Smart protection system for identification and localisation of faults in multi-terminal DC microgrid

Rajeev Kumar Chauhan1, Kalpana Chauhan2

1Department of Electrical Engineering, Dayalbagh Educational Institute, Agra, UP 282005, India
2Department of Electrical Engineering, Central University of Haryana, Mahendargarh, Haryana 123031, India
E-mail: rajeevchr_nitj@yahoo.com

Abstract: DC microgrid provides the horizontal infrastructures to integrate distributed generation (DG) and loads. Unlike traditional AC systems, DC systems cannot survive or sustain high magnitude fault currents. It makes locating faults very difficult. The conventional protection techniques completely de-energises the DC link in the DC microgrid. A new protection scheme for multi-terminal DC microgrid against line-to-line fault and the low resistance earth fault is presented in this study. The scheme isolates the faulted section from the DC microgrid. Healthy sections are operated without any disturbance and supply continuity is maintained in a ring main DC bus system. The current sensors are mounted at DC bus segments to monitor the entering and outgoing current at different nodes. Further, the current sensors are also mounted at both ends of service mains to monitor their current difference at both ends of the service mains. The controller detects this current difference and opens circuit breakers. To meet the requirement of fast interrupting time and high short-circuit current withstand capability, insulated-gate bipolar transistors used as circuit breakers. The fault location scheme gives the fault location in various sections (service mains) and faults resistance in the microgrid. The proposed concepts have been verified by computer simulation.

1 Introduction

A healthy and well-functioned protection system is required for reliable and proper operation of a DC microgrid. At starting the protection schemes applied on high-power DC systems [1]. These systems are protected with rectifiers connected to the grid. During the DC fault, these rectifiers can limit the over-current [2]. Different protection schemes for DC systems have been found in literature, like finding short-circuit current with static source [3]. There is a module impedance-based fault detection for the DC power system, and the overcurrent protection on voltage source converter for the multi-terminal DC system [4, 5]. There is almost no analysis done for the protection devices for DC systems. Most of the protection devices are designed and tested for the high-voltage direct current (HVDC) systems [6]. There are no standards available for low-voltage direct current (LVDC) system protection [7].

The protection schemes available for LVDC lead the complete shutdown of the DC bus [8]. Besides many advantages of DC microgrid over the AC grid, the protection of DC microgrids face many challenges [9, 10]. Generally, the protection devices for LVDC systems are fuses and circuit breakers (CBs) [11]. These devices are specially designed for the LVDC system, but some can be utilised in AC systems also [12]. The protection for ring bus is discussed, but the diagnosis and protection of load, distributed generation (DG), and service main are not covered in the previous protection scheme [13–15]. However, a significant influence has been noticed during a fault in DG, as discussed in [16]. The main objective of the study finds the DG system performance during a fault. When the fault occurred at DG or load or service mains of the DC microgrid, then the complete section of the DC bus has to be isolated. Knowledge of the existing DC power system can play an important role in designing of an LVDC microgrid protection system. Most of them have a grid-connected rectifier with current-limiting capability at the time of DC faults. Therefore, a different protection scheme is to be required for an LVDC microgrid connected to an AC grid.

There are some adaptive fault detection and identification methods which are based on voltage derivative methods [17]. A communication less scheme based on the rate of change in the current-to-voltage ratio to identify the fault in the DC busbar is discussed in [18, 19]. A differential current based technique for fault detection and their isolation in multi-terminal DC microgrid, including DGs like photovoltaic, has been discussed in [20, 21]. Some DC microgrid protection schemes useful just for the isolated area supplied through a distributed generator or just for the DC bus [22–24]. In an earlier version of this research, a protection scheme was proposed with the four-node DC microgrid, consisting of two distributed generators and two homes [25]. The distributed generators and loads (homes) are connected to the DC ring bus at an individual node. The proposed approach is the advancement of [25], as it adopts knowledge of the DC power system and protects the DC bus included with DG, load, and service mains of the DC microgrid. A ring main DC microgrid is considered to explain the proposed protection scheme. There are four load clusters, two DGs and one battery bank (BB) connected to the DC bus via DC–DC converters. Each load cluster has five homes that are connected to the DC bus via cluster service mains. Unlike previous protection schemes, the DC microgrid is guarded at every zone with the proposed protection scheme. The CBs are mounted on generation, ring bus and load. The diagnoses of fault and opening–closing of the CBs is fully automatically. The proposed scheme is doing both the tasks; the fault detection and localisation in the DC microgrid. The goals of the proposed scheme are to detect the fault in the bus segment, service mains of DG and load using nodal analysis (NA) and current differential (CD) scheme and then isolate the faulted section without an outage of the entire system. The proposed scheme can detect the fault of low resistance as well as the fault of high resistance. The proposed scheme also detects the location of the fault. To achieve these goals, the proposed technique is tested in the ring main DC bus-based microgrid in this paper.

