Implementation of the Differential Protection for MVDC Distribution Systems Using Real-Time Simulation and Hardware-in-the-Loop

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***Abstract*—Development of Medium Voltage DC (MVDC) distribution systems require using proper protection schemes whereas due to the behavior of dc fault current, the conventional fault detection methods for ac distribution systems cannot provide a selective protection for these networks. In this paper, a differential based protection method using Ethernet communication has been implemented for a radial MVDC distribution system with integrated PV and WT. This method must be fast enough to detect the faults before involving the main converters and separate only the faulty feeder in order to increase the reliability of the power system. The experimental validation is performed by using Hardware-in-the-Loop (HIL) approach and communication based on the IEC61850 protocol. A real time simulator (OPAL-RT) and a development board (DK60) are used to evaluate the method and to calculate the time delay of this fault detection algorithm.**

Keywords—DC Protection, Medium Voltage DC, OPAL-RT, Real Time Simulation.

I. INTRODUCTION

The use of Renewable Energy Systems (RES), such as wind turbines (WT) or photovoltaic (PV) units, is constantly developing in the distribution systems. Some types of these RESs provide dc power and connect to existing ac grids via Voltage Source Converters (VSC). The other RESs provide ac power and use two power conversion stages: ac to dc and dc to ac. From this perspective, using dc distribution systems can reduce the number of power conversion stages [1], [2]. DC networks also have other advantages like: the absence of skin effect, reactive voltage drop and capacitive current, the possibility to connect between two asynchronous ac systems and manipulate the power flows in a very short time, which can be utilized to improve the stability of the ac system [3]-[5]. On the other hand, high voltage dc (HVDC) lines and low voltage dc (LVDC) distribution systems are becoming common parts of power systems. However, limited work has been focusing on using dc distribution system, in the level of 10 to 40 kV [6] and this part of distribution is handled by ac power systems. Using new VSCs, dc distribution systems are introduced as an alternative for medium voltage (MV) ac distribution in some applications like: industrial parks, connection between two ac grids with MVDC links, and offshore wind farm collection grids [6]. Even if, until now, using MVDC for commercial distribution systems remains a research topic, it is predicted that MVDC can be a major part of future distribution systems [7]. According to the lack of experiences and studies about these networks, there are some operational issues and concerns about their worldwide usage. Providing a complete protection scheme is one of the main issues in designing new MVDC distribution systems. The behavior of dc fault current is quite different with ac fault [3], [8] and in some cases protection system must detect and clear the fault only in several milliseconds which is much less than the required time for fault detection in most ac protection schemes.

Over current (O/C), differential, and distance relays are the most important relays which are being used for fault detection in ac grids [9]. Based on the problems of using O/C and distance relays for dc systems, the differential relays are the best choice for fault detection in these systems [1], [8], [10]. Differential relays are installed at one end of the feeder and require the current measurements of the other end, by relying on the communication link. This link transfers the data after a time delay whereas, as noted before, the protective scheme must operate in several milliseconds, before involving the VSC. For these reasons, the delay time of communication link is an effective factor for successful operation of the differential based methods. A literature review reveals that the differential protection algorithms based on the IEC61850 protocol are not experimentally tested for MVDC feeders. The communication delay was not considered in [8], [10] and the measured current values were transmitted with cables. This method is not applicable for MVDC feeders with several kilometers length. Also, using communication for differential protection is introduced in [1] without any calculation or estimation for time delay. Moreover, this method is used in [11] and [12] for ac systems, but there is no experimental test for using the differential methods based on the standard protocols for MVDC feeders.

The main objective of this paper are 1) to explain the weaknesses of conventional O/C relays and the capability of differential relays for fault location in MVDC system and 2) to evaluate the operation of differential based relays by calculating the time delay of the proposed method. HIL approach is used for this evaluation. In this approach, the measured currents are transmitted using standard messages of the IEC61850 protocol. This Ethernet based standard protocol is used in substation automation as it is designed to meet the demands of increasingly complex power system [13]-[15]. Also, using a real time simulator (OPAL-RT) a MVDC distribution system with DG units is simulated. The DK60 development board is used for implementing the differential relay outside the OPAL-RT and it sends trip messages to the simulated dc breakers via communication link (LAN).

