Design of a Centralized Protection Technique for Medium Voltage DC Microgrids

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Keywords

Fault handling strategy, smart microgrids, distribution of electrical energy, differential protection.

Abstract

This paper presents a communication-assisted protection technique for dc microgrids. The technique, consist of a centralized fault detection, by use of the differential method; and a fault isolation strategy by coordinated operation of dc breakers and isolator switches. Hardware in the loop simulation is used to evaluate the proposed protection.

Introduction

Due to the increasing penetration of distributed generation (DGs) units, especially renewable energy systems (RES), the concept of the microgrid has been proposed as a method of DG integration to electrical grids. Microgrid is a common concept between ac and dc system; and is defined as a small-scale low/medium voltage grid consist of loads and DGs which is capable to operate in islanded or grid-connected modes [1]. On the other hand, some types of RESs provide dc power and interface with the ac networks through power electronic converters; whereas, the other types of RESs provide ac power and use two power conversion stages: ac to dc and dc to ac. From this perspective, using the dc grids can reduce the number of power conversion stages [2], and consequently reduce the cost and losses of the grid. DC grids also have several advantages over the ac grids, such as: the absence of the skin effect, reactive voltage drop and capacitive current; the possibility to connect between two asynchronous ac systems; and manipulate the power flow in a very short time [3-5]. Therefore, there is a major interest in dc microgrids in the research and industrial centers.

Protection is one of the main issues in the widespread usage of the dc microgrids; this is mainly due to the special behavior of fault current in dc grids [6-9]. Indeed, because of the very fast increment in the dc fault current it is almost impossible to coordinate the conventional over current relays (OCRs) when they are used in the dc networks [2]; this will be explained more in Section II.

Versus the conventional protections, communication-assisted methods can provide a fast and selective protection without using any complex algorithm. By use of communication links, the differential method can be implemented in dc feeders. The differential protection is able to detect the exact faulty part of the dc network, considering the high rising rate of the dc fault current [10]. Furthermore, this method is more sensitive than OCRs and is able to detect the high impedance faults (HIFs) [1]. The use of the communication-based protection methods increase the costs of the protection system, however with development of smart-grids, the available communication infrastructures can be used also for protection requirements.

On the other hand, dc fault currents do not cross a zero point and hence, ac circuit breakers are not capable to interrupt them [11]. The use of ac-side breakers has been suggested in [12, 13], however, these breakers are not fast enough to prevent the damage on voltage source converters (VSCs). Besides, dc circuit breakers (DCCBs) in the level of medium voltage are more expensive rather than their ac counterpart breakers; therefore, it is not economic to use the individual DCCBs for all the dc feeders.

Based on the above mentioned specifications of the dc microgrids, a communication-assisted protection technique is proposed in this paper. The proposed protection consist of: 1) a centralized fault detection (CFL) unit, which is designed to detect/locate the dc faults; 2) the individual OCRs in the connection point of DGs; 3) hybrid DCCBs installed in the connection points of the microgrid with the host network and DGs, to interrupt the fault current; and 4) dc isolator switches to separate the fault. The proposed technique provides a selective protection with the minimum number of DCCBs. Moreover, the Hardware-In-the Loop (HIL) approach is used to evaluate the performance of the proposed protection technique. HIL method is used to consider errors and delays that do not appear in off-line simulation, such as time delay in data transferring.

The main objective of this paper are: 1) design of an effective and economic fault interruption/isolation strategy; 2) propose a selective protection with capability of high impedance fault (HIF) detection; and 3) evaluate the proposed method by use of HIL approach, considering the delay in data transferring by communication.

The paper is organized as follows: Section II describes the behavior of the dc fault current and the specification of the protection in dc networks. The proposed protection is explained in Section III. The HIL setup will be introduced in Section IV. Section V introduces the study microgrid. Finally, in Section VI the performance of the technique is illustrated for some case studies.