2 Materials and methods

A well design protection system is necessary to ensure the reliable operation of the DC microgrid. The layout of the DC microgrid is shown in Fig. 1. The DG and clusters of load are interfaced with...
The complete DC microgrid is divided into three fault zones: DG fault zone, load fault zone and bus fault zone. If the fault occurs in the DGs or service mains (the cable used to connect the DG and DC bus is called service main) of DGs as shown in Fig. 2a, then the fault comes under the DG fault zone. When a fault occurs at load end or service mains of the load, as shown in Fig. 2b, it comes under the load fault zone. When a fault occurs at the DC bus, as shown in Fig. 2c, then it belongs to the bus fault zone. The fault may be a short circuit or an earth fault. The short-circuit fault occurs when a path is formed between positive and neutral or negative and neutral or positive and negative poles. The earth fault occurs when the path is formed between positive or negative polarity conductor and the ground is created. The fault current direction for the different faults at a different location with the LFR is shown in Fig. 2.

The sensors monitor and retrieve the currents of every node at the controller end. While the controller executive the control algorithm and creates the control action to operate (open or close), the CBs connected with the respective node. The current flowing through the assigned CBs is monitored by respective current sensors for fault detection. The current measured by the current sensors of the node will be used for fault detection with the respective node controller. The goal of the proposed protection system is to detect the abnormal current in the bus segment, service main of the DGs and homes and isolate the faulted section from the healthy microgrid instantly. For example, a fault F1 occurs (Fig. 1), the current sensors CS_{81} and CS_{12} will retrieve high current at the control room, while the current sensor CS_{1} retrieves the decrease load current of the Cluster-2. The supervisory control and data acquisition (SCADA) runs the NA at node N_{1} and finds that the algebraic sum of entering currents (ECs) i_{k1} and i_{k2} is higher than the outgoing current (OC) i_{c1}. The SCADA detects that the low resistance fault (LRF) occurs at node N_{1} and sends control action to open the CBs CB_{81}, CB_{12} and CB_{1}.

2.1 Possible fault zones and faults

The fault currents for the different cases are shown in Fig. 2. When the fault occurs in the segment, the fault current (i_{f}) is the algebraic sum of the line segment current (i_{ls}) and load/generator current (i_{lg}). The fault current can be expressed as

\[ i_{f} = i_{ls} \pm i_{lg} \]  

The fault current is the function of the fault location and fault resistance. If the impedance of the fault path is low (e.g. the line-to-ground fault with the solid ground), the polarity at the receiving end could be reversed [13], preventing the load from being supported at all.

If the fault resistance (r_{f}) is too high, then the fault current \( i_{f} \) will be very small and can be neglected. In this case, the line segment current can be expressed as

\[ i_{ls} \approx i_{f} \]  

If the fault resistance (r_{f}) is too low, then the fault current \( i_{f} \) will be very small and can be neglected. In this case, the line segment current can be expressed as

\[ i_{ls} \approx i_{f} \]
The fault current from the power source and bus capacitor can be expressed as

\[ i_k = \frac{E}{R} \left( 1 - e^{-\frac{R}{L} t} \right) + \frac{E}{R} \left( 1 - e^{-\frac{R}{L} t} \right) \]

where \( E \) is the DC bus voltage, \( R_{eq} \) and \( L_{eq} \) are, respectively, the equivalent resistance and inductance including with source, line and ground component and \( R_C \) and \( C_{eq} \) are the equivalent series resistance and capacitance of the bus capacitors, respectively.

