A Localized–Protection Scheme for Ring DC Microgrids using Distribution-Sensitive Poverty Index

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Abstract—DC Microgrid protection is one of the challenges in utilizing DC Microgrids. This paper offers a protection scheme for DC Microgrids with ring configuration by using local intelligent electronic devices. This method is based on monitoring the distribution-sensitive poverty index, which is calculated by using the current in different sample times. Moreover, this protection method only uses the local data at the intelligent electronic devices without using any communication links; thus, it increases the reliability and also decreases the cost of the protection system. In addition, the proposed scheme is capable of detecting the high impedance faults within the DC Microgrid lines. The effectiveness of the proposed strategy is demonstrated by using simulations in different scenarios. Simulation results indicate that the proposed method can detect both low and high impedance faults within several milliseconds, and the comparison with other fault detection methods reveals the superiority of the proposed strategy.

Keywords—Protection, DC Microgrid, fault detection, high fault resistance, Localized protection scheme.

I. INTRODUCTION

In recent years, the increase in the usage of DC renewable energy sources (RESs) such as fuel cells (FCs), energy storages (ESs), and photovoltaics (PVs), also the DC consumers such as data centers, lead to great attention in implementing DC Microgrids for future grids [1]-[3]. The main advantages of DC Microgrids are reduction losses due to the lack of skin effect and fewer conversion stages, lack of frequency control requirement and synchronization, and removing the reactive power issues [4]. A DC Microgrid is connected to the AC network by an AC/DC converter in grid-connected mode or operated without connecting the grid as an islanded mode [5]-[7].

The lack of comprehensive protection strategy and the nature of DC faults make the protection of DC Microgrids a significant challenge for DC Microgrid implementations [8]. In the DC systems, due to the high rate and amplitude of fault current, the low cable impedance, the presence of power converters, and lack of zero-crossing point, the detection of a fault in the DC Microgrids is difficult [9]. Therefore, designing a fast, selective, and reliable protection strategy for reducing the cost and risk of DC Microgrids is crucial.

The suggested protection schemes for DC Microgrids are divided into two groups, communication-based protection systems, and local protection systems. The communication-based protection scheme proposed in [10] uses overcurrent relays to detect the fault in DC Microgrid. In this method, both ends of lines are equipped with overcurrent relays, and all relays are calculated to each other through communication links. In [11], a differential fault detection method by using a modified cumulative sum average approach is presented, and this method uses two protection devices at both ends of each line that are connected to each other. The suggested method in [12] minimized the number of protection devices as well as communication links to detects and isolate the faulty zone and line by using comparing the variations in current. Communication-based protection methods require communication infrastructures, which increase cost and also the probability of failure.

The second group scheme is proposed to reduce the cost and increase the reliability by using localized protection methods. The method in [13] uses the first and second-order derivative of current to detect faults. However, in this method, the high impedance faults (HIFs) increases the operation time and error of fault detection. An estimation method is proposed in [14] to detect the fault in DC Microgrids. In addition, a method is suggested in [15] to detects the fault by using the cumulative sum average. However, the suggested local protection systems require to consider the HIFs and also provide a fast protection system. In addition, in the aforementioned studies, the coordination between protection devices of each section is missed.

To address these issues, this paper proposes a localized directional protection system for ring DC Microgrids, that utilizes the current samples measured at one end of each line. Each section has an intelligent electronic device (IED) to calculate the Distribution-Sensitive Poverty Index (DSPI) to detect the fault. Based on the DSPI information, measured by local measurement, the faulty line is identified. In this method, IEDs are coordinated with other IEDs without any communication links. Also, this scheme is effective against HIFs. The main contribution of this paper are:

• Proposing a fault detection strategy with high sensitivity based on the DSPI
• Modifying the conventional protection methods using the DSPI to protect DC Microgrid
• Proposing a method for detecting HIFs
• Coordinating IEDs to provide selectivity for protection system

II. PROPOSED PROTECTION SCHEME

The bidirectional current flow in the DC Microgrids with ring configuration emphasis using directional protection schemes. Moreover, during the HIFs, no significant changes in the current cause difficulty in the detection of the fault. On the other hand, due to the increase in cost and failure probability in the communication-based protection systems, suggesting a local protection method for DC Microgrids is essential. To address these issues, this paper proposes a directional protection scheme that employs the information of the local measurement unit of the protected segment. In the first step, the fault variation parameter is calculated to monitor the rate of change in the current of the protected line during low and high impedance faults. During the normal conditions, this parameter is zero, and it changes during the fault conditions. In the second step, the value of DSPI is calculated by the monitored value of the current change rate. The value of DSPI is compared with a threshold to detect the faults. Then the IEDs of other segments should be coordinated to avoid false tripping. Therefore, the coordination of all IEDs is performed by defining Modified Coordination Time Interval (MCTI). Then, the tripping signal is sent to Solid State Circuit Breakers (SSCBs) by local IEDs to trip the faulty line.