Specification of The DC Grids Protection

When a fault occurs in the VSC-based dc grids, the dc-link capacitor is discharged due to the voltage drop of the dc bus. Following the dc-link capacitor discharged, the energy stored in the cable inductances is discharged through the freewheeling diode. On the other hand, subsequent to the fault occurrence, the control scheme of the converter turns off the VSC switches (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 (through the freewheeling diodes paths). Therefore, the dc fault current have three different components with the especial behaviors [4, 14], that are: *i*) the dc link capacitors discharging current, *ii*) the cable inductance discharge through freewheeling diodes, and *iii*) the grid current. Converters do not contribute in the fault during the capacitor discharging period, and remains safe; whereas, the fault current flows through freewheeling diodes during two other components of dc faults. Therefore, the protection schemes of the VSC-based dc microgrids have to be designed considering the following notes:

1) The adequate protection of the dc microgrids should be able to operate during the capacitor discharging period; this is necessary to prevent any damage to the converter components (especially freewheeling diodes). It means that a relatively much faster protection is required for dc networks.
2) The raising rate of the dc fault current is very high due to the absence of the cable reactance [4]. Therefore, it is almost impossible to coordinate the conventional OCRs when they are used in the dc grids [2]. Indeed the OCRs cannot provide a selective protection for the dc microgrids.

Proposed Protection Technique

Protection systems must be able to detect/locate the various types of faults, interrupt the fault current and isolate the faulty part before serious damages on the vital devices. Thus, the proposed protection strategy equipped by a CFL unit, which is able to detect the exact fault location by use of the communication links. The CFL is installed on the point of common coupling (PCC) of the microgrid.

On the other hand, fault isolation is achieved by the coordinated operation of DCCBs and isolator switches. The main parts of the technique are:

DC breakers. Due to the specification of DCCBs, they are relatively more expensive than the counterpart ac breakers. Thus, in this paper, to provide an economic protection strategy, DCCBs are installed only on the connection point of microgrid to the host network, i.e. (PCC), and of DGs to the microgrid. On the other hand, although solid state CBs (SSCBs) are the fastest types of DCCBs, they are expensive devices and increase the initial costs of the protection system. Therefore, hybrid DCCB is used as the fault interruption devices of the proposed strategy. A hybrid DCCB has introduced by ABB which is able to interrupt the fault current in 5ms [15].

Isolator switches. To separate the faulty part, dc isolator switches are installed on the both sides of the dc feeders/busbars. Isolator switches are cheaper than DCCBs; however they must be opened/closed only in the no-load condition. Therefore, they are able to isolate the faulty part, when the fault current was interrupted by DCCBs. AC breakers can be applicable as isolator switches. The typical medium voltage ac breakers operate in around 60ms [16].

Instantaneous OCRs. Fault current will be supplied by the host grid and DGs which are located inside the microgrid. Therefore, fast fault detection can be achieved by monitoring of currents in the connection point of the microgrid with the host network and DGs. For this reason, in the proposed strategy, the instantaneous OCRs are installed on these points. Indeed, OCRs are installed where DCCBs are placed. As mentioned before, the first part of the fault current is due to the discharge of the dc-link capacitors. This current increases very fast; hence, the OCRs can detect the fault after several microseconds.

Central current differential unit. The OCRs installed on the connection points can detect the fault; however they are not able to locate the exact location of the fault. For this reason, current-differential method is used to locate the faulty part of the microgrid, and to facilitate the restoration of the sound parts of the microgrid. To achieve this goal, a centralized fault location (CFL) unit equipped by a differential-based protection (Diff), is located on the PCC. The Diff, in turn, consists of several current differential elements; each of them protects a feeder/bus of the microgrid, as shown in Fig. 1. To detect/locate a fault by the differential protection, the measured current in both sides of all the dc feeders are transmitted to the Diff by the communication media.

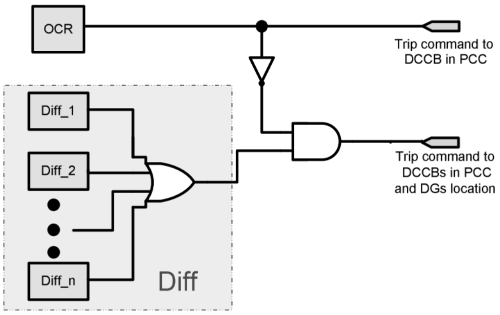

Fig. 1. The trip command generated by CFL.

