Protection Strategies for LVDC Distribution System

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***Abstract*—DC power system is gaining popularity. Research is being conducted worldwide on implementation of LVDC (low voltage direct current) and MVDC (medium voltage direct current) in applications such as ship power systems. One major hurdle to this path is the immaturity of the protection systems. This paper deals with the modeling of LV/MVDC power system with different marine loads and faults. Since LV/MVDC power systems are still in preliminary stages, their modeling and fault analysis will help in addressing the requirements of various protection strategies. The system modeling and fault simulations are done in simulation software Power Systems Computer Aided Design (PSCAD). The components of DC ship power system are also described.**

***Index Terms*—DC protection, Diesel generator, Fault analysis, LVDC distribution, MVDC distribution, PSCAD, Ship Power System.**

I. INTRODUCTION

Electricity distribution networks are experiencing a transformation toward direct current (DC). This transformation is due to the significant increase of electronic loads and the introduction of renewable energy sources. DC power systems provide improved reliability compared to the AC counterparts in certain cases [1]. Attracted by the advantages of increased power density and simplified modularized systems [2]–[4] researchers are considering the use of DC for ship power distribution systems. The more electric ship helps in easy integration of variable frequency generators, energy storages with less number of power conversion stages. This type of more electric ship will also help in integrating electric propulsion system [2]. The US Navy has studied shipboard power distribution based on DC distribution system [5]. One main hurdle in the path of DC distribution system is the protection system. Although research has been conducted worldwide to study DC systems under fault and devise suitable protection algorithms, it is believed that there is still opportunity for improvement. This study looks at the performance of the DC systems under fault conditions which will help in devising the protection strategies in future. The DC power system in this paper is simulated in PSCAD [6].

The paper is organised as follows. In Section II, the state of art in LV/MVDC distribution systems is presented along with the IEEE standards 1709-2010 which is concerned with MVDC ship power systems. In the Section III, the circuit diagram for hypothetical ship power system is presented and the various components are described in detail. Section IV deals with fault studies followed by discussions & future directions in Section V and finally the conclusion is presented in Section VI.

II. LVDC: STATE OF ART

A. Literature Review

The DC power systems have been used extensively in transportation systems, telecommunication infrastructures and for interconnection of AC grids with different frequencies. The feasibility of using MVDC/LVDC over AC for commercial power distribution has been studied and analysed by several researchers in the past decade. The researchers in [7] conducted an experiment comparing the performance of AC and DC loads during transient and steady state faults. Their results showed that AC systems may be replaced with DC distribution system without significant degradation in performance and in some cases the performance improved.

The lack of natural current zero in DC system makes the protection system challenging. The protection system should be reliable, high speed, well-performing, economical and simple [8].

The DC grid needs high capacity filters to mitigate the DC voltage ripples. However, when a DC bus is short circuited, the filter capacitors rapidly discharge into the fault point resulting in overheating, EMI and may cause unpredictable operation of switches and circuit breakers [9]. There are mainly two types of fault in DC systems which are:

- Short circuit between positive pole and negative pole.
- Short circuit between positive pole or negative pole to ground.

The authors in [10] have studied MV/LVDC distribution system and mentioned the protection requirements. A small DC microgrid was studied in [11] for different faults in order to investigate the type of protective devices required.

B. IEEE Standards

According to IEEE standard 1709-2010 [12], recommended DC bus voltage for LVDC system is less than 1.5 kV and between 1.5 kV to 30 kV for MVDC system. IEEE standard 1709-2010 for MVDC system in ships [12] recommends that the DC system should avoid standards of AC systems. A typical MVDC power system for ship comprises of the shore power interface, prime-movers, generators, DC-DC converters, DC-AC inverters, energy storages, pulsating loads, propulsion systems, dedicated constant power loads and ship service