### 2.3 Fault protection algorithm

The fault protection scheme for the DC microgrid protection is based on the NAOC and the CD. The NAOC is used to detect the fault in the segments of the bus. The conceptual diagram of the NAOC is shown in Fig. 3. The CD approach is used to detect the service mains. The conceptual diagram is shown in Fig. 4. The control algorithm of the proposed protection scheme for DC microgrid is shown in Fig. 5.

The current in each segment of the DC bus and the service main of power source is monitored by connecting current sensors of the segment and service main, which is retrieved at the control room. The NAOC controller executes the NAOC approach for the nodes of the DC bus and creates the control action to ‘open’ the respective CBs in case of any fault current and isolate it from the healthy DC microgrid.

For example, at node \( N_2 \), the current sensors \( CS_{23} \) and \( CS_{12} \) retrieve the currents \( i_{23} \) and \( i_{12} \) of the segment-23 and segment-12, respectively, while the cluster current \( i_N \) of the cluster-2 is monitored and retrieved by the current sensor \( CS_2 \). The NAOC controller executes the NA scheme for the signal values received from their connected current sensors for particular location and check the sum of EC and OC for the node \( N_2 \). For example, the cluster-2 current \( i_N \) is the OC for node \( N_2 \), while the segment-23 current \( i_{23} \) and segment-12 current \( i_{12} \) are the ECs for node \( N_2 \). The addition of ECs \( (i_{23}, i_{12}) \), greater than the OCS, validates that the fault has occurred at node \( N_2 \). The NAOC controller creates a control action to open the CBs \( CB_{23} \) and \( CB_{12} \) and isolate the node \( N_2 \).

The sum of the ECs \( (i_{23}, i_{12}) \) equal to the OC \( i_N \) and the overcurrent is flowing in the service main of the cluster-2. It shows that the fault occurred in the cluster-2 at the node \( N_2 \) or in the service main of one or more homes in the cluster-2. The NAOC controller run the NA algorithm for the nodes \( N_2 \) of cluster-2. The EC \( i_N \) is equal to the algebraic sum of OCs \( (i_{231}, i_{232}, i_{231}, i_{231}, i_{231}) \) of the Home-1 to Home-5, respectively, in Cluster-2. It verifies that the fault occurs in the service mains of the home. To find out the faulty service mains, the CD protection scheme is used. The conceptual diagram of the CD scheme is shown in Fig. 4. The input current of the service main should be equal to the output current (home load current).

For example, the service main of Home-3 in Cluster-2, in the normal conditions, the input current \( (i_{233}) \) and output current \( (i_{233}) \) remain equal. As the fault F3 occurred, the EC \( (i_{233}) \) is divided into two parts; the first one is the fault current \( (i_{233}) \) and the second one is Home-3 load current. The fault current depends on the fault resistance. So the current sensors \( CS_{231} \) and \( CS_{232} \) monitor the different values of the current in the fault condition and retrieve it in the control room. While the current sensors mounted on the service mains of Home-1, Home-2, Home-4 and Home-5 monitor and retrieved the same amount of input and output currents. The CD controller creates the control action to open the CB \( CB_{23} \) of faulty service main and isolate the service mains of Home-3 from the DC microgrid.

After localising the faulted section controller check weather, there is the current flowing in the faulted segment, and if so, it means there are any CB remains in their closed state and that has to be open. Therefore, the controller sends the control signal to turn ‘open’ the CBs of the faulted section; these are connected to the faulted section to the live DC microgrid. The DC voltage source is connected to the faulted section to find out the fault distance and fault resistance. As the fault repaired, the controller connects the faulted section with the voltage source to ‘charge the line’ in a no-load condition. As the line holds, it shows that the fault is clear. Therefore, the controller creates the control action to close the CBs to connect the isolated (faulty) section to the healthy DC microgrid.