A. Calculation of DSPI

The poverty gap index was proposed in [16] for measuring the poverty severity in a population. Also, the DSPI is proposed in [16] for measuring the poverty in a society with higher sensitivity. Therefore, in [17], the application of DSPI is investigated in the protection of DC Microgrids with communication lines. In this paper, the DSPI is used for the protection of a segment locally without using the data of other sections. At the first stage, the line current is monitored by a sample rate of 5 kHz and passed via a low path filter to remove noise. Then, the change rate of current is calculated by

\[
I_{CR}(kT_s) = I_f(kT_s) - I_N(kT_s)
\]

(1)

where, \(I_{CR}\) is the rate change of current \(I_f\) is the fault current, and \(I_N\) is the normal current. \(k\) and \(T_s\) are the sampling step and period, respectively. Then, the value of DSPI can be obtained by

\[
DSPI = \frac{1}{N} \sum_{i=1}^{N} \left[ \ln(z) - \ln(I_{CR}) \right] \times u(I_{CR} - z)
\]

(2)

where \(N\) is the number of data, \(z\) is the poverty line. During the disturbance and noise in the measurement, the value of \(I_{CR}\) can be more than zero in the normal conditions. Also, in the overload conditions, the value of current can be increased to a higher value than \(I_N\), which causes maloperation of protection devices. In the protection standards of AC systems, it is mentioned that 20% more than the overload current should be determined as a fault condition. Therefore, to reduce the computational burden, the value of \(z\) is considered 20% more than the normal conditions, and the presence of \(u\), which is the step function, causes to make a zero DSPI for currents less than \(z\).

B. Line Protection

This paper proposes the use of a directional protection scheme to protect DC Microgrid lines, as shown in Fig. 1. To isolate the faulty segment, each line is equipped with two SSCBs, which are connected to the nearest IEDs, and can interrupt the current within a few microseconds. The IED of each line monitors the current values and calculates the value of DSPI based on (2). Due to the lack of communication links, the total delays are processing delay, without any transmission and propagation delays. The value of DSPI is compared with a threshold, \(\mu\), which is calculated for the lowest value of DSPI for different conditions and fault resistances. Consequently, if the value of DSPI becomes more than \(\mu\), the IED detects the fault.

![Fig. 1. The case study and position of IEDs of proposed scheme](image-url)
C. Determining the faulty segment and coordination of IEDs

After fault detection, the faulty segment should be determined. The current direction during fault compared with the normal condition may change. Therefore, after fault detection, the direction of each IED shows the position of the IED compared with the faulty section. Then, all IEDs should be coordinated with each other depending on the direction of the fault current. For example, for a fault of \( F \) in Fig. 1, first the IED7 and IED8 should send the trip signal and in case of failure of each part of the protecting system, IED1 and IED6 should send the trip signal as the backup protection system. In this case, an MCTI parameter is determined to coordinate IEDs, which defined by

\[
MCTI = \frac{\alpha e}{DSPI} t_c
\]

where, \( I_{F_{\text{max}}} \) is the maximum value of fault current, \( \alpha \) is a constant coefficient factor with the unit of Ampere Second (As) that is determined based on the system parameter. Therefore, the operation time of each IED is indicated by

\[
t_i = t_{Dc} + MCTI
\]

where, \( t_i \) is the operation time of IED, \( t_{Dc} \) is the fault detection time of the relay. Based on (3) and (4), the maximum fault current, \( I_{F_{\text{max}}} \), of the nearest IED to fault is higher than other IEDs. Therefore, the value of MCTI is lower for the primary IEDs, and backup IEDs have higher MCTI. On the other hand, the value of \( \alpha \) is within the range of several micros, thus, the value of MCTI is within the range of several milliseconds. Therefore, it cannot cause a high delay for IEDs. In the proposed method, the value of MCTI should be less than 10 ms.

D. Flowchart of the Proposed Method

Fig. 2 represents the flowchart of the proposed local DSPI-based protection strategy for DC Microgrids. The local measurement units monitor the values of the current of each IEDs place. Then, the values of DSPI are calculated for each line and compared with the threshold. If the current exceeds the value of the threshold, the direction of fault current is monitored and the values of MCTI for all IEDs are obtained. Therefore, based on the operation time of the IEDs, the trip signal sends to the corresponding SSCBs, and the faulty segment will be isolated.

After fault detection, the opening signal is sent to SSCBs of the faulty segment. If the SSCBs failed to isolate the faulty segment, the presence of MCTI causes the backup operation for other IEDs, after a small operation margin.

III. SIMULATION RESULTS

In this section, a set of simulation studies is performed to investigate the proposed protection scheme. The case study is the DC Microgrid of Fig. 1, and the parameters of this system are shown in Table I. The developed scenarios are based on the different fault resistances for low to high impedance faults, and different locations for fault. The value of \( e \) is assumed to 20% more than the normal current, and the value of \( \alpha \) is 0.3 As. The values of \( \mu \) for all IEDs are assumed to be 0. For presenting the performance of the values MCTI in different situations, in Fig. 3, the behavior of MCTI against variations of DSPI and \( I_{F_{\text{max}}}/I_N \) is depicted. Based on Fig. 3, by increasing the values of DSPI and fault current the value of MCTI decreases, therefore, the operation speed of the primary IED will be more than the backup IED, which causes selective coordination between IEDs.