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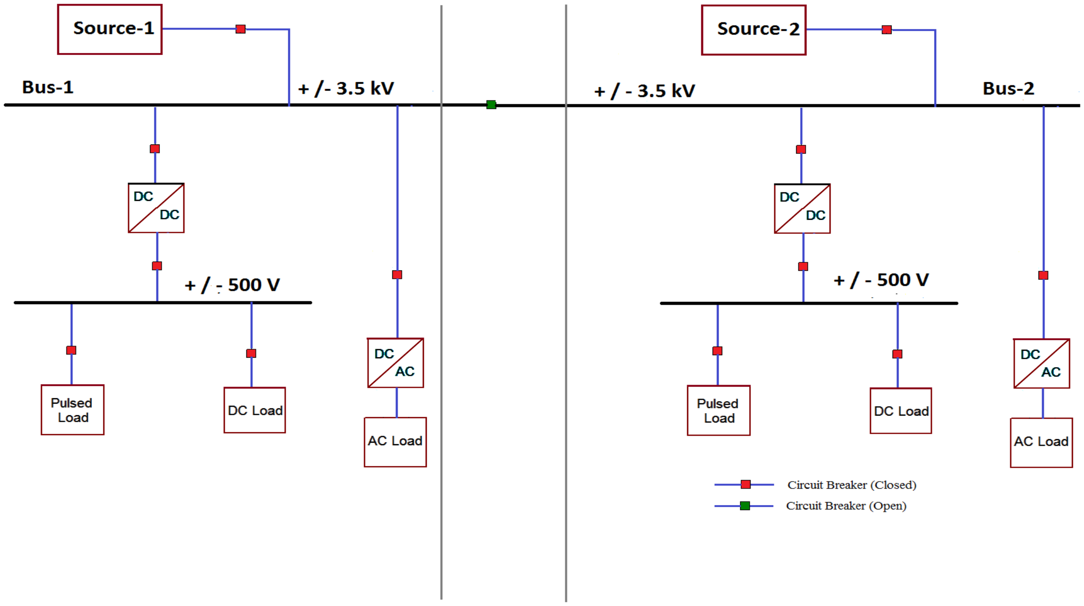


Figure 1: Layout of LV/MV Distribution System.

loads. In this paper we will consider only the power generation, pulsating load, dedicated constant power load and AC motor drive.

Grounding is an important issue for the MVDC power system. For human safety, touch voltage and step voltage should be limited to acceptable levels. In this analysis, test system with mid-point grounding is considered as it has certain advantages such as lower insulation requirements, lower corrosion problems and the system can operate at half power with one pole out of service [12]. The power electronic converters should also comply with the IEEE standards 1662-2008 [13].

III. SYSTEM MODEL

Figure 1 shows an example of the proposed shipboard with DC distribution system designed according to recommendation of IEEE Std 1709-2010 [12]. The whole DC power system is divided into two parts Section-A and Section-B. The topology is sectionalised to increase the reliability and enabling economic dispatch of generator.

In Section-A source-1 is of bipolar structure which consists of positive and negative output and is connected to the bus-1. So, bus-1 consists of two rails, positive DC rail and negative DC rail owing to bipolar nature. Section B is the exact replica of the Section A. The bus bar stray resistance and inductance is assumed to be 100 $\mu\Omega$ and 12 nH respectively. Each section consists of a generating source, a step down DC-DC converter, DC-AC inverter and three different type of loads namely pulsating load, DC resistive load and induction motor drive. The DC-DC converter and DC-AC converter are connected by cables which are represented by simplified models consisting of inductance and resistance only. It is assumed that the cable length is 20 m for all loads and the same so resistance and inductance values are chosen as 0.003 Ω/m and 0.0004 mH/m respectively [14].

