated devices than if higher rated devices were chosen. This in turn means that, when a higher turn ratio of the isolation transformer is chosen, the BCA has shorter time to detect, identify and protect against faults. Therefore, the BCA has to be faster, which can make the protection task of the BCA much harder.

Therefore, various scenarios of different turn ratio were simulated. Different values of turn ratio of the isolation transformer was chosen (8kV:8kV, 8kV:4kV, 8kV:2kV, 8kV:1.6kV and 8kV:1kV). For these scenarios, many parameters were observed, such as maximum allowable current through ETOs, maximum current through the diodes of BCRS, typical duty ratio, input current ripple, output voltage ripple, rise time of fault current, time for the buck converter to completely shut-down (end-time for freewheeling of BCRS diodes), current through ETOs during normal operation, losses in the buck converter. It was found that a 5:1

turn ratio, 8kV:1.6kV was suitable for normal operation and during protection. Devices chosen with such a duty ratio allows enough time for the BCA to detect, identify and protect the buck converter effectively. Therefore, a 5:1 turn ratio was chosen for the isolation transformer.

With a turn ratio of 5:1, the current for normal operation of the Buck converter under full load is about 200A. Since, typically the threshold of the protective devices is set to 2.5x the normal rated current, the threshold of the BCA, to detect the faults, is set to 0.5kA. The SLAP which provides backup protection to the BCA is set to 1kA, to achieve proper coordination as described earlier. Therefore the CSDs (ETOs) of the BCIS are chosen to be just higher than this with a rating of 1.1kA. The choice of such devices ensures that the BCA has enough time to detect and identify the different faults.

The choice of the switching pattern function for the buck converter has three options [29]. First option is to turn off all the switches, the second option is to turn off S1 and S3 and the third option is to turn off S2 and S4 as shown in Figure 45. The second and third options are functionally indistinguishable.

The first option of turning off all the switches is employed here since with this switching pattern, the switches of the BCIS carry only unipolar current. Due to this, the switches of the BCIS can be realized by ETOs without an anti-parallel diode. This topological change is important from protection perspective as with this modified topology, the Buck Converter can provide protection and isolation for faults, by turning off all the CSDs (ETOs) of the BCIS. By turning off all the switches of the BCIS, the magnetizing current is not chopped off; it in forced to flow through the secondary winding and freewheeled through the diodes of the BCRS. Therefore, this prevents any excessive voltages.

Note that another advantage results from the choice of this switching pattern. When all the switches are off, the voltage is shared equally (3.5kV) between switches of same leg (S1, S4) and (S2, S3), thereby reducing the voltage stress on the devices.

Another issue is the choice of L_{in}. A larger L_{in} aids in limiting the rate of rise of fault current, while at the same time during turn-off of the current, a larger L_{in} will cause a higher voltage rise ($=L_{in}$*di/dt). Therefore, L_{in} should be chosen such that it provides enough time for the BCA to detect the fault and at the same time does not cause an excessive over voltage.

The last important issue is the crowbar selection. As discussed in paragraph (c) of section 3.6. A crowbar device is connected from the positive bus to the negative bus at the input of the Buck Converter. The device is a thyristor or a silicon-controlled rectifier (SCR) which is normally OFF. When the failure of SLAP of the buck converter is detected, the thyristor or the SCR is turned ON. The thyristor or the SCR must be chosen such that it has surge current rating equal to or greater than the fault current level of the source side of the buck converter for 1ms (Rectifiers detect and interrupt the fault in about 0.5 ms).

Appendix C System Diagrams

The PSCAD simulation diagram for the prototype system is shown in Figure 72. Blocks R1 and R2 represent the Rectifier PEBBs. The blocks B1, B2 and B3 represent the buck converter PEBBs. The block, Iin1 represents the three-phase inverter.

The simulation circuit for the rectifier PEBB is shown in Figure 73, the buck converter is shown in Figure 74 and the circuit of the three-phase inverter is shown in Figure 75.