It is notable that although OCRs offer fast fault detection in the case of solid faults, the HIF detection is one of the main challenges in the performance of this type of relays. Differential relays are more sensitive than OCRs and typically present a better performance for HIF detection. On the other hand, the pickup current of the OCR unit of the CFL will be set according to the nominal current of the PCC ($I_{OCR} = (1.2) * I_{PCC}$) which is more than the nominal current of dc feeders, whereas the pickup settings of the differential elements of Diff are set related to the nominal current of each protected feeder (for example, for a typical feeder named L1: $I_{Diff1} = 0.1 * I_{L1}$). A comparison of the pickup currents in OCR and Diff units shows that the probability of HIF detection by Diff is dramatically more than the OCR. Therefore, Diff is used not only to locate the faulty part, but also to detect the HIFs. Fig. 2 shows the algorithm of the fault detection in the CFL; when the OCR detects a fault, the trip command is sent to the DCCB of PCC. Moreover, in the case of HIF occurrence; i.e. when the

OCR cannot detect the fault (and fault is detected by Diff), the trip command is sent to all the DCCBs (CB of PCC and DGs). This remote command is due to this fact that the local protection of DGs is not adequate for the HIF detection. Indeed, when a HIF is detected by the CFL, the trip signal is sent to DGs connection points, too.

By use of the above mentioned protection devices/methods, the proposed strategy in implemented by the following steps:

1. Fault detection by the OCRs which are installed in the PCC and the connection point of DGs.
2. Trip the DCCB of PCC and disconnect the DGs by trip command of the local OCRs (in the case of HIF detection, the CFL sends the trip command to all the DCCBs).
3. Detect the fault location by Diff unit of CFL and send the open command to the dc isolator switches.
4. Monitor the status of the dc isolators to be sure that the switches in both sides of the faulty line are opened.
5. Re-close the DCCBs and re-energize the sound parts of the microgrid.

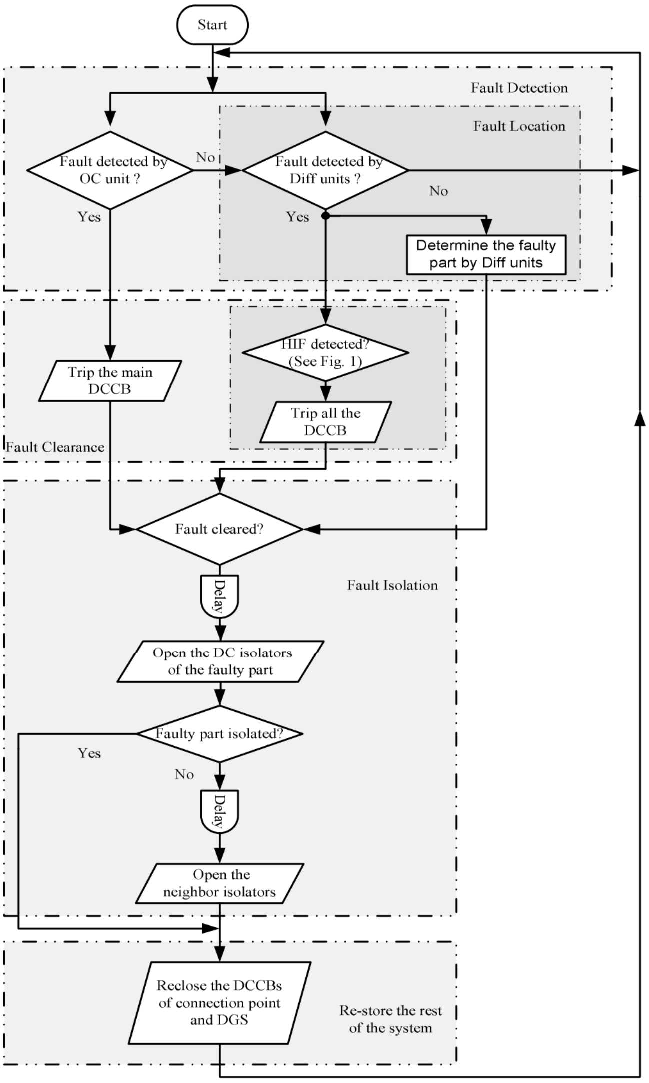

Fig. 2. The proposed algorithm implemented in CFL.