### 2.4 Fault location and fault resistance

The conductor resistance is the ratio of the voltage applied across the conductor to the current passing through the conductor. The resistance measurement-based scheme is used to find the fault location and their resistance. The schematic layout of the proposed
scheme is shown in Fig. 6. The DC voltage source (V volt) is connected to the sending end terminal of the faulted section of the line to measure the equivalent resistance (\( R_{N1} \)) of the faulty line from the sending end side. The \( R_{N1} \) is the combination of the line resistance (\( R_l \)) and the fault resistance (\( R_f \)), as shown in Fig. 6a and can be expressed as

\[
\frac{V}{I_1} = R_{N1} = R_l + R_f
\]  

(5)

Also, the \( R_{N2} \) is the equivalent resistance of the faulted section of the line from the receiving end side. The DC voltage source (V volt) connects to the receiving end of the faulted section of the line to measure the circuit equivalent (\( R_{N2} \)) of the faulted section of the line from the receiving end side. The \( R_{N2} \) is the combination of the line resistance (\( R_2 \)) and fault resistance (\( R_f \)). The \( R_{N2} \) can be expressed as

\[
\frac{V}{I_2} = R_{N2} = R_2 + R_f
\]  

(6)

The line resistance (\( R_l \)) between the input ports to the output end can be obtained from (5) and (6) and can be expressed as

\[
R_l = \frac{R_{N1} - R_{N2} + R_f}{2}
\]  

(7)

The line resistance (\( R \)) of the fault section can be expressed as

\[
R = IR_{ul}
\]  

(8)

where \( R_{ul} \) is the resistance of the unit length of the line, \( l \) is the length of the line.

The fault location (\( \lambda \)) from the sending end of the line can be calculated as

\[
\lambda = \frac{R_l}{R_{ul}}
\]  

(9)

The fault resistance (\( R_f \)) can be obtained after solving (5) and (7) and can be expressed as

\[
R_f = \frac{R_{N1} + R_{N2} - R}{2}
\]  

(10)

3 Simulated results

The performance test of the proposed protection scheme for the DC microgrid, as shown in Fig. 1, is done with MATLAB simulations. The simulation of this paper is performed using a personal computer based on Intel®, Core™ i5-3320M CPU 2.6 GHz, 4 GB RAM with Microsoft Windows 7 Professional Edition 64-bit operating system. The microgrid consists of four clusters, two distributed generators DG-1 and DG-2, and one BB. The PCC for the cluster, sources with DC bus are considered as nodes. The faults F1, F2 and F3, are considered at the bus, service main of DG-1 and service main of Home-3, respectively, as shown in Fig. 1, to demonstrate the proposed fault detection scheme in the DC microgrid. The simulation parameters can be found in Table 1.

The length of the DC bus segments (distance between nodes), service mains of the power sources, homes and BB can be found in Table 2.

The current injection \( I_{in1} \) and \( I_{in2} \) (measured by current sensors CS1 and CS2) to DC bus by distributed generators DG-1 and DG-2, respectively, are shown in the subplot of Figs. 7a and b. The BB current (\( I_{bb} \)) sharing with the DC bus is measured by current sensor CS3 and shown in the subplot of Fig. 7c. The DC bus power is balanced by both the DGs and BB during normal conditions, i.e. no fault at the power source. In normal conditions, the current follows the Kirchhoff’s current law (KCL) at each node and satisfies the following equation:

\[
\sum I_{in} + \sum I_{out} = 0
\]  

(11)

3.1 Fault at DC bus (fault F1)

The current sensors CS12 and CS81 are mounted on segment-12 (\( I_{12} \)) and segment-81 (\( I_{81} \)) to monitor their current at a different time instant. The cluster-1 is the load for node \( N_1 \). The cluster current (\( I_{C1} \)) is measured by the current sensor CS1. At time instant

![Fig. 6 Conceptual layout for the fault location and their resistance](image)