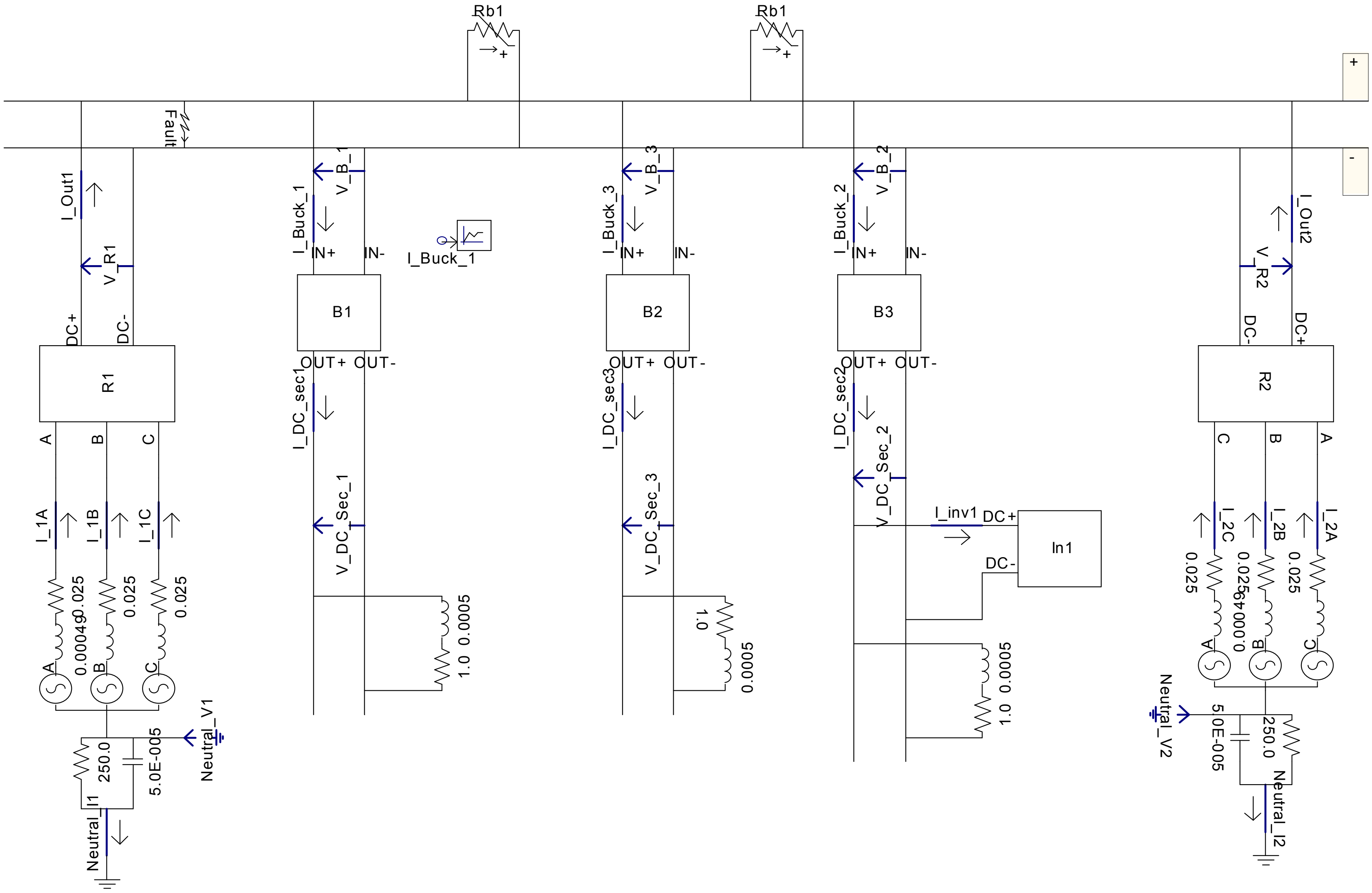


Figure 72 : Prototype System in PSCAD

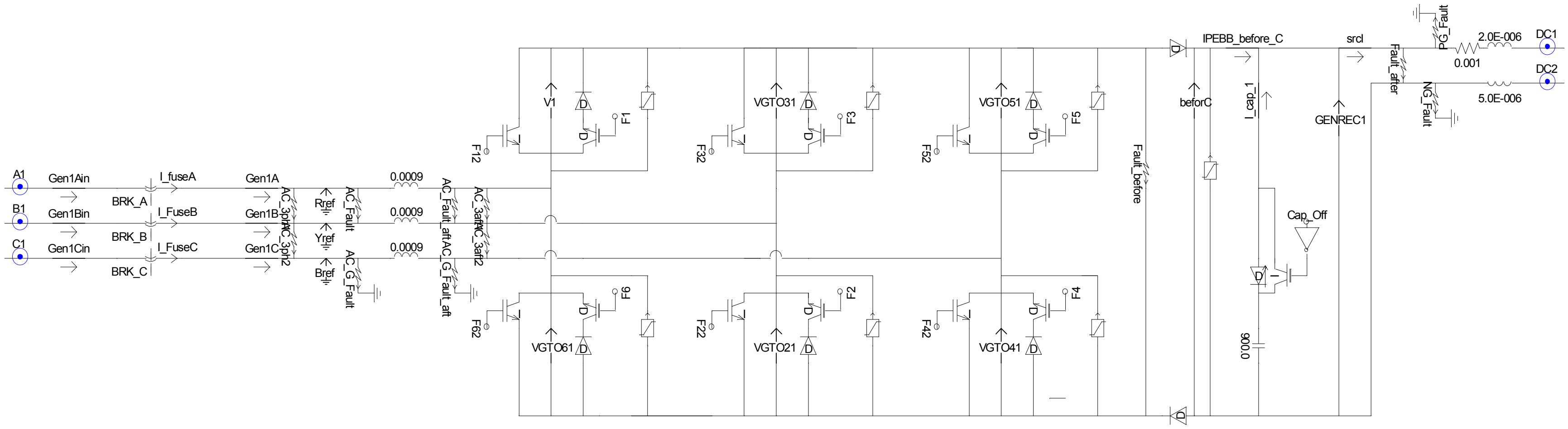


Figure 73 : Rectifier PEBB in PSCAD