II. Protection of MVDC Distribution Systems

Protection schemes must operate based on the fault characteristics. For this reason, in order to design a perfect dc protection it is necessary to recognize the behavior of the dc faults. On the other hand, the behavior of dc fault current is related to the topology of converters which are used to contract the dc bus and to feed dc loads.

In MVDC grids different types of VSCs are applicable for connection of distributed generation (DG) units and also construction of dc switchgear. For instance, in order to connect the MVDC grid to an existing MV ac system a Multi-level (ML) converter, as shown in Fig. 1, is necessary. Whereas, connection of PV and WTs to these networks requires a conversion topology, including a medium frequency transformer, as shown in Fig. 2. This transformer is necessary to provide the required output/input ratio for connection of DG units that deliver their power on low level of voltage.

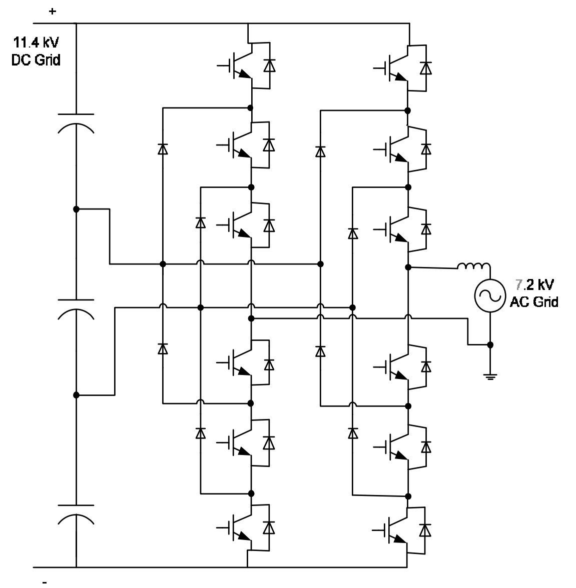

Fig. 1. Four level NPC for MVDC to ac grid connection [16].

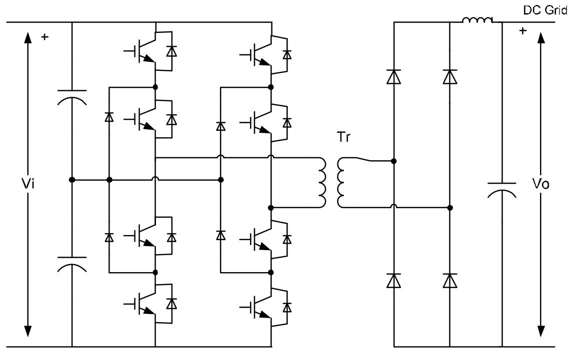

Fig. 2. DC/dc topology for MVDC applications[17].

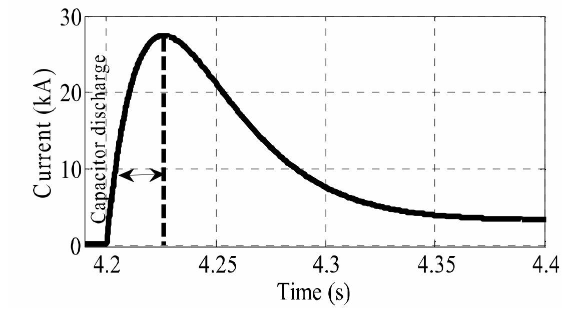

Fig. 3. A typical waveform of fault current in dc distribution systems.

The behavior of dc fault current when the dc network is feeding with two levels VSCs has been analyzed in [3]. This analysis is also is valid for ML converters. In [17] the dc fault was analyzed when dc network supplied by a conversion topology with high frequency (HF) transformer.

Based on these analyses, three different sources can contribute in supplying the dc fault, and therefore, dc fault current may have three different components with especial behaviors. These components are: the dc link capacitors discharging current, as shown in Fig. 3, the inductance discharging current through the freewheeling diodes and the grid current [3]. Almost in all of the VSC-based dc networks, the first part of fault current, which is the main and most hazardous component, is due to discharge of the dc-link capacitor. In this case, because of the formation of a low resistance RLC circuit (consisting of cables and fault impedance) all of the capacitors connected to the dc buses discharge through this passage. Consequently, during a very short time interval a very high level dc current flows through the capacitors, cables, and other devices.

