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Directional Protection Scheme for MVDC Shipboard Power System

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Abstract—DC shipboard power systems are gaining popularity primarily because they allow each prime mover to be operated at an optimal speed with respect to fuel efficiency. Another notable advantage is the simplified operation of generators in parallel without concern for frequency synchronization. Careful design of the protection system for dc shipboard power systems is necessary as the continuity of electrical power is required to carry out critical marine missions. In this paper the protection requirements for MVDC shipboard power system with multiple parallel generation system are discussed and the ‘Directional Protection’ method is presented as an attractive candidate. The backup protection algorithm is also developed for increased redundancy. The protection settings for main and backup protection system are discussed and the results are presented. The various challenges associated with the directional protection are also highlighted.

Index Terms—DC Shipboard Power System, DC Protection, Directional Protection, Fault Studies, Ship Operation.

I. INTRODUCTION

DC microgrids are increasingly being considered as an alternative to traditional 50/60Hz ac distribution systems [1]. DC power systems are also being considered for marine [2], [3], submarine and specialist vessels such as survey vessels that use dc propulsion systems. Optimal operation of prime movers is the primary advantage however other advantages include the reduction of cabling requirements, ease with which energy storage sources may be run in parallel [4] and potential reduction in the number of power conversion stages. A typical dc shipboard power system is envisaged to be comprised of generator fed active front rectifiers (AFE), inverter fed propulsion loads and inverter fed houseloads. One of the factors hindering the adoption of dc power system is the lack of practical experience and comprehensive protection systems [5], [6]. The dc shipboard power system is compact with high power density and is critical in the sense that loss of power may adversely effect the critical marine missions which might endanger the lives of crew and passengers. These characteristics distinguish the shipboard power systems from most land based power systems. An accurate and reliable protection system is required for dc ships to avoid inadvertent tripping and power black-out. The protection system should be fast enough to isolate the system without affecting the ship operation. During a fault in a dc power system, the dc-link

capacitors of the rectifiers and inverters discharge rapidly into the fault location. The current direction during a fault may be different from the direction under normal operating conditions which is dependent on the fault location. This change in direction of fault current is used to identify fault location and this protection approach is referred to as *directional protection*. This interesting phenomenon of current reversal is widely used in ac systems [7]. Moreover, the researchers have applied this method in land based dc systems [8] with the help of intelligent electronic devices (IEDs) that perform current measurements and enable communication with other IEDs which are strategically positioned throughout the distribution system. The target protection system should fulfil the criteria which are accuracy, reliability, speed of operation, continuity of service, economical operation and simplicity [5]. This paper focuses on using the directional nature of faulted currents and aims in developing independent protection system which fulfils the criteria of the protection system. The protection algorithm is developed for the generators, propulsion loads and the bus-bar. Sectionalisation of the bus-bar is needed to increase the reliability of the marine power system operation [9]. A detailed analysis of the bus-bar protection revealed that protection algorithm for bus-bar protection needs assistance of low bandwidth communication. The selection of protection settings and thresholds are also described and it is seen that the protection algorithm has minimum reliance on the accuracy of the current sensors except for back-up protection system. The effect of the current reversal during faults on ship propulsion system has been studied as it might effect the critical ship operation. Thus the paper aims to address the following problems:

- Estimating the time within which the dc protection system should act.
- Devising the necessary protection algorithm considering multiple parallel generation sources.
- Determining the location of faults so that optimal discrimination can be achieved.
- Establishing independent protection system (both main and backup) with minimum use of communication.

The remainder of the paper is organised as follows: Section II covers the state of the art of the dc protection system and Section III describes the target dc shipboard power system. Section IV covers the fault analysis of the dc power system and “*directional protection*” based protection algorithm is

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developed in Section V. Discussions are cited in Section VI which is followed by conclusion in Section VII.