(a) Faulty segment resistance measurement from the sending end, (b) Faulty segment resistance measurement from the receiving end

| Table 1 Simulation parameters |
|------------------------------|
| **System parameters**        |
| cable cross-section area      | 241.9 mm² |
| unit inductance of bus (\( L_{ul} \)) | 0.97 mH/km |
| unit resistance of bus (\( r_{ul} \)) | 121 mΩ/km |
| segment length of bus (\( l \)) | 2 km |
| fault resistance (\( r_f \)) | 0.5 Ω |
| distributed generators DG-1 and DG-2 | 220 V |
| bus voltage                  | 325 V |
| cluster voltage              | 48 V |

| Table 2 Length of DC bus segments and service mains |
|-----------------------------------------------------|
| **Bus segments and their location** | **Length, m** |
| N7-N1 (segment-81)                  | 200 |
| N1-N2 (segment-12)                   | 100 |
| N2-N3 (segment-23)                   | 100 |
| N3-N4 (segment-34)                   | 200 |
| N4-N5 (segment-45)                   | 100 |
| N5-N6 (segment-56)                   | 100 |
| N6-N7 (segment-67)                   | 200 |
| service mains of homes in clusters   | 10 |
| service mains of power sources       | 20 |
| service mains of the BB              | 10 |
0.2, the current sensors CS\textsubscript{12} and CS\textsubscript{81} retrieve ~600 and 1600 A at the control room, which is very high current as compared to the current retrieved at the previous time instant, as shown in the subplot of Figs. 8a and b. While the current sensor CS\textsubscript{1} retrieves very low current (~100 A) as compared to the current retrieved (~170 A) at the previous time instant. The algebraic sum of the ECs and OCs for the \( N\text{\textsubscript{1}} \) is not equal to zero. It shows that (11) is not verified for the node \( N\text{\textsubscript{1}} \), i.e. KCL failed. It verifies that the LRF has occurred at node \( N\text{\textsubscript{1}} \). Therefore, the NAOC controller creates the control signal to open the CBs CB\textsubscript{12} and CB\textsubscript{81} to isolate the node \( N\text{\textsubscript{1}} \) from the health DC microgrid. The CBs CB\textsubscript{12} and CB\textsubscript{81} are opened at 0.201 s and the bus segment-12 and segment-81 are disconnected from the DC microgrid that’s why the current sensors CS\textsubscript{12}, CS\textsubscript{81} and CS\textsubscript{1} retrieve zero during 0.201–0.299 s, as shown in Figs. 8a–c. As the fault removed at 0.299 s, the NAOC controller again creates the control action and sends to the actuators to switch ON the DG-1 and closed the CB CB\textsubscript{8}.

### 3.2 Fault at service main of DG-1 (fault F2)

The DG-1 is the connected power source at node \( N\text{\textsubscript{7}} \). The DG-1 current (\( I\text{\textsubscript{g1}} \)) is measured by the current sensor CS\textsubscript{8}. The current sensors CS\textsubscript{81} and CS\textsubscript{67} are mounted on segment-81 (\( I\text{\textsubscript{81}} \)) and segment-67 (\( I\text{\textsubscript{67}} \)) to monitor their currents at a different time instants. At time instant 0.5 s, the LRF (Fig. 2a case) occurred in the service main of DG-1. The current sensor CS\textsubscript{8} retrieves the value of EC \( i\text{\textsubscript{c1}} \) of node \( N\text{\textsubscript{1}} \) is 4.5 kA, which is approximately eight times higher than the full load current, as shown in Fig. 7a, while the OCs \( i\text{\textsubscript{81}}, i\text{\textsubscript{67}} \) remain in their earliest stage. It verifies that the LRF occurs in the service main of DG-1. The NAOC controller creates the control action and sends it to the respective actuators to ‘open’ the CB CB\textsubscript{8} and switch ‘OFF’ the distributed generator DG-1. The DG-1 current becomes zero, as shown in a subplot of Fig. 7a. It verifies that the CB CB\textsubscript{8} has been ‘opened’. The power is balanced by DG-2 and starts feeding higher current during 0.501–0.6 s time interval, as shown in the subplot of Fig. 7c. The fault F2 is removed at 0.599 s, the NAOC controller again creates the control action and sends to the actuators to switch ON the DG-1 and closed the CB CB\textsubscript{8}.