In different types of VSC, which consist of main valves (IGBT) and freewheeling diodes, main valves are blocked after the fault occurrence and two other components of the fault current can flow through the freewheeling diodes. Therefore, during the capacitor discharging period, converters do not contribute in the fault feeding and therefore it will be safe; whereas, during two other parts, which fault current flows through freewheeling diodes, these diodes will be damaged. For this reason, the external protection must operate during capacitor discharging. For the faults which are very close to the converter, this time is very short, but in

MVDC grids which consist of loads and cables, if the fault occurs in each feeder, this time will be more than several milli-seconds. This is due to the increase of the resistance of discharging circuit including cable and fault resistance.

- *DC Fault Clearance*

Blocking the converter is a conventional method to protect two terminal dc systems [9]. For a typical HVDC line with only two terminals system, it is acceptable that after any fault in any point of the line, the converters of the two sides de-energize the dc buses to prevent the harmful effect of the fault current. However, distribution grids are multi-terminal systems consisting of switchgears which supply several feeders with radial or loop configuration [18]. A MVDC distribution system that was used test the algorithm is shown in Fig.4 consisting of underground cables.

In this system, if assumed that the protection is handled by converters without any dc breakers, after any fault, all of the loads de-energize. On the other hand, blocking the converters cannot break the capacitor discharge current. Hence, in order to provide selectivity and safety, the proposed protection schemes, it based on the using the dc Circuit Breakers (DCCB) for each feeder [1]. The solid state DCCB are very fast and are able to clear the fault current in less than 0.1ms[8].

- *DC Fault Detection*

In conventional distribution systems, over current (O/C) relays are the main devices for fault detection. These relays operate based on the flowing current from the protected element in time-inverse or definite-time modes.

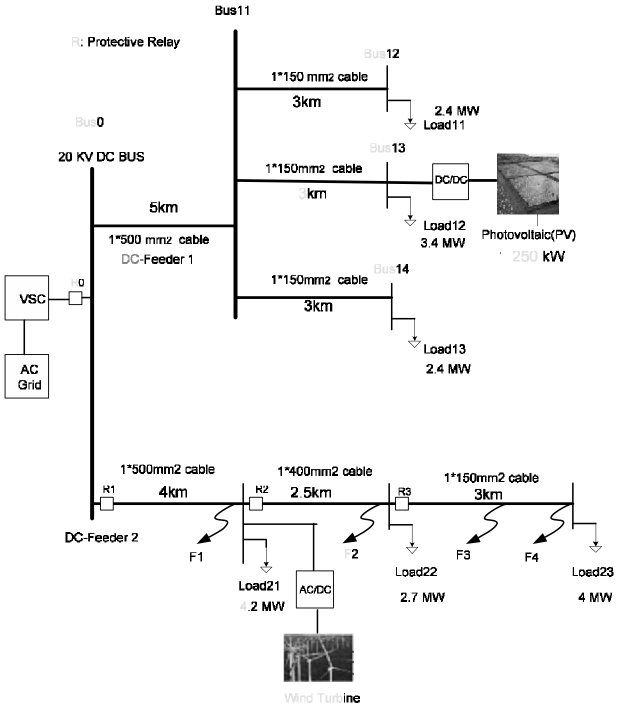

Fig. 4. A prototype MVDC Distribution System.

The O/C relay is a non-unit relay without any physical borders for its protected zone [9]. The operation time of each relay is determined according to the value of the fault current and the relay's settings. Based on the time-inverse curves, there is no significant different between the operation time of these relays when the amplitude of the fault current is very high (e.g. when $I_F/I_{set}>20$). Also, coordination between main and backup relays is an important part of designing a complete protection scheme, to provide selectivity and reliability. In order to evaluate the operation of O/C for the MVDC, the distribution system shown in Fig. 4 was simulated. Table I shows the maximum values of dc fault currents in different locations of feeder2.

TABLE I. FAULTS IN DC DISTRIBUTION SYSTEM

Fault Name	Fault Type	R0: I_F/I_{set}	R1: I_F/I_{set}	R2: I_F/I_{set}	R3: I_F/I_{set}
F4	DC-PP	14.25	24.71	39.75	63.2
F2	DC-PP	26.15	46.02	74.63	0

For example, for F4, the results of simulation presented in Table I show that the measured fault current by R1, R2 and R3, when a pole to pole (PP) fault is occurred, are larger than $20I_{set}$. Hence, there is no enough time margin between the operation time of these relays and it is very difficult to coordinate them. As a consequence, O/C relays cannot provide a complete protection, especially for detecting the faulty zone and do not provide selectivity for MVDC distribution systems [8].