II. DC PROTECTION: STATE OF THE ART

Research in the protection system and fault studies for dc power systems have been ongoing for some time. Short circuit faults on the dc distribution bus are characterized by two responses: one is the transient discharge current from the dc-link capacitors of the converters and the other is steady-state discharge current from the generating sources and regenerative motors [10]. This high current alone may cause thermal damage to components in the fault path (especially capacitors), mechanical damage caused by magnetic forces exerted on conductors and overvoltage damage. The consequences of dc fault are [11]:

- Converter loses voltage and current control resulting in poor protection coordination.
- The converters become defenseless. To withstand the higher short-circuit currents the converters should have higher power ratings which increases the cost of the system.
- The other generators connected to the system might be sensitive to the faults which may result in cascade tripping.

Researchers have been trying to devise suitable algorithms to address the above mentioned problems. Fault studies have been carried out for low voltage dc (LVDC) [10], [12] and medium voltage dc systems (MVDC) [13] to study the fault characteristics of the dc system. Active research is being carried out to devise comprehensive dc protection system. DC power system protection from the ac side [14] has been successfully implemented in SCR based HVDC transmission systems where the link is typically point to point. However in the dc shipboard power systems which comprises of multiple generation sources and motor loads, this method may result in indiscriminate tripping and power outage which is not recommended for the dc shipboard power systems as they carry out critical marine operations. This protection system from ac side is furthermore dependent on the tripping of electromechanical breakers that are slow and are ineffective in protecting IGBT based VSCs. Current differential protection for dc power systems offers certain advantages of being highly sensitive and simple operation. However, the main drawback is the need of high bandwidth communication link between the device terminals, precise zonal distribution and requirement of high precision current sensors without which the protection system may result in indiscriminate tripping and protection blinding. Active impedance based dc power system protection can be integrated with the existing power system with ease without need of any communication system [15]. However, the choice of frequency is dominant for its successful operation and it requires high bandwidth measurements which is more suitable for post-fault processing rather than the immediate processing. Travelling wave (TW) based protection system has gained popularity as it offers results with sufficient accuracy [16]. TW based protection system uses naturally occurring surges

generated by the faults and uses common time reference to calculate the TWs. Digital communication is used to exchange the local time stamps to calculate the fault location. This method is widely considered for the protection of the transmission lines. Since the dc shipboard power system is compact, the application of TW is difficult due to stringent measurement and communication requirements. Artificial neural networks and wavelets [17] have been used recently used for the dc shipboard power systems. These approaches are robust and provide accurate results but these require complex algorithms which increases the computation burden.

From the existing research on dc protection systems, it can be inferred that the ideal protection system should have minimum dependence on communication systems or at most rely on a low-bandwidth communication interface. The protection system should be less dependent on the accuracy and precision of the current/voltage sensors and the protection algorithm should be simple to place less burden on the relays. The directional protection has been implemented to mitigate these challenges and is discussed in subsequent sections.

III. SYSTEM DESCRIPTION

Figure 1 shows a representative dc shipboard distribution system comprising of generator side connected with the load side via bus-bar. This type of topology is extensively used for offshore vessels [3]. The bus-bar voltage is 1500 V which according to the IEEE standard 1709-2010 [18] is classified as medium voltage dc (MVDC) system in dc shipboard power systems. The generator side comprises of 2x2048 kVA synchronous generator fed active front rectifiers to control the bus voltage and power flow. Since the time-frame of the dc fault transient is very small and owing to large inertia of the synchronous generator, it is assumed that the generator speed will not change significantly during fault detection and isolation. Hence the brushless synchronous generator is modelled as a constant speed machine. DC voltage droop control [19] is used to ensure equal power sharing between the generators. The load side comprises of 2x883 kW volt-

Figure 1. Single line diagram of proposed system.

