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), as well as the modern DC consumers such as sensitive computer loads, lead to great attention in implementing DC Microgrids for future grids [1]–[4]. The main advantages of DC Microgrids are reduction losses due to the lack of skin effect and fewer conversion stages, lack of requirement for frequency control and synchronization, and removing the reactive power issues [5]–[6]. A DC Microgrid can be connected to the AC grid by an AC/DC converter in grid-connected mode or operated without connecting the grid as an islanded mode [7]–[9].

The lack of effective protection strategy and the nature of DC faults make the protection of DC Microgrids a significant challenge for DC Microgrid implementations [10]. 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 [11]. 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 [12] 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 [13], 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 [14] minimized the number of protection devices as well as communication links to detect 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 [15] 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 [16] to detect the fault in DC Microgrids. In addition, a method is suggested in [17] to detect 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 scheme for ring DC Microgrids, which uses the current samples measured at one end of each line. Each section is equipped with 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 the proposed protection strategy, each IED is 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

The rest of the paper is organized as follows: Section II presents the details of the proposed strategy. In section III, the simulation results of the proposed method are discussed. Finally, the conclusion of the paper is explained in Section IV.

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 [18] for measuring the poverty severity in a population. Also, the DSPI is proposed in [19] for measuring the poverty in a society with higher sensitivity. Therefore, in [20], 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 [21]

$$I_{CR}(kT_s) = I_F(kT_s) - I_N(kT_s) \quad (1)$$

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

$$DSPI = \frac{1}{N} \sum_{i=1}^N [(\ln(z) - \ln(I_{CR})) \times u(I_{CR} - z)] \quad (2)$$

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 [22]. 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 [23]. The IED

Fig. 1. The case study and position of IEDs of proposed scheme

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, μ , which is calculated for the lowest value of DSPI for different conditions and fault resistances. Consequently, if the value of DSPI becomes more than μ , the IED detects the fault.

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

$$MCTI = \frac{\alpha e^{-\left(\frac{I_{Fmax}}{I_N}\right)}}{DSPI} \quad (3)$$

where, I_{Fmax} is the maximum value of fault current, α 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

$$t_i = t_{Di} + MCTI \quad (4)$$

where, t_i is the operation time of IED, t_{Di} is the fault detection time of the relay. Based on (3) and (4), the maximum fault current, I_{Fmax} , 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 α 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

Fig. 2. The flowchart of the proposed method

TABLE I. RATING OF DC MICROGRID COMPONENTS

System component	Rating
DC grid voltage	500 V
Battery	200 Ah
PV	V _{oc} = 64 V, I _{sc} =6, 66 parallel strings, 25 series modules
WT	200 kW, Rotor type= salient-pole
FC	100 kW, Absolut temerature= 1273 K, Number of series cells: 384
Loads	DC Load ₁ =14 kW, DC Load ₂ =46 kW , DC Load ₃ =150 kW , DC Load ₄ =58 kW
Cable parameters	R=0.2 Ohm/km, L=0.22 mH/km, Copper

Fig. 3. The performance of $MCTI$ against variation of $DSPI$ and I_{Fmax}/I_N

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 z is assumed to 20% more than the normal current, and the value of α is 0.3 As. The values of μ 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_{Fmax}/I_N is depicted. Based on Fig. 3, by increasing

Fig. 4. The DSPI values during different fault conditions at F_1

Fig. 5. The DSPI values during different fault conditions at F_2

TABLE II. THE RATIO OF MAXIMUM FAULT CURRENT TO THE NORMAL CURRENT

IED number	I_{Fmax}/I_N	IED number	I_{Fmax}/I_N
IED ₁	1.9128	IED ₅	0.8094
IED ₂	1.9128	IED ₆	0.9590
IED ₃	2.6258	IED ₇	1.7199
IED ₄	2.2240	IED ₈	3.0792

TABLE III. OPERATION TIME OF IEDs

IED number	Operation time (ms)	IED number	Operation time (ms)
IED ₁	581	IED ₅	283
IED ₂	581	IED ₆	66
IED ₃	63	IED ₇	63
IED ₄	77	IED ₈	56

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 , 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 F_2 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 IEDs, and then the value of $MCTI$ is obtained by (3). The fault current at F_1 and F_2 , 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 IEDs. These values for a fault at F_1 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 F_1 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 F_1 are IED₇ and IED₈, which have the lowest operation time. In addition, the operation time of IED₆ is higher than IED₇ 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 F_1 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 a DSPI-based protection method to detect the fault in a DC Microgrid with ring configuration by local measurement units. The proposed protection strategy is based on the directional 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 changes of current during HIFs.

Fig. 6. The fault current behavior at (a) F_1 (b) F_2

Fig. 7. The isolation operation of fault 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.