A. Fault detection

At the first stage, the performance of the DSPI-base fault detection scheme during different fault conditions is investigated. An arc fault is simulated in the line of IED7 at \( F_1 \),

![Fig. 2. The flowchart of the proposed method](image-url)

![Fig. 3. The performance of MCTI against variation of DSPI and \( I_{F_{\text{max}}}/I_N \)](image-url)
as shown in Fig. 1. The fault resistance is assumed to be 0.5, 1, and 10 Ω at the t = 7 s. Fig. 4 shows the DSPI values of all IEDs for this case and the values of the threshold of each IED. The results represent that the DSPI values of all IEDs during fault with different fault resistances are higher than the threshold. In addition, by increases the fault resistance, the value of DSPI will change. Also, the values of DSPI at F2 are shown in Fig. 5. By comparing Fig. 4 and 5, it is an undeniable fact that by increasing the distance of fault from an IED, the value of DSPI will change.

B. Coordination of IEDs

After the fault detection stage, all IEDs should be coordinated with each other to avoid false tripping. For this aim, the value of maximum fault current is calculated for each IED, and then the value of MCTI is obtained by (3). The fault current at F1 and F2, seen from the IED1, are shown in Fig. 6, and the value of fault current is reduced by increasing the distance of IED from the fault location. The main parameter in calculating MCTI is the ratio of maximum fault current to the normal current of each IED. These values for a fault at F1 with fault resistance of 1 Ω are shown in Table II. Therefore, IEDs with higher MCTI sends the trip signal with a delay after the nearest IEDs. The values of operation times of IEDs for a fault at F1 with fault resistance of 1 Ω are represented in Table III, which proves appropriate coordination between IEDs. As shown in Table III, the primary IEDs for fault at F1 are IED7 and IED8, which have the lowest operation time. In addition, the operation time of IED6 is higher than IED1 and the operation time of IED1 is higher than IED8, therefore, the primary IEDs are sent the trip signal before backup IEDs. Consequently, the fault current behavior of Fig. 7, for a fault at F1 with fault resistance of 1 Ω represents successful tripping of the protection system within 56 ms. In the DC systems, it is important to clear the fault with the lowest operation time; because, the thermal tolerant characteristic of components is defined by $I_{2t}$. Therefore, clearing the fault by the proposed method within 56 ms ensures the safety of all components in which the fault current has flowed through them.

IV. CONCLUSION

This paper proposed DSPI-based protection method for detecting the short-circuits in DC Microgrids with ring configuration by local measurement units. The proposed protection approach is based on the transient current in each line. The first stage is determining the value of DSPI of all IEDs in the system. Using the changing of fault direction and DSPI factor eliminates the problem of low variations of HIF current. The proposed strategy consists of one IED in each line, and it only uses the local measurement to detect the fault. Moreover, a new MCTI factor is proposed to coordinate all IEDs in different segments without using any communication links. The DSPI is compared with a threshold to detect the fault by the lowest operation time, in the range of several milliseconds. The simulation results show that the protection method detects the HIFs up to 10 Ω within an appropriate operation time. Consequently, the effectiveness of the

![Fig. 4. The DSPI values during different fault conditions at F1](image)

![Fig. 5. The DSPI values during different fault conditions at F2](image)

![Fig. 6. The fault current behavior at (a) F1 (b) F2](image)

![Fig. 7. The isolation operation of fault current](image)

### Table II. The Ratio of Maximum Fault Current to the Normal Current

| IED number | $\frac{I_{\text{max}}}{I_{\text{N}}}$ | IED number | $\frac{I_{\text{max}}}{I_{\text{N}}}$ |
|------------|-------------------------------|------------|-------------------------------|
| IED1       | 1.9128                        | IED5       | 0.8094                        |
| IED2       | 1.9128                        | IED6       | 0.9590                        |
| IED3       | 2.6258                        | IED7       | 1.7199                        |
| IED4       | 2.2240                        | IED8       | 3.6792                        |

### Table III. Operation Time of IEDs

| IED number | Operation time (ms) | IED number | Operation time (ms) |
|------------|---------------------|------------|---------------------|
| IED1       | 581                 | IED5       | 283                 |
| IED2       | 581                 | IED6       | 66                  |
| IED3       | 63                  | IED7       | 63                  |
| IED4       | 77                  | IED8       | 56                  |

This paper proposed DSPI-based protection method for detecting the short-circuits in DC Microgrids with ring configuration by local measurement units. The proposed protection approach is based on the transient current in each line. The first stage is determining the value of DSPI of all IEDs in the system. Using the changing of fault direction and DSPI factor eliminates the problem of low variations of HIF current. The proposed strategy consists of one IED in each line, and it only uses the local measurement to detect the fault. Moreover, a new MCTI factor is proposed to coordinate all IEDs in different segments without using any communication links. The DSPI is compared with a threshold to detect the fault by the lowest operation time, in the range of several milliseconds. The simulation results show that the protection method detects the HIFs up to 10 Ω within an appropriate operation time. Consequently, the effectiveness of the
proposed method is proved in different scenarios of an 8 bus DC Microgrid equipped with different RESs.

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