Fig. 3 shows the operation sequence of the protection devices based on the proposed strategy. During t0 to t1 OCRs detect the fault and send the trip command to the corresponding DCCBs. As mentioned in Section II, the OCR can detect the fault after several microseconds. Then, the DCCBs interrupt the fault current at t2. The time interval between (t1- t2) is related to the operational time of DCCBs which is around 5ms [15]. Moreover, during (t0-t3) the Diff unit of CFL detects the faulty part and sends the open command to the corresponding dc isolators at t4, when the fault current interrupted. The time interval between t3 and t4 is according to the required time to monitor the status of the dc isolators and to be sure that they are opened. The fault will be isolated at t5; assuming to use ac CBs as the isolator switches, the time interval between t4 to t5 is around 60ms[17]. When the faulty part was isolated, the DCCBs will receive the close command after a time margin (TM) and re-energize the rest of the microgrid at t7. This time margin (t5-t6) is defined to guarantee the isolation of the faulty section before re-energizing the sound parts.

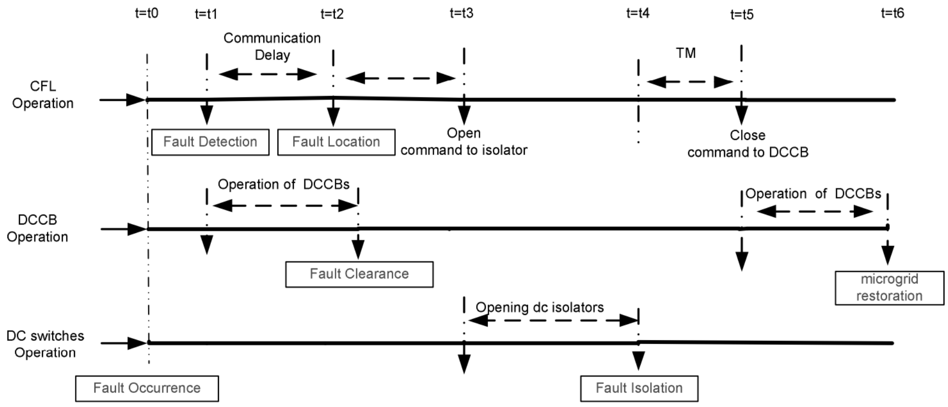

Fig. 3. The time sequence of the proposed strategy.