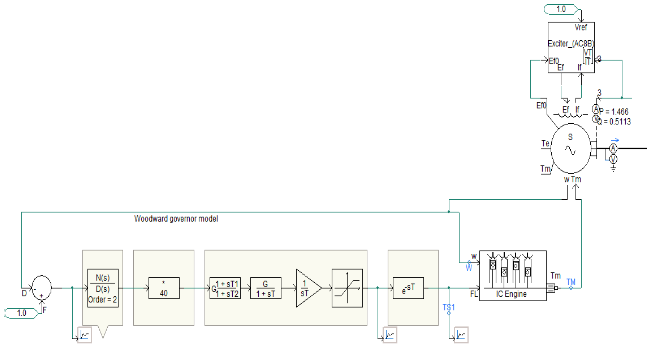


Figure 2: Schematic of diesel generator

The details of the system components are discussed below.

A. Generating Source

The generating source comprises of a diesel generator followed by a three phase uncontrolled rectifier. The diesel generator is simulated in PSCAD using the available components such as the synchonous generator, excitation system, IC engine and woodward governor model [6] [15]. The sychronous generator is run in *'constant speed'* mode. The schematic is shown in Figure 2 and the specifications are mentioned in Table I.

B. DC-DC Step Down Converter

DC-DC step down converters are used to step down the voltage of $\pm 3.5kV$ to $\pm 500V$. A single phase SPWM (Sine pulse width modulation) inverter [16] followed by a step down transformer is used for this operation. An uncontrolled rectifier is used to rectify the voltage. This type of DC-DC converter is

TABLE I: Parameters of the Generating Source

Parameters	**Values**
Synchronous generator rated power	2 MW
Synchronous generator rated voltage (L-N RMS)	3 kV
Synchronous generator base angular frequency	314.14 rad/s
Synchronous generator unsaturated reactance (Xd)	0.920 pu
IC engine machine rating	2MVA
IC engine rated speed	3000 rpm
Uncontrolled rectifier output	±3.5 kV
Diode ON Resistance	0.01 Ω
Diode withstand voltage	10^6 kV

suggested in IEEE std 1709-2010 [12]. The primary purpose of using this topology is the galvanic isolation of the downstream loads from the MVDC bus for ground fault decoupling. This galvanic isolation is achieved because the transformer forms a part in the DC-DC converter. Thus the downstream loads which are the pulsating load and constant DC load is galvanically isolated from the source. The downstream of the DC-DC converter is kept ungrounded to enable continuity of operation during single ground fault. The schematic of DC-DC converter is shown in Figure 3 and the parameters are given in Table II.

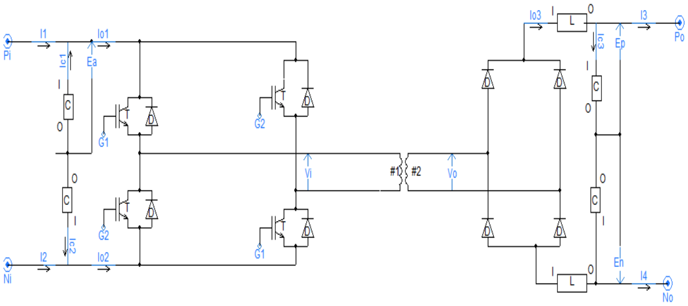


Figure 3: Schematic of the DC-DC converter

TABLE II: Parameters of the DC-DC Step-Down Converter

Parameters	**Values**
Input DC link voltage	±3.5 kV
Output voltage	±500 V
High frequency transformer rating	2.5 MVA
High frequency transformer transformation ratio	10 kV /1.45 kV
1-phase SPWM inverter modulation index	0.8
1-phase SPWM inverter carrier frequency	750 Hz
Transformer leakage reactance	0.10 pu

C. DC-AC Inverter

The inverter employed for the AC drive is a 2-level 3-phase SPWM based inverter [16]. The output is fed to the induction motor. Unlike the pulsating and DC constant loads, the induction motor is not galvanically isolated from the source. The specification of the inverter is given in Table III.

TABLE III: Parameters of the DC-AC Inverter

Parameters	**Values**
DC Link voltage (positive pole to negative pole)	7 kV
Output AC voltage (L-L) rms	3.43 kV
Output frequency	50 Hz
Modulation index	0.8
Carrier wave frequency	5 kHz

D. Loads

In this paper, we have considered three types of loads DC constant loads, pulsating loads and induction motor drive. These loads are further described below.