age source inverter fed propulsion motors (Thruster-1 and Thruster-2) and 1x300 kVA house load. Indirect field oriented controlled squirrel cage induction motor is considered for the propulsion systems. One of the major differences between the land-based and shipboard power systems is the type of loading. In shipboard power systems, the propulsion system constitutes the largest share of all the combined marine loads and depending on the operating conditions power demand may vary widely. The propulsion loads are also critical and

should the power supply fail the vessel is unable to manoeuvre. Thus robust protection scheme is needed for uninterrupted power supply for specialised shipboard operations. Houseloads represent lighting, ventilation, accommodation loads and auxiliary systems such as small pumps. Their contribution to the total loads is usually quite small except for vessels such as passenger cruise carriers and survey vessels which may have significant sensor and operational loads during the mission. However, in this paper an offshore supply vessel is considered where the houseload is small but are nonetheless of high importance. The generator side and the load side are connected with the bus-bar with their respective intelligent devices (IDs) (see Figure 1(b)). The IDs consist of current transducer (CT) & voltage transducer (VT), relays comprising of protection algorithm and dc breakers for fault isolation. The CT measures the branch current and VT measure the bus-bar voltage. The IDs are discussed in detail in the subsequent sections. The steady state current direction is from generator side to the load side which is shown in Figure 1(a) and Figure 1(b) and is considered as positive direction. F1, F2 and F3 mark the location of pole-pole short circuit fault at the generator side, load side and bus-bar side respectively as indicated in Figure 1(b). Direct-current bipolar arrangement with solidly grounded middle point is considered because of various advantages [18]. It can be seen that each of the generators and the loads are connected to the dc bus through a two level VSC thus the size of dc link capacitor for each converter is an important design parameter as it is the dc-link voltage that is regulated by the generator facing converters. In this paper the dc-link capacitor of the converters are designed according to the power hold-up time ($t_{\text{hold up}}$) according to the following relation:

$$\frac{C(V_1^2 - V_2^2)}{2} = P \cdot t_{\text{hold up}} \quad (1)$$

where, $t_{\text{hold up}}$ is set to be 5 ms $V_1 = 1500$ V and $V_2 = 0.8V_1$ which is in-line with the performance of commercial drives. For motors the dc-link capacitor is calculated to be 10 mF and for generator the dc-link capacitor is calculated to be 25.2 mF. From Eq. 1, it can be calculated that the dc-link capacitor of motor drive will completely discharge in 12.74 ms. The $t_{\text{hold up}}$ can theoretically be increased without bound. This would in effect become an ideal voltage source but the cost and size would be prohibitive.

A. Fault current and voltage characteristic without any protection system

A pole-pole fault is incepted at point F1 which is at the dc power cable of the Gen-1 rectifier (Figure 1(b)) at $t = 0.25$ s. Figure 2 shows the direction of current during fault F1 when simulated without any protection algorithm. From the Figure 2(a,b), it can be observed that during the fault F1, the dc-link capacitors of the motor loads (Thruster 1 & 2), Gen-2 and the house-load discharge through the fault point. The current direction of the motor loads and house-load change from its normal path to the opposite direction. This change

Figure 2. Direction of flow of faulted current during fault F1 in direction of fault current becomes the basis of operation of directional protection system.

B. Effect of current reversal on motor drives

The change in current direction or current reversal during the fault has substantial effect on the operation of propulsion system. From Figure 3(a) it can be seen that during the fault F1, the dc-link voltage collapses, the torque becomes negative and the motor regenerates into the bus. If the negative fault current were however blocked then the motor would work quite normally for a short period of time due to the appropriately sized dc-link capacitors which is shown in Figure 3(b). From the Figure 3(c), it can be seen that the negative current is blocked at 0.25 s and the motor runs normally till 0.2627 s where effective control is lost and the motor current and torque collapses. This is because the dc-link capacitor is discharged completely at that point. The capacitor takes 12.74 ms to discharge completely which is according to the calculations shown by Eq. 1. When the negative current is blocked, no current flows to the motor and during this time the power supplied to the motor is by the dc-link capacitor as it is designed as per hold-up time as explained by Eq. 1. Moreover, the severity of fault current at F1 is reduced when the reverse current is blocked which can be seen from Figure 3(d).

The discharge time of the dc-link capacitor would be increased if the propulsion load were curtailed at the moment of fault detection. To accommodate full load without need for load curtailment the fault should be isolated within $t_{\text{hold up}}$ which in this paper is considered to be 5ms (Eq. 1).