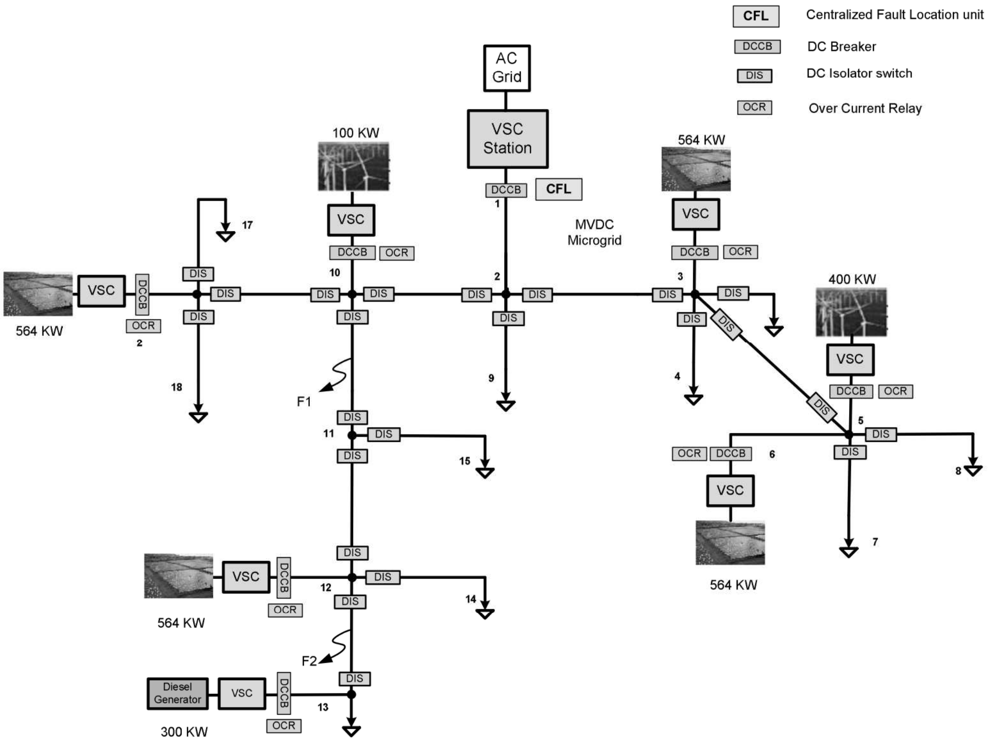

Fig. 4. Study dc microgid.

HIL Verification

In order to evaluate the proposed protection schemes, the Hardware-In-the Loop (HIL) simulation approach is used. HIL method is used to consider errors and delays that do not appear in off-line simulation, such as the time delay in the data transferring. Fig. 5 shows the structure and the general parts of the HIL test-bed setup. This setup consist of 1) OPAL-RT that simulate the distribution system of Fig. 4; 2) a PC as command station (programming host) that is used to run the Matlab/Simulink model that will be executed on the OPAL-RT; 3) a development board (DK60) that is used to implement the proposed protection algorithm, and 4) a router that is used to connect all the setup devices in the same sub-network.

In this test-bed, the OP5600 HIL box from OPAL is used as real time (RT) simulator which running the simulations with a multi-processor configuration to provide fast computation. An FPGA controller is used inside the OPAT-RT to connect the PCI bus of the processors to the digital and analogue inputs/outputs. Moreover, the board of this simulator is equipped with multiple analog and digital inputs/outputs for connecting to different hardware and provides a powerful tool for HIL testing.

To develop the real-time applications for the OPAL-RT, the RT-LAB software is used. This software is fully integrated with Matlab/Simulink. RT-LAB processes the Matlab/Simulink models, convert them to C-codes and finally upload the converted model to the OPAL-RT. Moreover, it 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).

The OPAL-RT is connected to the DK60 board through Ethernet port. The DK60 board provides communication capabilities through various ports and protocols, including Ethernet, SPI, and CAN. For the processor running on the board, an IEC61850 stack implementation is available from SystemCORP that provides functionalities for all the three communication messages (MMS, GOOSE, and SV) of the IEC61850 protocol. This makes possible the development of custom applications using the IEC61850 communication protocol. This board embed an application developed in C++ and involved the implementation of the relay's algorithm. During the experiment tests, messages are being exchanged between the OPAL-RT, and the DK60, running the CFL application.

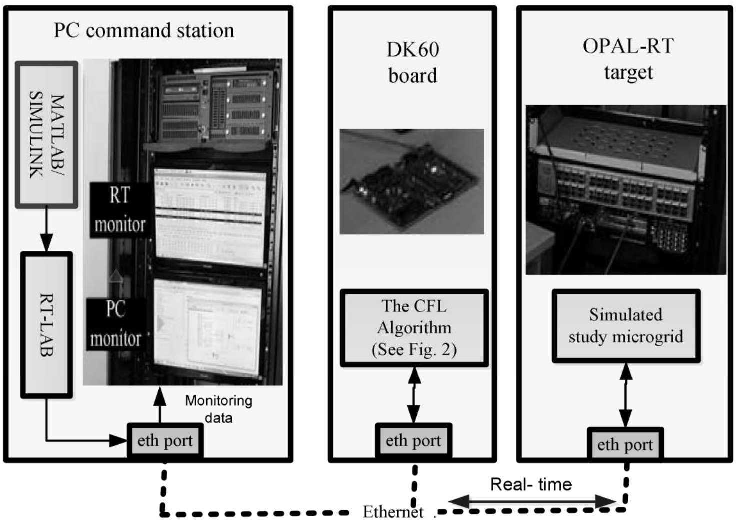

Fig. 5. The schematic diagram of HIL setup.