Because of the above mentioned problems for O/C protection in MVDC grids, a distance protection scheme was suggested in [3]. However, the main problem of this method, and other unit protection methods, is the effect of the fault resistance on the detection of the faulty zone. For this reason, in many cases it is impossible to be sure that the faulty zone is detected correctly. This can cause undesirable delays on operation of the relays and, as a result, cannot provide the selectivity. Therefore, non-unit protection methods such as O/C and distance relays cannot provide a selective protection for MVDC networks with small distribution lines while unit protection, i.e. differential method, can be introduced as a solution for these networks.

III. IMPLEMENTATION OF DIFFERENTIAL BASED PROTECTION SCHEME

As mentioned before, the logic of differential method theoretically can detect the location of dc faults and therefore provides selectivity. In differential protection, which is a unit protection, the currents of the two sides of the protected element are compared and, if their difference is more than a predetermined value, the relay detect the fault, as shown in Fig. 5. The main advantage of this protection is its capability of fault detection in very small amount of time without any effect regarding to the fault resistance. Also, it has a physical border and after the fault diagnosis, it only disconnects the faulty zone. Therefore, they can provide acceptable selectivity and prevent mis-coordination. However, it is necessary to know the requirement of this method and validate its operation during specific tests.

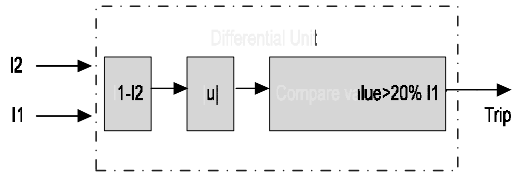

Fig. 5. The trip Logic of Differential algorithm.

When differential relays is used as a protection of dc lines, it is important to compare the measured currents at the two ends of the protected line. Besides, this relay is installed at one end of the line and receives the current measurements from the other end via the communication link, as shown in Fig. 6. However it should be able to detect the fault in the absence of communication. Hence, a backup unit is necessary for situations that the communication link is interrupted. This backup must be able to operate independent of communication. For this reason, proposed relay equipped by an O/C unit. The trip logic of this relay is shown in Fig. 7. The fault detection with this relay, introduces some sources of time delays which are explained here.

- *Delay of Measuring Devices*

Due to the high increasing rate of the fault current in dc grids, Hall Effect sensors are used for current measurement. In [19], the presented sensor has a time delay of less than 3μs that has the capability of correctly following a fault current with a 100 $\frac{A}{\mu s}$ rising rate.

- *Delay of the Fault Detection Algorithm*

According to the high speed micro-possessor which can use for these relays, this time is in the range of several μs.

- *Delay on Communication link*

This delay is based on different parameters like the type and speed of the communication link, the size of the transferred data and the distance on which this data is transmitted. Different types of communication were used for protection in AC power system: Wi-Fi [20], fiber optic [10] and Ethernet [11].

Moreover, in [21], different sources of delays were considered for a WAN network. According to this information, for a 10Gbits/s WAN the total delay time for sending data over 10km is about 0.1ms.

Based on the importance of protection, it can be assumed that an especial network is used for transmitting the protection related signals, eliminating the other network traffic. These time delays are illustrated in Fig. 8. The delay of the measuring devices is very small and is negligible in comparison with other time delays. Another delay time is related to the operation of the breaker. As noted before, it is necessary to use solid state dc breakers for fault clearance in MVDC grids and the operation time of these devices is less than 0.1 millisecond [8]. Other time delays will be calculated in the next parts using the real time simulator and the DK60 development board.

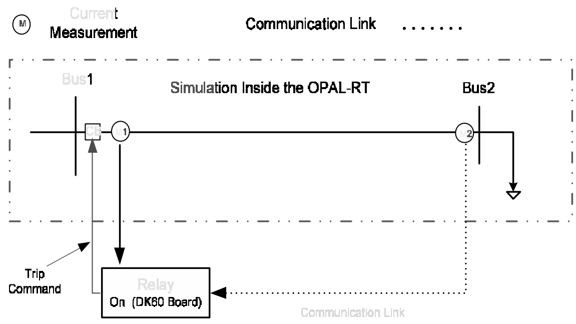

Fig. 6. Differential algorithm implemented on DK60 Board.