IV. DIRECTIONAL PROTECTION SYSTEM

The direction of current is the key indication whether fault has occurred or not and it can be used for effective fault localisation. Since the current may reverse during motor regeneration, for higher reliability, a combination of branch current and bus-bar voltage is taken for fault identification as the bus-bar voltage always collapses in case of low impedance faults on the dc cables. A protection scheme has been proposed based on the direction and magnitude of branch current and dc bus voltage magnitude using multiple intelligent devices (IDs). It is seen in the subsequent sections that, the proposed protection scheme works independently for generator and load side and furthermore requires only low-bandwidth communication for bus-bar protection. Thus this scheme has particular advantages over other schemes. The faults are incepted at locations (F1, F2 and F3 (see Figure 1(b))) and the respective protection algorithms are developed. The generator and propulsion system

Figure 3. (a) Motor current, motor torque and motor drive input current during fault F1, (b) motor current, motor torque and motor drive input current when negative current is blocked during fault F1 (c) motor current, motor torque and motor drive input current for sustained fault F1 with negative current blocked and (d) severity of fault current with and without blocking reverse current.

are interfaced with the bus-bar with the help of IDs. For dc shipboard power systems with converter interfaced loads, the following scheme is proposed:

- 1) **Generator Faults :** For the fault at generator side (see Figure 1(b)), the prime identification of the fault is the reversal of current direction (Figure 2) and the dip in dc bus voltage beyond permissible limit at the ID of the faulted generator.
- 2) **Load Side Faults:** For the fault at load side (see Figure 1(b)), the identification of the fault is overcurrent and dip in dc voltage beyond prescribed limit at the ID of the faulted load side.
- 3) **Bus-bar fault:** Similarly during the bus-bar fault (Figure 1(b)), all the current direction of all the generator IDs are positive whereas all the current direction of all the load IDs are negative. To increase the reliability of the system, the bus-bar is generally sectionalised. In this paper the bus-bar is sectionalised into section-1 & section-2 as shown in Figure 4(a) using ID6 as bus sectionalizer. With the help of current direction of ID6 along with current direction of IDs of respective sections, it would be possible to identify the fault location. The current direction of ID6 is set to be positive when current flows from section-I to section-II.
- 4) It can be seen from Figure 2(b) that the current direction of the normally functioning load side IDs change during the fault at any other parts. The load side IDs are programmed to block the negative current. This helps in reducing the severity of the fault current (see Figure 3(d)) and allows the propulsion system run normally as explained in Section III-B. Hence the working of load side ID would be different from generator ID and bus-bar ID.

A. Intelligent Device (ID)

The generators and loads are connected with the bus-bar with the help of IDs. A typical ID comprises of relay, current transducer (CT) & voltage transducer (VT) and breakers (S) to isolate the fault as shown in Figure 5. The information from CT and VT is sent to relay for processing. After necessary computation, the relay gives decision output to breakers S1

and S2. The breakers in the ID can be either solid state circuit breakers (SSCBs) or mechanical breakers or combination of both [20]. It is assumed that suitable breaker exists to break the fault current. The suffix “p” and “n” in S1 and S2 represents the breakers associated with “positive dc rail” and “negative dc rail” respectively. In addition to the protection, the load side ID blocks the negative current; hence the breaker of load side ID is different from ID of generator and bus-bar.

B. Setpoints used for the protection algorithms:

Faults in dc system are identified by a steep rise in current and under-voltage of the bus-bar. It is important to establish correct threshold values for the current and voltage for early fault detection and isolation.

1) **Current Setpoints:** In case of fault, the dc-link capacitors discharge and the dc bus voltage collapses and the anti-parallel diodes within each IGBT module start conducting [11] once the dc-link voltage has fallen below the line-line voltage of the source. For safer operation, the maximum current limit may be chosen from I^2t of the diode. A representative IGBT module is chosen from Infineon datasheet [21] where the I^2t of the diode is $140 \text{ kA}^2\text{s}$ [21]. If the fault is to be extinguished within 5 ms ($t_{hold \text{ up}}$), then the maximum current flowing through the diode should be 5291A. Hence, the current limit for short circuit protection should be well below 5291A.