1) DC Load: A constant DC load is simulated by a simple resistance.

2) Pulsating Load: Pulsating loads are of particular importance in naval power systems. The main functions of the pulsating loads are winches, steering gear, EMALS (electromagnetic aircraft launch systems), rail guns and FELs (free electron lasers) [12]. The circuit diagram of the pulsating load is given in Figure 4.

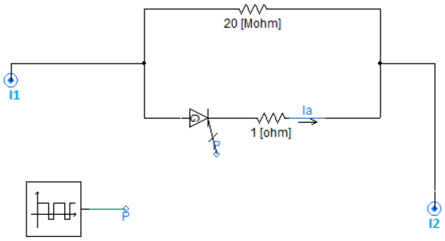
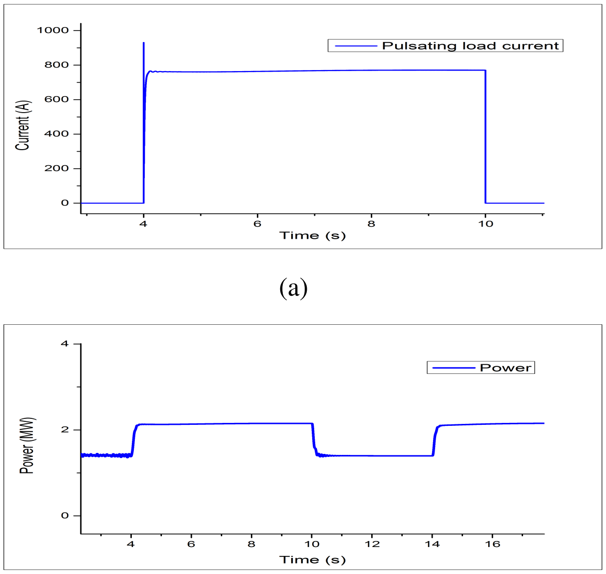


Figure 4: Schematic of a pulsating load.

The pulsating load is modelled with an ideal switch that is activated at regular intervals. The pulsating load is connected between the positive and negative rail of the DC-DC converter output in both Section A and Section B. The firing pulse width is of 6s and firing is repeated in every 10s. The time duration of the pulsed load is according the notional report on DC ship power system prepared by ESRDC [17]. The pulse load current and the source-1 output power is shown in Figure 5.

3) Induction Motor Drive Load: The induction motor is an important load in ship based power systems. The motor may be a part of the cargo handling, ballast, ventilation or propulsion system. The schematic of the induction motor is shown in Figure 6. The torque-speed characteristics depends on the specific application. For propulsion load the relation between torque and shaft speed is [18]:

$$T \propto n^2, \qquad (1)$$



(a)

(b)

Figure 5: (a) Pulsating load vs time and (b) source-1 output power vs time.

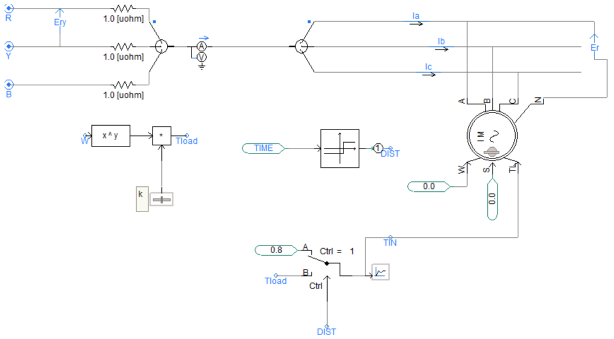


Figure 6: Schematic of the induction motor.

where, T is the torque in Nm and n is the shaft speed in rpm (revolutions per minute).

For this paper we have considered the motor loads to be of propulsion type. The specification of the squirrel cage induction motor is given in Table IV.