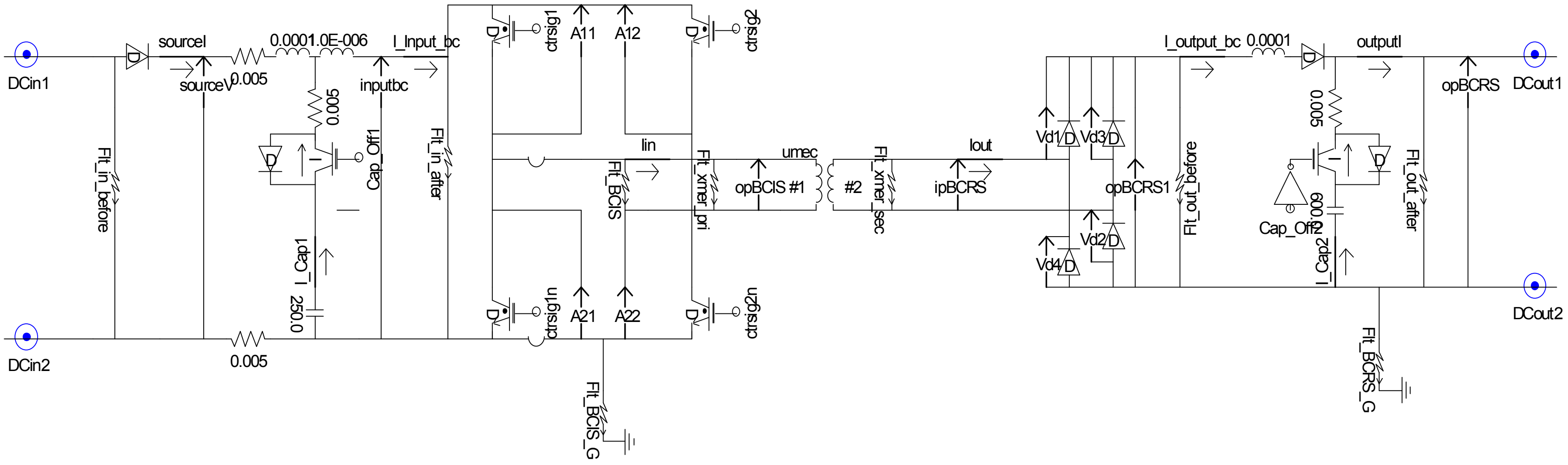


Figure 74 : Buck Converter PEBB in PSCAD

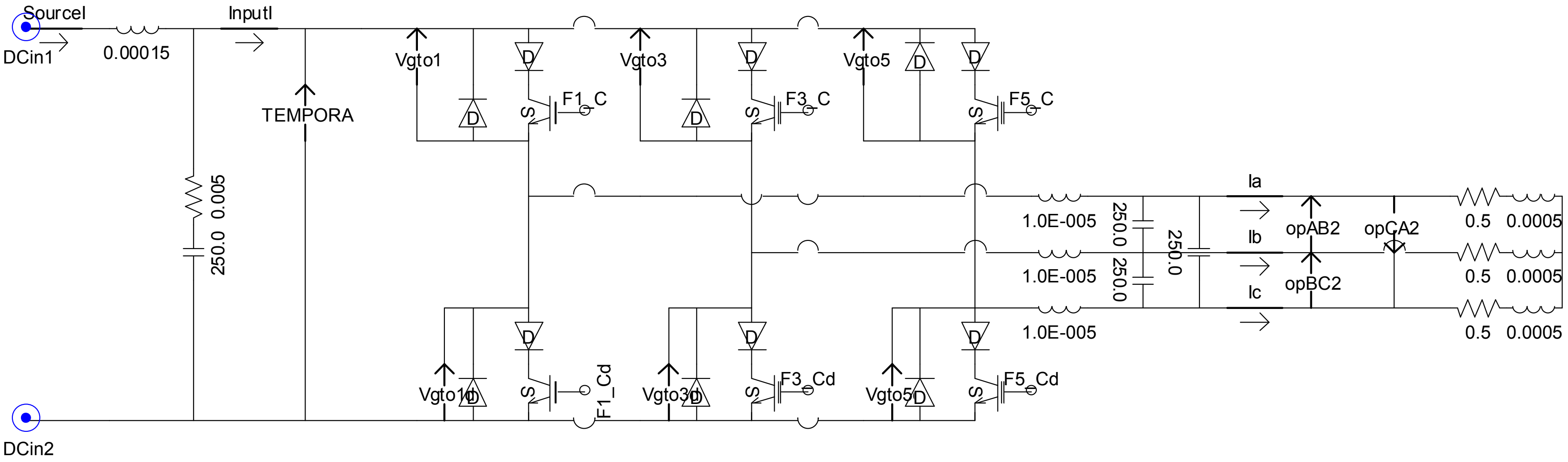


Figure 75 : Inverter PEBB in PSCAD