2) **Voltage Setpoints:** The power input to the load is proportional to the square of the voltage i.e.

$$P_{\text{input}} \propto V^2. \quad (2)$$

If the dc bus-bar voltage drops to 90% then the input power drops to 81%. If the dc bus-bar voltage drops to 80% then the input power drops to 64% and so on. This paper considers the input power drop to 70% as the limit hence the corresponding bus voltage comes out to be 1250 V. Hence the under-voltage limit is set to 1250 V which comes around 83.33% of nominal voltage or 0.833 p.u.

C. Algorithm for Generalised Directional Protection

Based on the previous discussions a generalised protection algorithm is developed.

Figure 4. Fault current direction during fault (a) F3d (b) F1 with ID6 as backup (c) F2 with ID6 and ID2 as backup.

Figure 5. Detailed diagram of (a) load side ID (b) generator side ID and (c) bus-bar side ID.

Algorithm 1 Generalised Directional Protection

```

1: —Set  $V_{threshold}$  and  $I_{threshold}$ .
2: —Read dc bus voltage and current at all IDs.
3: if current at Load ID  $< 0$  &&  $V_{dc} < V_{threshold}$  then
4:   BLOCK reverse current
5: end if
6: while dc bus voltage  $< V_{threshold}$  do
7:   if current at Gen ID  $< 0$  then
8:     TRIP Gen ID ▷ Generator Protection
9:   end if
10:  if current at load ID  $> I_{threshold}$  then
11:    TRIP Load ID ▷ Load Protection
12:  end if
13: end while
14: while all Gen currents  $> 0$  && all Load currents  $< 0$  &&  $V_{dc} < V_{threshold}$  do
15:   if current at bus-bar ID  $< 0$  then
16:     TRIP Busbar ID && Gen IDs && Load IDs in upper section ▷ Bus-bar Section-1 Protection
17:   else
18:     TRIP Busbar ID && Gen IDs && Load IDs in lower section ▷ Bus-bar Section-2 Protection
19:   end if
20: end while
21: —Goto Step 2

```

D. Results with the Generalised Protection Scheme

The generalised protection scheme is applied for generator, load and bus-bar protection and the following results are presented:

1) *Generator Protection*: During fault F1, the current direction of Gen-1 ID reverses and according to line 7-9 of Algorithm 1, the generator gets tripped. The result is shown in Figure 6(a).

2) *Operation with Load Side Faults*: During fault F2, the current magnitude of Thruster-2 ID exceeds $I_{threshold}$ and according to line 10-12 of Algorithm-1, the generator gets

tripped. The $I_{threshold}$ is set to be $3 \cdot I_{full \text{ load current}}$ of the thruster. The result is shown in Figure 6(b).

3) *Operation with Bus-bar Faults*: After sectionalization the two possible fault locations in the bus-bar are F3d which is in the Section II of the bus-bar and is shown in Figure 4(a). The other possible fault location is at Section I of the bus-bar. During the fault F3d, the current direction at gen IDs are positive and current direction at other load IDs become negative but the prime identification is the current direction of ID6 which is positive (discussed in Section-III). Thus according to line 14-19 of Algorithm 1, the ID6 gets tripped along with ID2, ID4 and ID5. From line 14 of Algorithm 1 it can be seen that only zero current condition of all IDs are checked hence the low-bandwidth communication can be used for protection of bus-bar faults. The result is shown in Figure 6(c).

E. Back-up protection for the Directional Algorithm

Back-up protection comes into action when the primary protection fails. The following back-up protection logic is developed for faults F1, F2 and F3d and is compiled in Algorithm 2. The fault current direction is shown in Figure 4.