TABLE IV: Parameters of the Induction Motor

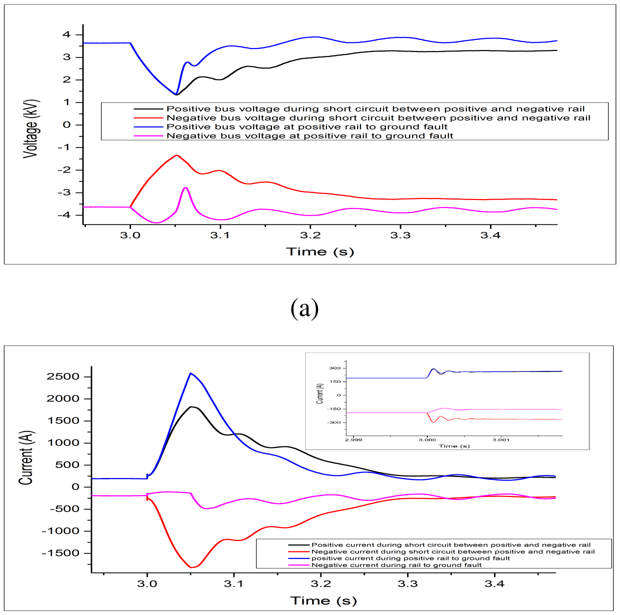
Parameters	**Values**
Motor Rating	2.5 MVA
Motor Speed	315.14 rad/s
Motor L-L Voltage	3.3 kV
Angular moment of inertia	2s

IV. Fault Studies

In this paper, faults are simulated at the vulnerable areas such as bus bar, DC-DC step down converter and the DC-AC inverter. Two types of faults are considered which are short circuit between positive pole and negative pole & low impedance (0.001 Ω) earth fault between positive pole and earth. The faults are simulated with fault starting at $t = 3s$ and the duration of the fault is 0.05s. The results are superimposed on the same graph. Please note open loop control system is used for controlling both DC-DC converter and DC-AC inverter and network is simulated without any protective devices. This has been done to study the trend of fault current in the worst case scenario. The faults and their impact at specific locations are discussed in following sections.

A. Bus Bar

Fault is simulated by short circuiting the positive and negative rail of bus-1 and ground fault is simulated between the positive rail to ground. Both sets of results are placed on the same graphs for comparison. The various parameters such as bus-1 voltage, source-1 output current, induction machine speed and induction machine terminal voltage variations are studied for both the faults. The results are shown in Figure 7 and 8 respectively.



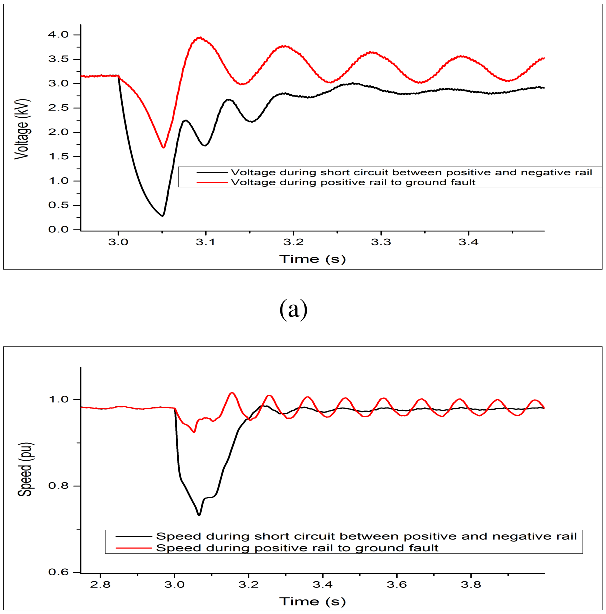
(a)

(b)

Figure 7: (a) Bus-1 voltage and (b) source-1 current variation during positive-negative pole short circuit and positive pole-ground faults of bus-1.