Study Microgrid

The performance of the proposed protection technique is explained and evaluated, for a set of case studies in the context of the distribution network of Fig. 4. The basic configuration and parameters of this network is extracted from the benchmark proposed in [18] and re-designed to operate as a dc microgrid. The network is a VSC-based dc system; consist of: DGs which are interfaced to the grid through VSCs; residential/industrial loads; and the dc feeders. The two-level ±10-kV VSCs are used to interface the AC network and RESs to the DC network. Hall-Effect current transducers (CTs) installed on both ends of the DC lines. The data transfer amongst the DC buses and CFL is made possible via dedicated communication links.

Case Studies and HIL results

The performance of the proposed technique is studied for various operational condition of the study microgrid.

Case Study 1: occurrence a pole to pole fault in point F1.

In the first case study assumed that at t = 1 s a solid pole to pole (PP) fault impacts the microgrid at point F1, as shown in Fig. 4. The operational time of the various parts of the proposed protection technique is shown in Fig.6. This test illustrates that the proposed protection is able to isolate the faulty part and re-store the sound parts of the microgrid in around 100ms.

It is worth noting that, the time delay on communication can be categorized to: i) required time to data preparing in the sending node, i.e. from the moment that measured current enter to the node to the moment that leave it; ii) required time for data propagation from the sending node to the receiving node; and iii) required time for opening the receiving data package in the destination node. In the first and the third categories, the required time of data packing/opening is taken into the account. On the other hand, the delay on data propagation between two nodes, second category, is related to distance between two nodes and also transmitting rate. Assuming the transmission rate based on the speed of the light, this time delay is less than 0.1ms when the distance between two nodes is less than 30 km [1]; this is acceptable almost for all the typical distribution feeders. This part of time delay, which is much less than the other parts, is ignored in this work.

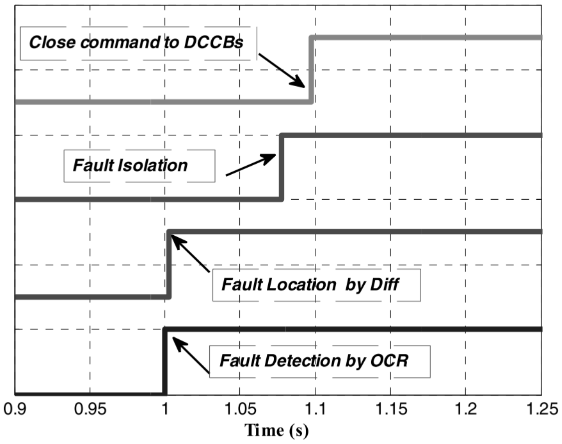

Fig. 6. The main operation instances of the proposed technique.

Case Study 1: occurrence a high-impedance pole to ground fault in point F2.

In this assume that a high-impedance fault occurs at point F2. In this case, due to the fault impedance as well as fault location (which is far from the main source), the fault current has a limited increment and hence the OCR, located at the VSC station and busses 2,6 can not detect the fault. However, the differential units located at the CFL detect the fault due to their lower threshold and more accuracy. In this case, the CFL sends the tip command to all the DCCBs. The rest of the process is similar to the previous case. Fig. 7 shows the instants of the important operations of the proposed protection scheme.

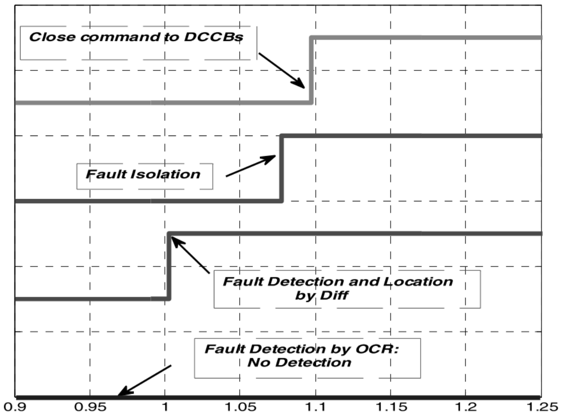

Fig. 7. The main operation instances of the proposed technique.

Conclusions

In this paper, a communication-assisted protection technique consists of a fault location method and a fault clearance strategy is proposed for dc microgrids. The use of communication links between the current measurement devices and CFL, results in providing a selective protection. HIL results will be shown and analyzed in the final version of the paper, however the first case study illustrates that the proposed method is able to re-store the sound parts of the microgrid after around 100ms.

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