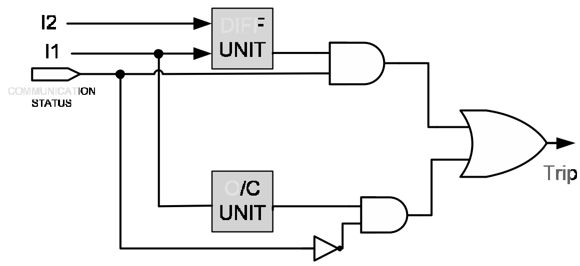

Fig. 7. The trip Logic implemented on DK60 Board.

IV. SETUP DEVICES

Two applications were developed for this experiment: At first, the MVDC grid was designed on a PC (Command station) using SimPowerSystem and then, using the RT-LAB, the model was compiled into an application and transferred on the OP5600 HIL box. The second application was developed for the DK60 board in C++ and involved the implementation of the dc relay's algorithm and the IEC61850 communication configuration.

To determine the delay of the fault detection using the differential method, the setup presented in Fig. 9 was used which consists of the following hardware resources:

A. OP5600 HILbox from OPAL

The OP5600 is a real-time (RT) digital simulator with a multi-processor configuration and a FPGA for fast computation [22]. The board is equipped with multiple analog and digital inputs/outputs for connecting to different hardware and provides a powerful tool for HIL testing, capability that was used for the experimental part of this paper. For developing the real-time applications for the OPAL-RT, the RT-LAB software is used. This software is fully integrated with Matlab/Simulink and provides additional Simulink libraries, including an IEC61850 implementation that allows the exchange of two types of messages, defined by the standard: GOOSE (for sending status messages, e.g. trip commands) and Sampled Values (SV, used for transmitting current and voltage measurements).

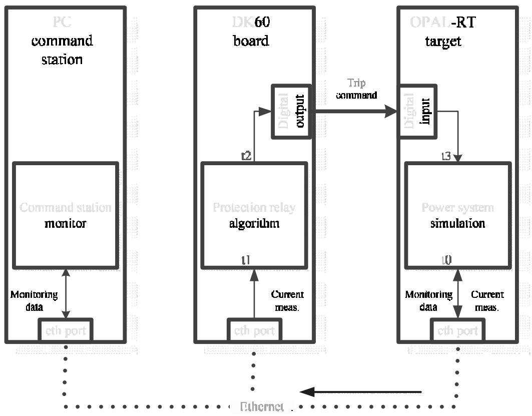

Fig. 8. Hardware in the loop structure.

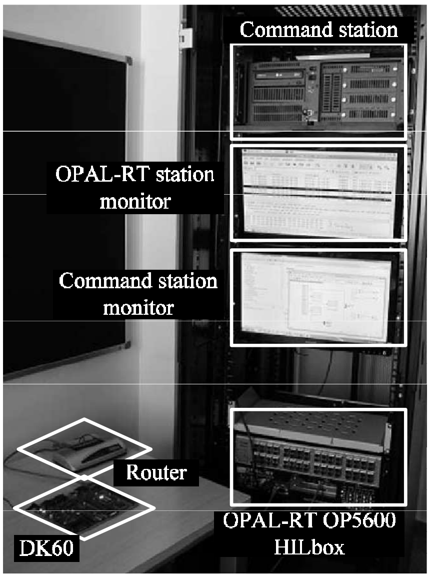

Fig. 9. Experimental setup.

B. *Command station*

The command station is a PC used to design the Matlab/Simulink model that will run on the OPAL-RT target, transfer it to the real time simulator and monitor/supervise the operation of the hardware in the loop setup.

C. *DK60 development board*

This development board provides communication capabilities through various ports and protocols, including Ethernet, SPI, and CAN.

For the processor running on the board, a IEC61850 stack implementation is available from SystemCORP[23] that provides functionalities for all the three communication messages (MMS,GOOSE, and SV) of the protocol; this makes possible the development of custom applications using the IEC61850 communication protocol.

The differential relay considered in this paper is implemented on the DK60 board using the algorithm presented in Fig. 7: if the difference between the two sides' currents becomes more than a preset value, the relay sends a trip command. The tripped CB is permitted to receive "close" command after the clearance of the fault and after resetting the relay manually.