- **Fault at Gen-1 (F1)**: If ID1 fails to trip for fault F1, ID6 trips on directional overcurrent. This is shown in line 11-13 of Algorithm 2.
- **Fault at Motor-1 (F2)**: If ID4 fails to trip then ID6 trips on directional overcurrent (line 23-25 of Algorithm 2) and ID2 trips on overcurrent (line 26-28 of Algorithm 2).
- **Fault at Bus-bar (F3d)**: If ID6 fails to trip for fault F3d, then ID1 (line 39-41 of Algorithm 2) & ID2 (line 42-44 of Algorithm 2) trips on overcurrent.
- **Motor Back-up Tripping**: The ID of the loads blocks the negative current during the faults. If the ID is still blocked after t_{holdup} then the respective ID gets tripped. This logic can be seen in line 15-17; line 30-32 & line 46-54 of Algorithm-2.
- **Current and Voltage Setting**: For ID1 and ID2 the current setting is done at $I_{backup, gen} = 2 \cdot I_{gen \text{ full load current}}$. For ID6, the current setting is done at

Figure 6. (a) Generator Protection (F1) (b) Motor protection (F2) & (c) Bus-bar protection (F3d)

$I_{backup,bb} = 1.5 * I_{gen \text{ full load current}}$. The current setting is different to avoid inadvertent tripping. The voltage setting is fixed at 1250 V for both main and back-up protection.

F. Result with Back-up Protection

Back-up protection setting is tested at F2 (see Figure 4(c)) when ID4 fails to generate trip command. From Figure 4(c), it can be seen that the fault current contribution for F2 is done by Gen-1 and Gen-2. Since the fault is at Section II (Figure 4(c)), ID6 and ID2 is tripped as back-up protection according to line 23-28. The result is shown in Figure 7.

Figure 7. Back-up protection for fault F2 at ID4.

From Figure 7, it can be seen that ID6 trips as soon as the bus-bar current reached 1.5 p.u. (generator full load current taken as base current). The ID2 is tripped when Gen-2 current reached 2 p.u. It can be seen that ID1 and Gen-1 current is not effected as the current threshold setting of ID6 is lower than ID1 & ID2.

G. Protection Settings

The consolidated protection settings for all the IDs are shown in Table I. The base current is taken as generator fed AFE output full load dc current (1365 A) and base voltage is taken as 1500 V. From Section IV-B, the threshold voltage $V_{threshold}$ is set at 1250 V which becomes 0.83 pu and

current setpoint is chosen well below I^2t of the freewheeling diodes. The main protection of the generator is based on current direction and the motor and houseloads are based on directional overcurrent feature. For the loads, overcurrent of 3 times the full load current is set for main protection. For the back-up protection the bus-bar ID is set to trip at 1.5 p.u. and generator ID is set to 2 p.u. This differentiation in the current setting is done to avoid protection malfunction.

TABLE I
PROTECTION SETTINGS

Fault Location	ID Name	Main Protection	Back-up Protection
Gen-1	ID1	$i1 < 0$	$i6 < -2048A (1.5 \text{ pu})$
Gen-2	ID2	$i2 < 0$	$i6 > 2048A (1.5 \text{ pu})$
Motor-1	ID3	$i3 > 1800A (1.32 \text{ pu})$	$i6 < -2048 (1.5 \text{ pu}); i1 > 2730A (2 \text{ pu})$
Houseload	ID4	$i4 > 600A (0.44 \text{ pu})$	$i6 > 2048A (1.5 \text{ pu}); i1 > 2730A (2 \text{ pu})$
Motor-2	ID5	$i5 > 1800A (1.32 \text{ pu})$	$i6 > 2048A (1.5 \text{ pu}); i1 > 2730A (2 \text{ pu})$
Bus-bar	ID6	$i1 > 0 \ \&\& \ i6 < 0 \ \&\& \ i4 < 0$	$i1 > 2730A (2 \text{ pu}); i2 > 2730A (2 \text{ pu})$
Up-stream	ID6	$i2 > 0 \ \&\& \ i6 > 0 \ \&\& \ i4 > 0$	$i1 > 2048A (1.5 \text{ pu}); i2 > 2730A (2 \text{ pu})$
Down-stream	ID6	$i4 > 0 \ \&\& \ i5 > 0$	