### 3.3 Fault at service main of DG-1 (fault F2)

The node \( N\text{\textsubscript{2}} \) is connected to the DC bus via DC–DC buck converter to supply all the five homes of the cluster-2. Therefore, the current sensor CS\textsubscript{2} is mounted on the output of the DC–DC converters to monitor the EC (\( i\text{\textsubscript{c2}} \)) of node \( N\text{\textsubscript{2}} \). Besides that, these two sensors are mounted on the service mains of every home to monitor the current at both the ends of the homes service mains to implement the CD scheme for the service mains of the homes. The current sensors CS\textsubscript{211}, CS\textsubscript{221}, CS\textsubscript{231}, CS\textsubscript{241} and CS\textsubscript{251}, monitor the ECs in service mains of Home-1, Home-2, Home-3, Home-4 and Home-5, respectively. While the current sensors CS\textsubscript{212}, CS\textsubscript{222}, CS\textsubscript{232}, CS\textsubscript{242} and CS\textsubscript{252} monitor the actual load currents of Home-1, Home-2, Home-3, Home-4 and Home-5, respectively. As the fault, F3 occurred at time instant 0.9 s at the service mains of Home-3 in cluster-2. As the fault location is between the current...
sensors $CS_{231}$ and $CS_{232}$, the EC ($i_{231}$) and the sum of OCs ($i_{211}$, $i_{221}$, $i_{231}$, $i_{241}$ and $i_{251}$) remain equal at every time instant at node $N_{c2}$, as shown in the subplot of Figs. 9k and l.

The EC ($i_{231}$) of the service main of Home-3 is divided into two parts; first one is the fault current ($i_{F3}$) and another is the load current of Home-3. The fault current depends on the fault resistance. Therefore, the current sensors $CS_{231}$ and $CS_{232}$ have monitored the different values of the current at time instant 0.9 s and retrieve it in the control room. While the current sensors mounted on the service mains of the Home-1, Home-2, Home-4 and Home-5 monitor and retrieve the same amount of input and output currents but slightly lower than the previous current value. There is a reduction in the current in the other homes service mains is due to voltage dip at the node $N_{c2}$. It verifies that the LRF has been occurred at service mains of the Home-3 in cluster-2. Therefore, the CD controller creates the control action to open the CB $CB_{231}$ of faulty service main to isolate the faulted section from the DC microgrid.

At time instant 0.901 s, the CB $CB_{231}$ has been opened and isolates service main of Home-3 from the healthy DC microgrid. This is verified by the zero reading of the current sensors $CS_{231}$ and $CS_{232}$, as shown in the subplot of Figs. 9e and f. The EC and OC of service mains of Home-1, Home-2, Home-4 and Home-5 of cluster-2 remain the same as shown in the subplot of Figs. 9a-d and g-j. As the fault F3 removed at 1.0 s and the CB $CB_{231}$ closed again to connect the Home-3 of cluster-2 with the DC microgrid.

The current sensors $CS_{231}$ and $CS_{232}$ retrieve the full load current at the CD controller again.

4 Discussions

It is clear that the NAOC and CD approach provide significant protection for the fault that occurred in the multi-terminal DC microgrid. The NAOC approach has been used to detect the fault in the DC bus. While the faults in the service mains are detected using the CD approach. The proposed protection scheme has been validated in MATLAB simulation.

The detection of the high resistance fault (HRF) is a great challenge in the DC microgrid. If the fault resistance is too higher than the load resistance, it is very difficult to find out that the fault has occurred with the overcurrent protection approach. The inclusion of the CD approach in the proposed scheme makes it more accurate to protect the DC microgrid in case of the HRF (low fault current) and the LRF (high fault current). The previous protection scheme [14] is tested for the fault resistances 0.1, 0.9 Ω and fault distance 10 and 90% of the fault segment length. It shows that the previous protection method is useful for the LRF. While the accuracy of the proposed fault-location method is tested with respect to the wide range of variables, such as fault position (5–100% of the bus segment), and fault resistance (0–1 kΩ). It shows that the proposed protection method is useful for LRF as well as for HRF. Moreover, the previous protection scheme for the ring bus is discussed and tested for the fault at bus segments only, but the diagnosis and protection of load, DG and service main are not
covered. Therefore, when the fault occurred at DG or load or service mains of the DC microgrid, then the complete section of the DC bus has to be isolated. While the proposed method provides the diagnosis and protection for fault at DC bus as well as load, DG and their service mains. Therefore, the proposed method shows better reliability and accuracy.