B. DC-DC Converter

The downstream loads of the DC-DC converter are galvanically isolated from the source side. The DC-DC converter output is ungrounded system, a single ground fault will have no effect on the system, but double earth fault will effect the system. For simulation of double earth fault, first earth fault is simulated at positive input of pulsating load at 2.5s and second ground fault is simulated at negative input of DC load at 3s. The DC-DC converter output voltage variation, DC-DC converter output current variations and the bus-1 voltage variation are shown in Figure 9.



(a)

(b)

Figure 8: (a) Induction motor terminal RMS voltage and (b) induction motor speed variation during L-G and L-L faults of bus-1.

C. *DC-AC Inverter*

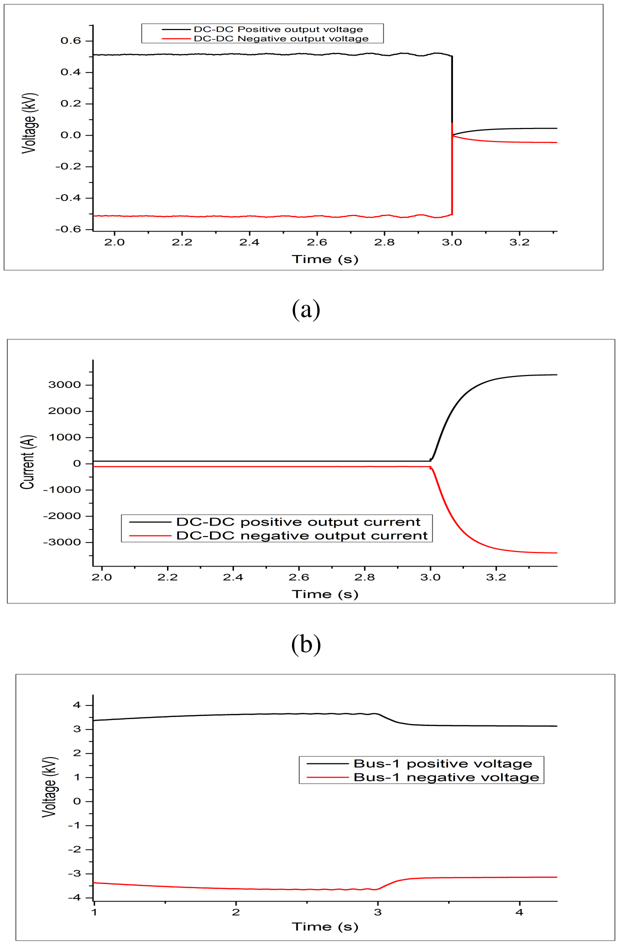
Faults are simulated at the input of DC-AC converter. The short circuit between positive pole and negative pole & earth fault between postive pole to ground are considered. The effect of the faults on the induction motor phase voltages and motor terminal line to line voltage is plotted in Figure 9 and 10 respectively.

V. DISCUSSION

In the previous section faults were simulated at critical locations of the network. A LV/MV DC network was simulated as per IEEE standard [12]. The discussions are cited.

1) The power demand from the source increases with the operation of the pulsating load which can be seen from Figure 5. Since the pulsating load is of intermittent type, the energy storage systems such as flywheels, battery banks can be used to cope up with this demand. With the inclusion of energy storage, rating of generator can be decreased resulting in more efficient and economic operation of the system.
2) Most vulnerable fault location of the system is at bus bars. The positive rail to negative rail and positive rail to ground faults at bus-1 resulted in disruption of the whole system which can be seen in Figure 7(a). A low impedance ground fault simulated at the positive rail resulted in very low voltage of 1.35 kV while the negative rail voltage is not much severely effected. Both positive and negative rail voltage drop to very small value 1.30 kV for the L-L faults.