REFERENCES

- [1] N. Bayati, H. R. Baghaee, A. Hajizadeh and M. Soltani, "A Fuse Saving Scheme for DC Microgrids With High Penetration of Renewable Energy Resources," in *IEEE Access*, vol. 8, pp. 137407-137417, 2020,
- [2] Bayati N, Hajizadeh A, Soltani M. Protection in DC microgrids: a comparative review. *IET Smart Grid*. 2018 Oct 18;1(3):66-75.
- [3] Alfieri, S., S. Piccini, and M. Kermani. "Feasibility study of Nearly Zero Energy Building in a real Microgrid case study." 2019 IEEE International Conference on Environment and Electrical Engineering and 2019 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe). IEEE, 2019.
- [4] Aghaee, Fateme, et al. "Distributed Control Methods and Impact of Communication Failure in AC Microgrids: A Comparative Review." *Electronics* 8.11 (2019): 1265.
- [5] Kermani M, Carni DL, Rotondo S, Paolillo A, Manzo F, Martirano L. A Nearly Zero-Energy Microgrid Testbed Laboratory: Centralized Control Strategy Based on SCADA System. *Energies*. 2020 Jan;13(8):2106.
- [6] Bayati N, Hajizadeh A, Soltani M. Accurate Modeling of DC Microgrid for Fault and Protection Studies. In2018 International Conference on Smart Energy Systems and Technologies (SEST) 2018 Sep 10 (pp. 1-6). IEEE.
- [7] Martirano L, Kermani M, Manzo F, Bayatmakoo A, Graselli U. Implementation of SCADA systems for a real microgrid lab testbed. In2019 IEEE Milan PowerTech 2019 Jun 23 (pp. 1-6). IEEE.
- [8] Arani AA, Bayati N, Mohammadi R, Gharehpetian GB, Sadeghi SH. Fault Current Limiter optimal sizing considering different Microgrid operational modes using Bat and Cuckoo Search Algorithm. *Archives of Electrical Engineering*. 2018;67(2):321-32.
- [9] Baayeh AG, Bayati N. Adaptive Overhead Transmission Lines Auto-Reclosing Based on Hilbert–Huang Transform. *Energies*. 2020 Jan;13(20):5416.
- [10] Klosinski C, Ross P, Hemdan N, Kurat M, Gerdinand F, Meisner J, Passon S, Heinrich A. Modular protection system for fault detection and selective fault clearing in DC microgrids. *The Journal of Engineering*. 2018 Oct 25;2018(15):1321-5.
- [11] N. Bayati, H. R. Baghaee, A. Hajizadeh and M. Soltani, "Localized Protection of Radial DC Microgrids With High Penetration of Constant Power Loads," in *IEEE Systems Journal*.
- [12] Shabani A, Mazlumi K. Evaluation of a communication-assisted overcurrent protection scheme for photovoltaic based DC microgrid. *IEEE Transactions on Smart Grid*. 2019 Jun 19.
- [13] Dhar S, Patnaik RK, Dash PK. Fault detection and location of photovoltaic based DC microgrid using differential protection strategy. *IEEE Transactions on Smart Grid*. 2017 Jan 17;9(5):4303-12.
- [14] Bayati N, Hajizadeh A, Soltani M. Fault Analysis and Protection of Low-Voltage DC Microgrid Equipped by Renewable Energy Resources. In *Handbook of Research on Recent Developments in Electrical and Mechanical Engineering 2020* (pp. 341-375). IGI global.
- [15] Meghwani, A., Srivastava, S.C., Chakrabarti, S.: 'A non-unit protection scheme for DC-microgrid based on local measurements', *IEEE Trans. Power Deliv.*, 2017, 32, (1), pp. 172–181.
- [16] Meghwani A, Srivastava SC, Chakrabarti S. Local measurement-based technique for estimating fault location in multi-source DC microgrids. *IET Generation, Transmission & Distribution*. 2018 Apr 27;12(13):3305-13.
- [17] Patil DD, Bindu S. Real time protection technique for DC microgrid using local measurements. In2018 Technologies for Smart-City Energy Security and Power (ICSESP) 2018 Mar 28 (pp. 1-6). IEEE.
- [18] W. B. Institute, "Introduction to poverty analysis," <http://siteresources.worldbank.org/PGLP/Resources/PovertyManual.pdf>, Tech. Rep., 2005.
- [19] Martin-Legendre JI. The challenge of measuring poverty and inequality: a comparative analysis of the main indicators. *European Journal of Government and Economics*. 2018;7(1):24-43.
- [20] Bayati, N., Hajizadeh, A., Soltani, M., Lin, Z., "A Distribution-Sensitive Poverty Index–Based Protection Scheme for Interconnected DC Microgrids", The 15th International Conference on Developments in Power System Protection, IET, Liverpool, UK, 2020.
- [21] Salehi M, Taher SA, Sadeghkhani I, Shahidehpour M. A Poverty Severity Index–Based Protection Strategy for Ring-Bus Low-Voltage DC Microgrids. *IEEE Transactions on Smart Grid*. 2019 Apr 23.
- [22] Bayati N, Dadkhah A, Sadeghi SH, Vahidi B, Milani AE. Considering variations of network topology in optimal relay coordination using time-current-voltage characteristic. In2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe) 2017 Jun 6 (pp. 1-5). IEEE.
- [23] A. A. S. Emhemed and G. M. Burt, "An advanced protection scheme for enabling an LVDC last mile distribution network," *IEEE Trans. Smart Grid*, vol. 5, no. 5, pp. 2602–2609, Sept. 2014.