V. DISCUSSION

Directional protection scheme for MVDC shipboard power system comprising of multiple generation sources with active loads has been proposed which is based on the measurement of current and voltage magnitude and determining the direction of the current flow using multiple intelligent devices (IDs). The following comments are made on the proposed method with its challenges and possible solutions:

- 1) It is seen from Section-III B that the protection system should work within the $t_{hold \ up}$ otherwise the propulsion loads would be affected. The current direction helps in identification and localisation of faults with sufficient accuracy. From line 14-19 of Algorithm 1, it can be inferred that low-bandwidth communication is needed for bus-bar protection as it detects only the change of current direction of all the components pertaining to that particular section (Figure 4(a,b)).
- 2) The directional overcurrent type back-up protection is proposed if the primary protection fails to operate. The back-up protection scheme for all the system components are independent meaning that no communication is required. However, the accuracy of the CT is important.

Algorithm 2 Directional Protection with Backup

```
1: —Set  $V_{threshold}$  and  $I_{threshold}$ .
2: —Set  $I_{backup,gen}$ ,  $I_{backup,bb}$ ,  $t_{holdup}$ .
3: —Read dc bus voltage and current at all IDs.
4: if current at Load ID  $< 0$  &&  $V_{dc} < V_{threshold}$  then
5:   BLOCK reverse current
6: end if
7: while  $V_{bus} < V_{threshold}$  do
8:   if  $i1 < 0$  then ▷ F1 Detected
9:     TRIP ID1 ▷ F1 Isolated
10:  end if
11:  if  $i6 < -I_{backup,bb}$  then
12:    TRIP ID6 ▷ F1 Back-up Bus-bar Trip
13:  end if
14:  wait  $t = t_{holdup}$ 
15:  if  $i3 == 0$  &&  $V_{bus} < V_{threshold}$  then
16:    TRIP ID3 ▷ F1 Back-up Motor Trip
17:  end if
18: end while
19: while  $V_{bus} < V_{threshold}$  do
20:   if  $i4 > I_{threshold}$  then ▷ F2 Detected
21:     Trip ID4 ▷ F2 Isolated
22:   end if
23:   if  $i6 > I_{backup,bb}$  then
24:     TRIP ID6 ▷ F2 Back-up Bus-bar Trip
25:   end if
26:   if  $i2 > I_{backup,gen}$  then
27:     TRIP ID2 ▷ F2 Back-up Gen-2 Trip
28:   end if
29:   Wait  $t = t_{holdup}$ 
30:   if  $i5 == 0$  &&  $V_{threshold}$  then
31:     TRIP ID5 ▷ F2 Back-up Load Trip
32:   end if
33: end while
34: while  $V_{bus} < V_{threshold}$  do
35:   if  $i1 > 0$  &&  $i2 > 0$  &&  $i3 < 0$  &&  $i4 < 0$  &&  $i5 < 0$  then
36:     if  $i6 > 0$  then ▷ F3d Detected
37:       TRIP ID1, ID3, ID6 ▷ F3d isolated
38:     end if
39:     if  $i1 > I_{backup-gen}$  then
40:       TRIP ID1 ▷ F3d Back-up Gen-1 Trip
41:     end if
42:     if  $i2 > I_{backup-gen}$  then
43:       TRIP ID2 ▷ F3d Back-up Gen-2 Trip
44:     end if
45:     wait  $t = t_{holdup}$ 
46:     if  $i3 == 0$  &&  $V_{threshold}$  then
47:       TRIP ID3 ▷ F3d Back-up Thruster-1 Trip
48:     end if
49:     if  $i4 == 0$  &&  $V_{threshold}$  then
50:       TRIP ID4 ▷ F3d Back-up Thruster-2 Trip
51:     end if
52:     if  $i5 == 0$  &&  $V_{threshold}$  then
53:       TRIP ID5 ▷ F3d Back-up HouseLoad Trip
54:     end if
55:   end if
56: end while
57: —Go to Step 2.
```