   The inset of Figure 7(b) shows that the source current increases instantly to 300A from 190 A when the fault is incepted at the bus bar. The current rises because of the immediate discharge current of the filter capacitors. Later on it rises to 1.8 kA for positive rail to negative rail fault and 2.6 kA for positive pole to ground faults which can be detrimental to the conductors and system safety. This difference in the bus voltage and source current during positive rail to negative rail and positive rail to ground fault current is due to the effect of system

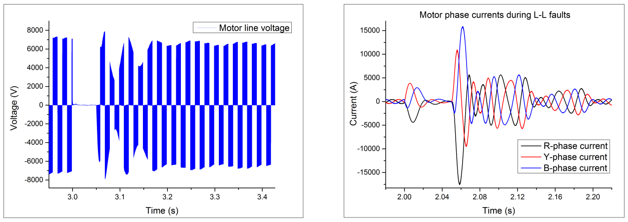


(a)

(b)

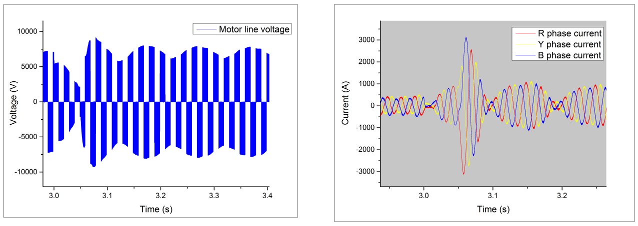
(c)

Figure 9: (a) DC-DC converter output voltage, (b) DC-DC converter output current and (c) bus-1 voltage fluctuation during earth faults of DC-DC converter output of Section-1.



(a) (b)

Figure 10: (a) Induction motor terminal L-L voltage and (b) induction motor phase current variation during short circuit of positive to negative pole at DC-AC inverter input.



(a) (b)

Figure 11: (a) Induction motor terminal L-G voltage, (b) induction machine phase current variation positive pole to ground fault at DC-AC inverter input.

impedance.

The bus voltage change also changes the inverter output to the induction motor. The motor terminal RMS voltage drops to very low value 0.25 kV for positive rail to negative rail fault and 1.5 kV for positive rail to ground fault. According to the IEEE guide for motor protection [19] the terminal voltage should not deviate more than 10 % from of rated voltage. Huge deviation will result in increase in operating temperature and will effect insulation. From Figure 8 it is seen that the motor is also mechanically effected as the speed change during the faults are high.

3) The loads connected to the DC-DC converter are ungrounded and are galvanically isolated from the source. The system behaves normally in the first earth fault at 2.5s as the DC-DC converter output voltage, output current and the bus-1 voltage remains unchanged which can be seen in Figure 9. During the second earth fault at 3s the DC-DC converter output voltage collapses to zero and the output current increases to 3.4 kA (refer Figure ((9a) and Figure (9b)). The bus-1 voltage is also effected as it can be seen that the bus voltage reduces from 3.5 kV to 3.15 kV (refer Figure ((9c))).
4) The motor input current rises upto 4 kA for positive pole to negative pole fault and 3 kA for positive pole to ground fault which can be seen in Figure 10(b) and 11(b) respectively. This current rise can cause temperature rise and may damage the windings. The IEEE guide for motor protection [19] mandates that such high currents should be avoided and the overcurrent protection should be limited within 125 %. So clearance of such faults are needed as soon as possible. The motor terminal line voltage drops to very low value during the positive pole to negative pole fault as compared to the postive pole to groud fault.

It can be seen that even the fault duration is low (0.05s), the system is severely effected.

A. Future Directions

To mitigate the adverse effects of fault currents following future directions are foreseen.

1) To test the system under different grounding options and study the fault effects.
2) Develop robust closed loop control system to control DC-DC and DC-AC converters under faults.
3) Consider regenerative braking of the induction motor during fault conditions and modelling the interface converters accordingly.

VI. CONCLUSIONS

In this paper a LVDC/MVDC network for DC ship power system with different marine loads is simulated in PSCAD [6] and is based on the recommendation by IEEE Std 1709-2010 [12]. The faults are simulated for 0.05s at various plausible locations and it is observed that the whole system gets disrupted even the fault duration is very small (0.05s). So, the detection and isolation of the faults are demanding because of time constraint. The challenge is to not only to detect the fault but also to isolate the fault as soon as possible. This fault study was done to devise the protection algorithms in near future.

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