The sensitivity analysis has been done at the service main of Home-3 in the cluster-2. Therefore, the faulty segment length is 10 m (i.e. service main length), as mentioned in Table 2. The sending end voltage (i.e. cluster voltage) is 48 V, as mentioned in Table 1, while the load resistance is considered as 2 Ω. The LRF and HRF (Fig. 2b case) for the fault location at 5 and 100% of the faulty segment can be found in Table 3. In addition to the absolute current magnitude, the difference in segment input current ($i_{231}$) and load current ($i_{232}$) can be used by the controller for fault current detection, which triggers the different current faults. The segment input current is higher with LRF (0.1 Ω) because it decreases the equivalent resistance of the circuit. While the segment current is lower with HRF (1 kΩ) because it increases the equivalent resistance of the circuit.

5 Conclusions

The fault detection, isolation and localisation scheme has been proposed for various locations in the ring main-based multi-terminal DC microgrid system consists of DG and energy storage unit. The proposed protection scheme consists of node and segment controllers capable of detecting the fault current in the bus segments, service mains and isolating the faulty segment to avoid the entire system blackout. The NAOC algorithm and OC algorithms are executed by the SCADA system for the bus segments and service mains of the DGs and homes, respectively. The proposed scheme is tested for low resistance as well as for high resistance of the fault at various locations (ring bus, service main of load and service mains of the distributed generator). Moreover, for the separated faulted segment, a fault location algorithm using a power unit without having to reclose the CBs for the estimation of fault location and fault resistance has also been presented. The proposed scheme depends on the communication network. This scheme can be applied to DC power systems, for example green residential and commercial buildings with renewable energy resources and data centres. In the future, the cybersecurity protocols may be added for its advancement. While the scheme is applied to the more populated mesh of the consumers, the request to send (RTS)/clear to send (CTS) delay of the system may increase. The use of the data comm for business LL9.6 fast poll modem will reduce the RTS/CTS delay in the system. Additionally, the systems can also operate over dataphone digital service networks at speeds from 1200 to 57,600 bps over multi-drop networks with RTS/CTS delays of <1 ms, which avoids error conditions.

6 References

[1] IEEE Recommended Practice for the Design of DC Auxiliary Power Systems for Generating Stations, IEEE Std. 946-2004, 2004
[2] Morton, J.: ‘Circuit breaker and protection requirements for DC switchgear used in rapid transit systems’, IEEE Trans. Ind. Appl., 1985, IA-21, (5), pp. 1268-1273
[3] Sutherland, P.: ‘DC short-circuit analysis for systems with static sources’, IEEE Trans. Ind. Appl., 1999, 35, (1), pp. 144–151

[4] Feng, X., Ye, Z., Liu, C., et al.: ‘Fault detection in dc distributed power systems based on impedance characteristics of modules’. Proc. IEEE 35th IAS Annual Meeting and World Conf. on Industrial Applications of Electrical Energy, Rome, Italy, 8–12 October 2000, vol. 4, pp. 2455–2462

[5] Baran, M., Mahajan, N.: ‘Overcurrent protection on voltage-source converter-based multi terminal dc distribution systems’, IEEE Trans. Power Deliv., 2007, 22, (1), pp. 406–412

[6] Litzenberger, W., Lips, P.: ‘Pacific HVDC intertie’, IEEE Power Energy Mag., 2007, 5, (2), pp. 45–51

[7] Cuzner, R.M., Venkataramanan, G.: ‘The status of dc micro-grid protection’. Proc. IEEE IAS Annual Meeting, Edmonton, Alta, 5–9 October 2008, pp. 1–8

[8] Tang, L., Ooi, B.T.: ‘Protection of VSC-multi-terminal HVDC against DC faults’. Proc. IEEE 33rd Power Electronic Specialist Conf., Cairn, Qld, Australia, November 2002, vol. 2, pp. 719–724