D. *Router*

It is used for connecting all the devices in the same sub-network. During the experiment, messages are being exchanged between the OPAL-RT, running the real time simulation and the DK60, running the relay application. In Fig. 8, four time events can be defined, related to this communication:

t0 – the OPAL-RT simulation is generating a value which is published using the IEC 61850 protocol (event occurrence).

t1 – the application running on the DK60 is reading the message that was published by the OPAL-RT.

t2 – after the fault detection by relay's algorithm, the trip message is published by the DK60.

t3 – the trip message is decoded in the simulation by the use of a specialized *GOOSE Subscriber* Simulink block.

The time interval [t0, t3] represents the delay between the moment when the fault occurs and the breaker is opened.

V. RESULTS OF REAL TIME SIMULATION

Different pole to pole (PP) and pole to ground (PG) faults were simulated in RT simulator. The first study case considers a PP fault occurrence (F2) in the simulated distribution system. Fig. 10 shows the time delay of the implemented relay between the event occurrence at the feeder level and the trip event. The figure reveals that the required time for data transfer to the relay, fault detection and sending the trip command to the DCCB is less than 4 ms.

As already mentioned, the proposed scheme must operate before the fault current arrives to flow through the freewheeling diodes of VSC. Fig. 11 shows the fault current with and without protection. This figure validates that the differential relay operates during the capacitor current discharging time and therefore, can provide a fast enough protection for MVDC feeders.

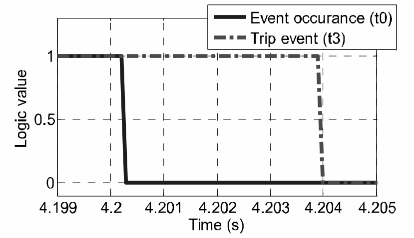

Fig. 10. Time delays of differential method.

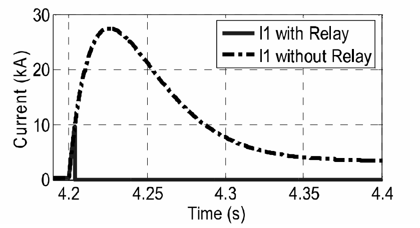

Fig. 11. DC Fault current.

Table III. DIFFERENT TYPE OF DC FAULTS DETECTED BY THE RELAYS

Case	Fault Name	Type	Fault Resistance	Operated Relay	Time delay(ms)
1	F1	PG	10	R1	3.3
2	F1	PP	50	R1	3.2
4	F2	PP	0	R2	3.5
5	F2	PG	100	R2	3.8
7	F3	PP	50	R3	3.6
8	F3	PG	0	R3	3.6
9	F4	PP	0	R3	3.6
10	F4	PG	0	R3	3.7

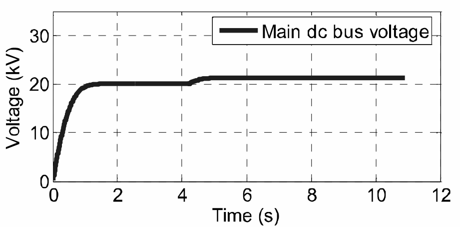

Fig. 12. Voltage of the Main DC bus (Bus0)

Table III summarize the results of other tests for different types of dc faults in the MVDC distribution system presented in Fig. 4. In these simulations the coordination of relays on feeder 2 was investigated, hence all the simulated faults are at this feeder. The table specifies the type of fault, the fault resistance and the operated relay. The last column represents the time delay [t0, t3] explained before. This table shows that the implemented relay can detect the different types of fault in an acceptable time and that it provides selectivity in addition to safety. Also, the voltage of the main dc bus (B0) is shown in Fig. 12. This figure illustrates that due to fast operation of protection, other feeders and loads, which are connected to this bus, can continue their operation without any effect from the faulty part. It means that selectivity was provided by using differential relays for MVDC system.

VI. CONCLUSIONS

In this paper, the HIL method is used to evaluate the operation of the differential method with Ethernet communication capability for protection of MVDC feeders. The results of this implementation show that the method is fast enough to guarantee the safety of the converters that supply the main dc bus and of the other important elements of the system. Also, in comparison to other methods which are based on blocking the converter, this method provides a selective protective and hence, increases the reliability of dc systems. This method is applicable not only for MVDC systems but also, is useful for LVDC systems and dc Microgrids. Application of this method for HVDC lines requires more investigation due to the high length of these lines.

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