A Communication-Assisted Protection for MVDC Distribution Systems with Distributed Generation

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Abstract— In this paper, a communication-assisted protection scheme is proposed for medium voltage dc (MVDC) distribution networks. MVDC grids are applicable for connection between microgrids, upgrading the transmission capacity of ac lines by the conversion to dc, and integration of renewable energy systems to the distribution grids. However, protection issues are one of the main challenges in the development of the VSC-based dc networks. Due to the special behavior of the dc fault currents, it is almost impossible to coordinate the overcurrent relays based on the time inverse grading. Hence, in the proposed scheme, to provide a fast and selective protection, each proposed relay communicates with two other relays to operate as the main protection for a dc feeder and the backup protection of the adjacent feeder. Hardware in the loop simulation approach by use of the OPAL-RT real time simulator is used to verify the performance of the proposed method.

Keywords— Communication-assisted protection, dc distribution systems, dc fault current, voltage source converters (VSC).

I. INTRODUCTION

Due to the advantages of the dc networks over the ac grids, and also because of the new developments in the technology of voltage source converters (VSCs), nowadays there is a major interest in dc grids in both research and industrial centers [1, 2]. Although using MVDC for commercial distribution systems still remains a research topic, it is predicted that MVDC can be a major part of future distribution systems [3]. Different applications are introduced for dc systems in the level of medium voltage [1, 3-6]; however, protection is one of the most important challenges in development of multi-terminal dc distribution networks. Protection issues mainly arise due to the especial behavior of fault current in VSC-based distribution grids. A simplified schematic diagram of a typical pole to pole (PP) fault, in a dc grid, is shown in Fig. 1. When a fault impacts the grid, the dc-link capacitor is discharged due to the voltage drop of the main dc bus. Then, the energy stored in the cable inductance also is discharged through the freewheeling diodes. On the other hand, subsequent to the fault occurrence, the control scheme of the converter turns off the main switches of the VSC (e.g. IGBTs) to protect them against the overcurrent; hence, the VSC operates as an uncontrolled full-bridge rectifier and the fault will be fed from the ac side of the VSC (through the freewheeling diodes paths) [7]. Therefore, dc fault current will have three different components, each with its special behaviors: *i*) the dc link capacitors discharge current (i_C), *ii*) the cable inductance discharge through the freewheeling diodes (i_L), and *iii*) the ac-grid current (i_{Grid}). These components are shown in Fig. 1.

According to the fault current behavior, the biggest challenges in the protection of VSC-based networks are:

- 1) The VSCs do not participate in the fault during the capacitor discharging period (starting from t_0 in Fig. 2), and hence initially they remain safe. However, further on, the fault current flows through the freewheeling diodes during two other components of dc fault current (starting from t_c). This current can quickly damage the freewheeling diodes [8]. Consequently, a system designed to protect the dc grids, should operate during the capacitor discharging component (before t_c) to prevent any damage to the converter [1]. It means that a relatively faster protection scheme is required for dc networks.
- 2) Due to the absence of the cable reactance, the raising rate of the dc fault current is very high [1]. Because of this very fast increment in the dc fault current, it is almost impossible to coordinate the conventional over current relays (OCRs) when used in dc networks. The analysis of the performance of the OCRs in dc networks showed in [7] illustrates that there is not enough time interval between the operation of series OCRs to guarantee their coordinated operation. Therefore, time inverse OCRs cannot provide a selective protection for dc grids.
- 3) AC circuit breakers (CBs) clear the fault during a zero crossing point of the current waveform, however there is no zero crossing point for dc currents. Moreover, the operation time of medium voltage CBs typically is around 60ms [9], whereas, dc fault currents must be interrupted much more faster in order to protect the VSCs. Thus, ac CBs are not applicable for the fault current breaking in dc grids.

The appropriate protection of the dc distribution networks must be designed considering the above mentioned notes. Besides, the necessity of a relatively faster protection scheme, prevent obtaining useful data for fault location from the voltage and current waveforms [7, 8]. This aspect also makes impossible the usage of fault detection methods with time consuming calculations. Communication-assisted protection schemes can provide a fast and selective protection without any complex and time consuming algorithm. The use of the differential-based method with a communication link between two sides of the dc feeder has been proposed in [7], [8]. In differential protection, since the values of the measured current in one side of the protected feeder must be transmitted to the other side, issues about data synchronization may cause some malfunctions. Furthermore, in the differential method, in order to obtain an accurate protection, the measured current must be transmitted continuously (maybe each 10 μ s in some cases); this can increase the value of the transmitted data and hence may

increase the time delay in the data transferring by communication links. In the proposed method the adjacent OCRs are connected via communication links. Each relay sends two signals to the other relays; one of them confirms that the fault is detected by the relay and the other one determines the fault current direction. The transmitted signals contain the binary codes and will be sent to the other side of the protected feeder when a fault was detected. The paper also introduces a central protection unit (CPU) to update the pickup current settings of the relays after any change in the DGs status or the network topology.