- 3) The dc-link capacitor can play a significant role in preserving the operation of motor drives in the event of dc faults. To be effective, the reverse discharge current must be blocked. The size of dc-link capacitor is proportional to the time duration the motor can ride through the fault period. Longer times require large capacitor banks which are not economical. Hence there should be a tradeoff between the fault extinguishing timing and normal motor drive operation. An alternative method (instead of increasing the size of dc-link capacitor) might be to use integrated energy storage (batteries) that can extend the hold up time for minutes.
- 4) Although the directional protection is quite useful for determining the fault location and isolation but there are challenges which must be addressed :
- a) *Bus-Voltage Spikes*: From the Figures 6(a,b,c) it can be seen that a large spike in bus-voltage occurs during the breaker switching. This is due to due to the use of an ideal switch in the simulation. In practice no such device exists but rather the fault current must be ramped down over a finite time period. This voltage may be mitigated by use of snubber circuits across the breakers [22] or through the use of varistors.
 - b) *Faults in case of resistive loads or DC loads*: In the given system all the loads are fed by voltage source inverter with a dc-link capacitor. In the directional protection, this dc-link is the key element as it indicates the probable fault location which can be known by the direction of its discharge. In case of resistive load this direction cannot be determined as it is not connected across dc-link capacitor. Thus the protection logic should be modified accordingly. Alternatively, a dc-link capacitor may be added to the terminals of the dc-load. Although not necessary for the dc load operation it does introduce the capacitor which is required for fault identification.
 - c) *Differing discharge rate and resonant frequency*: The rate of change of fault current is dependent on the nature of the fault circuit (under-damped or damped) and the resonant frequency. It is possible that circuits with very different time constants may appear within the same system. One network may respond extremely giving a high fault current and clear direction but may subsequently decay quickly as well. A second circuit may show very slow discharge characteristics, reaching a fault current peak well after the fault current in the first circuit has died away. In this case it may not be possible to simultaneously measure fault currents (exceeding a given threshold) on both circuits.
 - d) *Challenges with sampling time*: As mentioned in the previous point that the fault current greatly depends on the fault location. The fault current may be underdamped or overdamped. Figure 8 shows

the underdamped current waveform to which directional protection is applied. Although it eventually settles down to negative value but it fluctuates between negative and positive cycle before settling down to final value.

Figure 8. Dependence of fault identification on sample time.

- e) *Challenge with Sensor location:* The location of the sensor is of prime importance for the working of directional protection system. In this paper it is assumed that the current and voltage sensors are located at the IDs. For example, if the sensor is located between the generator rectifier-1 and ID block then during fault F1 the output of ID tells that the fault is somewhere in the bus thus initiating the bus-bar protection.
- f) *Sensor requirements:* One of the advantages of directional protection is that accuracy requirements imposed upon current sensors are not particularly stringent. Rather, during fault situations it is the direction of the fault current that is important. During fault conditions the capacitor discharge current may rise to some 50kA or more. This is many times the rated current. The accuracy of the measurement at 50kA is not significant. It is the measurement at rated current and at the threshold values that is important. The bandwidth of the sensor is however important and this raises the question on what type of sensors are appropriate.

VI. CONCLUSION

This paper introduces a dc protection algorithm based primarily on the change in current direction during a fault. The change in current direction during a fault depends on fault location and an algorithm is developed to process such changes to both detect faults and determine the location. An intelligent device (ID) detects the fault current at one or several locations and is responsible for tripping its own breaker. No communication is required between ID's for saving information and preserving synchronization, however low-bandwidth communication is needed for operation of the ID associated with bus-bar. In case of malfunction of primary directional protection, directional overcurrent based backup protection is developed. It is seen that the directional

protection may be a promising technique for fault mitigation. However, it is not devoid of challenges. The various challenges associated with the directional protection systems such as load dependence, sensor locations, sensor performance and sampling time dependence are described. Suitable solutions have also been proposed to mitigate these challenges.

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