[9] Tang, L., Ooi, B.T.: ‘Locating and isolating DC faults in multi-terminal DC systems’, IEEE Trans. Power Deliv., 2007, 22, (3), pp. 1877–1884

[10] Behestaean, S., Savaghebi, M., Vasquez, J.C., et al.: ‘Protection of ac and dc microgrids: challenges, solutions and future trends’. Proc. IECON - 41th Annual Conf. of the IEEE Industrial Electronics Society, Yokohama, 2016, pp. 005253–005260

[11] Salomonsson, D., Soder, L., Sannino, A.: ‘Protection of low-voltage DC microgrids’, IEEE Trans. Power Deliv., 2009, 24, (3), pp. 1045–1053

[12] Brozek, J.: ‘DC over current protection – where we stand’, IEEE Trans. Ind. Appl., 1993, 29, (5), pp. 1029–1032

[13] Park, J.D., Candelaria, J., Ma, L., et al.: ‘DC ring-bus microgrid fault protection and identification of fault location’, IEEE Trans. Power Deliv., 2013, 28, (4), pp. 2574–2584

[14] Sangeetha, R.S., Balachander, K.: ‘Unbalanced and over current protection in low voltage dc bus microgrid systems’, Middle-East J. Sci. Res., 2016, 24, (2), pp. 465–474

[15] Kalyan, R.S., Kulkarni, J.S.: ‘Protection of low voltage DC bus microgrid system’, Int. J. Innov. Res. Comput. Commun. Eng., 2015, 3, (7), pp. 6456–6463

[16] Kaddah, S.S., El-Sandawi, M.M., El-Hassanin, D.M.: ‘Influence of distributed generation on distribution networks during faults’, Electr. Power Compon. Syst., 2015, 43, (16), pp. 1781–1792

[17] Balasreedharan, S.S., Thangavel, S.: ‘An adaptive fault identification scheme for DC microgrid using event based classification’. Proc.3rd Int. Conf. on Advanced Computing and Communication Systems (ICACCS), Coimbatore, 10 October 2016, pp. 1–7

[18] Patil, G., Satarkar, M.F.A.R., Abande, G.: ‘New scheme for protection of dc microgrid’, Int. J. Innov. Res. Sci. Eng. Technol., 2014, 3, (3), pp. 103–107

[19] Elgeziry, M., Elaeddin, M., Elalady, N., et al.: ‘Non-pilot protection scheme for multi-terminal VSC-HVDC transmission systems’. IET Renew. Power Gener., 2019, 13, (16), pp. 3033–3042

[20] Dhar, S., Patnaik, R.K., Dash, P.K.: ‘Fault detection and location of photovoltaic based DC microgrid using differential protection strategy’, IEEE Trans. Smart Grid, 2017, 9, (5), pp. 4303–4312

[21] Mehdi, M., Ciobotaru, C.K., Luna, A., et al.: ‘Multi-terminal medium voltage DC grids fault location and isolation’, IET Genet. Transm. Distrib., 2016, 10, (14), pp. 3517–3528

[22] Mustafa, F., Mohammed, O.A.: ‘Protection of multi-terminal and distributed DC systems: design challenges and techniques’, Electr. Power Syst. Res., 2017, 143, pp. 715–727

[23] Pawan, P., Sandeep, K., Poonam, P.: ‘Fault protection of a loop type low voltage DC bus microgrid’, Int. J. Adv. Res. Electr. Electron. Instrum. Eng., 2015, 4, (12), pp. 9552–9559

[24] Park, J.D., Candelaria, J.: ‘Fault detection and isolation in low-voltage dc-bus microgrid system’, IEEE Trans. Power Deliv., 2013, 28, (2), pp. 779–787

[25] Chauhan, R.K., Rajpurohit, B.S., Wang, L.: ‘A simple approach of fault identification and localization for low-voltage DC microgrid’. Proc. IEEE, 7th India Int. Conf. on Power Electronics, Patiala, 17–19 November 2016, pp. 1–6, (DOI: 10.1109/ICPE.2016.8079448)

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