This paper is organized as follows: Section II describes the proposed protection scheme. The distribution system used as study case is introduced in Section III. In Section IV, the hardware in the loop (HIL) simulation approach is described and is used to evaluate the proposed method. Finally, the performance of the proposed protection is evaluated in Section V.

II. PROPOSED PROTECTION SCHEME

The proposed protection scheme is designed based on the data transferring between three adjacent relays, as shown in Fig. 3. Each proposed relay communicates with two other relays to operate as the main protection for a dc feeder and the backup protection of the adjacent feeder. In this way selectivity is achieved by data transferred between these relays. Fig 4. shows the algorithm of the proposed relay. Moreover, a central protection unit (CPU) is used to update the pickup current of the relays after any change in DGs status or network topology. The operation and components of the proposed strategy are described here.

Fig. 1. Components of the fault current in VSC-based dc networks.

Fig. 2. Typical fault current in VSC-based dc networks.

A. Communication-Assisted fault location

As stated in Section I, the conventional time-inverse OCRs cannot provide a selective protection for multi-terminal dc networks. Furthermore, coordination of the definite-time OCRs may results in a long fault-clearing time when the dc network consists of several series lines. Thus, in the propose method, the OCRs are coordinated according to the transferred data between the adjacent relays. In this method, to locate the fault position, the relay installed on each side of the dc feeders receives two signals from another relay installed on the other side. These signals are: *i*) the DET signal determines the fault detection by the relay and *ii*) the DIR signal which determines the direction of the fault current. The DET and DIR signals are binary codes as are shown in Table I. Each proposed relay has a main protective zone, for example Line 12 is the main zone of R1 in Fig. 3; and the relay operates instantaneously when a fault impacts this zone. Indeed, the main protection unit (MPU) of the proposed relay (e.g. R1 in Fig. 3) sends the trip signal when the relay installed on the other side of the feeder (e.g. R2 in Fig. 3) confirms that the fault has happened inside the main zone.

B. Backup protection for the adjacent relays

Conventional OCRs are non-unit relays which can operate as a backup for the adjacent relays. However, limiting the operation of the OCRs to the signals of the adjacent relay, as was done in part A, prevents the backup operation of these relays. In this case, the OCR operates as a unit protection with pre-determined borders. To enable the proposed relay to operate as a backup protection for the adjacent feeder, a backup unit was embedded into the proposed relay. The trip logic of the backup unit is shown in Fig.3. Here, a typical relay, e.g. R1, not only receives the signals from R2 to locate the faults in its main zone, but also receives the signals from R4 to operate as a backup for the protection of Bus2 and Line 12.

C. Central Protection Unit(CPU)

The operation of the OCR is according to the time-dial and the pickup current settings of the relay. In the proposed relay, the MPU operates instantaneously, whereas the backup unit sends the trip signal after a time interval (TM). Besides, the pickup current setting (I_p) is defined as the minimum value of the current at which the relay starts to operate and is chosen according to the largest flowing current through the protected element. Any change in the network topology may impacts on the direction and/or the magnitude of the current of distribution lines. Moreover, in the active distribution systems, which are networks that embed DGs, the connection or disconnection of the DGs, may also cause dramatic changes in the current of the feeders. Therefore, the protection of active networks must be able to adapt the pickup current of the relays according to the DGs status and the network topology. Hence, the CPU has been designed to analyze the operational conditions of the network and to re-calculate the pickup currents, after any change in the DGs status or the network topology.

Table I. Coding of the exchanged signals between neighboring relays

	1	0
Fault Detection (DET)	Fault detected	Normal Condition
Current Direction (DIR)	Inside: from bus to line	Outside: line to bus

Fig. 3. The structure of the communication-based protection

To achieve this goal, the CPU estimates the network topology by monitoring the status of the breakers. Furthermore, to recognize the status of the DGs, the CPU communicates with their local protection. The CPU collects the required information from the grid and determines the new pickup currents after any effective event. The new pickup settings are calculated by making use of the power flow equations in multi-terminal dc networks, as presented in [10]. To apply the new settings, the CPU also communicates with the proposed relays which are installed in both sides of each distribution feeder.

D. Fault clearance by use of the solid state dc breakers.

The external fault breaking devices are necessary to protect the VSCs against the dc fault currents [1]. References [11, 12] suggest to use the ac-side CB; however, ac-side CBs cannot interrupt the capacitor and cable discharge current which are the most serious parts of the dc fault currents. Moreover, as mentioned in Section I, ac CBs are not fast enough to prevent damage on the solid state switches of VSCs (diodes). The operation of the ac-side CBs also may impact negatively on the operation of the ac grid. Hence, in this paper we assume that the solid state dc CBs are installed on both sides of the dc feeders.

It should be underlined that the backup protection unit operates after a time margine. This time margine (TM), which is determined to guarantee the coordination between the main and the backup relays, is mainly related to the operational time of dc CBs. Solid state dc CBs are very fast devices and hence the TM can be set on 1ms. The solid state CBs are the only feasible breaking devices when the operation times faster than 1ms are required [13]. This TM also includes the delay of the measurement and interface devices, considering that the experimental results shown in [14] show that these delays are less than 10 μ s when Hall Effect current measurement are used.

III. STUDY CASE DISTRIBUTION NETWORK

The single line diagram of the distribution network used as a study case is shown in Fig. 5. The configuration and the parameters of this system are similar to the benchmark network presented in [15], however the system was re-designed to operate as a dc distribution network. This VSC-based dc grid includes: DGs which are interfaced to the grid through VSCs; 10kV dc feeders; and residential and industrial loads.

Fig. 4. Algorithm of the proposed method implemented on R1 of Fig. 3.

The dc-side capacitors of the main VSC station and DGs were calculated according to [16]. In the study system we assumed that DGs inject constant power when they are connected to the

grid (the intermittent behavior of the DGs is ignored); hence, only, the status of the dc CBs of DG1 and DG2 are reported to the CPU to update the relays setting. Moreover, there is a breaker coupler between busses 14 and 8. Since the operation of this coupler changes the topology of the system, the status of this dc CB is also reported to the CPU. Furthermore, all the feeders are equipped with the proposed relay which communicates with the CPU to receive the new pickup currents.

IV. HARDWARE IN THE LOOP VERIFICATION

To validate the proposed protection scheme in the context of the network presented in the previous section, Hardware-In-the-Loop (HIL) simulation approach was used. The HIL method was introduced to investigate errors and delays that do not appear in the classical off-line simulations [17]; therefore, in this paper HIL method is used to consider the main parts of the time delay related to the proposed method, i.e., delay in data transferred by communication. Fig. 6 shows the schematic diagram of the HIL setup. In this setup, the study system is simulated in a real-time digital simulator (OP5600 from OPAL-RT), whereas the proposed trip algorithm is implemented on a development board (DK60 from Beko). In this manner DK60 operates as one of the relays of the study network. The OPAL-RT is also connected to the DK60 board through the Ethernet port. More details about the components of this setup are introduced in the previous work of the authors in [18].

In this test, since the components of the setup are close together, the delay of the data propagation between the sending and receiving nodes is not considered. However, this part of time delay which is related to the length of the feeder and transmission rate of the communication media, is less than 0.1ms for typical distribution feeders according to [19].

Fig. 6. Schematic diagram of HIL test-bed.

V. CASE STUDIES

The main objective of the following case studies is to demonstrate the performance of the proposed method for various type of faults in the proposed dc distribution network. In all the following cases, it is assumed that a fault occurs at $t=1$ s.

Case Study 1: Occurrence of a PP fault.

Assuming the occurrence of a PP fault in point F1 of Fig. 5, R34 detects the fault in its main zone, by use of DET and DIR signals of R43; and sends the trip signal to CB34. As shown in Fig. 7, the trip signal arrives to CB34 around 2.5ms after the fault occurrence. Simultaneously, R2 which is the backup relay of R34 detects the fault, however it will send the trip signal if the fault current is not interrupted before the TM. R2 will reset when CB34 interrupts the fault current. Furthermore, Fig. 8 illustrates that the trip signal is generated before the participation of the main converter on the fault feeding (it works during the capacitor discharge stage); and hence the proposed protection is fast enough to prevent the damage on the converters.

Case Study 2: occurrence of High Impedance Faults (HIF).

In the second test we assumed that a pole to ground (PG) fault occurs in F1 and the fault resistance is 100Ω . Fig. 9 illustrates that R34 locates the fault and sends the trip command after around 5.5ms. It should be noticed that although this time delay is relatively larger than the previous case, the operation of the proposed method still is fast enough to protect the VSCs. Indeed, the fault resistance reduces the raising rate of the fault current, and increases the capacitor discharge period. Hence, the proposed method also has acceptable performance for HIF detection.

Case Study 3: backup operation of the proposed relay.

For the final study case we assumed that R45 fails to detect/locate a PP fault on F2. In this case, R34 operates as a backup for this relay and sends the trip signal after 3.8ms. Fig. 10 shows the fault current for this case. It is worth noting that R34 must be able to operate as a backup for R45 and R411; thus, the backup unit of R34 communicates with R54 and R114.

Fig. 5. Study case dc distribution network.

Fig. 7. Fault detection signal of the proposed method.

Fig. 8. DC fault currents and trip signal of the main protection.

Fig. 9. DC fault currents and trip signal of the main relay.

Fig. 10. DC fault currents and trip signal of the main protection.

VI. CONCLUSIONS

In this paper, a communication-assisted protection is proposed for MVDC distribution systems. The use of communication links between the adjacent relays, enables them to detect the faulty feeder and hence, provide a selective protection. The proposed method also is stable when DGs are connected or disconnected. The HIL simulation results show that, by use of the dc CBs, the

proposed scheme is fast enough to break the fault current during the capacitor discharge period. This, guarantee the safety of VSCs that supply the dc buses and of the other important elements of the system. This method is applicable not only for MVDC systems but also, is useful for LVDC systems and dc microgrids.

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