Localized Fault Protection in the DC Microgrids with Ring Configuration

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***Abstract*— DC Microgrids with ring configuration promises a new opportunity for distribution systems, but it is still faced with critical protection problems. In this paper, a localized protection method based on the transient behavior of fault current is presented, which can locate the fault and calculate the fault resistance by only local measurements. Besides, due to the calculating the fault resistance in the proposed scheme, the High Impedance Fault (HIF) is locatable by this method. Another important feature of this method is the reduction of the number of relays. The proposed method is localized and only needs two Protection Detection (PD). This feature of the proposed method removes the communication link, noise, and reduce the cost of the system. Due to the bidirectional current flow in ring systems, the proposed protection scheme considers that and locates fault from two different sides. The mathematical equations for calculation of fault location and resistance by using local measured values are derived. The fault location is tested on a multi-source ring-type DC Microgrid in Digsilent, and results show the effectiveness of the proposed method in different fault locations and resistances.**

Keywords*— Protection, DC Microgrid, fault location calculation, fault resistance, Localized protection scheme.

I. INTRODUCTION

The use of DC-based systems potentially has significant efficiency and cost advantages to a range of power system applications. In this context, the development in the converters had led to the using DC Microgrids [1]. In Microgrids, loads are supplied from the local Distributed Generations (DGs) resources [2], also, the majority of loads and DGs are DC, hence, using DC voltages and currents in Microgrids are more suitable. The advantages of these systems are discussed in the [3] and [4], which makes a significant reduction in power losses, due to the lower conversion stages and lack of skin effect. Therefore, using these systems increase the cost of saving and efficiency.

One of the main problems in DC Microgrids is lack of effective protection scheme to locate faults in the system [5]. Also, it is essential to use a reliable protection scheme to ensure the reliable operation of DC Microgrids [6]. On the other hand, most of DC Microgrids have ring configuration. Hence, the protection scheme must be applied in these systems under bidirectional fault current. In [7], a fault location identification for DC ring Microgrids is proposed. This method uses the power probe to locate the faults, but, this method needs a communication link between each PDs.

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Thus, it can increase the failure probability and cost. The differential based protection method for DC Microgrids with ring configuration is proposed in [8]. This technique uses the input and outputs current of each terminal of line. Therefore, for each line, two PDs must be installed in the system. In [9], the protection method uses the parameter estimation method to locates the fault in ring DC Microgrid. In this method, the fault location uses transient behavior of fault current, but also this method is a communication-based method and needs two PDs for each line. Also, the usage of communication links in protection methods increases the delay and response time [10]. A fast fault detection method is proposed in [11], which uses the VSC disconnection during the fault. The limitation of this scheme is that it requires the shutdown of the system.

On the other hand, fault resistance estimation methods are used for improving the accuracy of fault location identification methods. In [12], an impedance estimation method is proposed for improving the operation of distance protection by using Artificial Neural Networks. Also, the fault resistance estimation for High Impedance Faults (HIFs) is investigated in [13] by using analytical formulation and developing a time domain protection method. However, these methods only apply to AC systems. [14] suggested an active resistance estimation method by supplying a voltage disturbance to DC line, and the current transients are measured at the capacitor point of connection. The results of this method are satisfying, but each line needs a disturbance injector and a PD.

Most common fault type in DC Microgrids is the pole to ground faults [15-16]. It causes electrical and environmental stress and damage to the inverters. A differential based protection method is suggested in [17-18] for protection DC system against cable fault. A communication link is required for this method, and due to the probability of data losses, delay, noise, and communication failure, this method requires a backup protection method. Then, it can increase the complexity and cost of the protection scheme.

In this paper, a localized protection scheme for calculating the fault distance and resistance is proposed. In this paper, the case study is a DC Microgrid with ring configuration, therefore, fault current would be supplied from two sides of the fault location. Thus, the proposed protection scheme considers the bidirectional current flow. In addition, using communication links in a protection method increases the cost of the system, sensitivity to the noise, and the failure of the system, which caused by communication failure. Accordingly, to solve these problems, the proposed scheme only uses two localized PDs at one place. The localized PDs uses equations of fault current deviations, based on the nature of DC current, and calculates the location of the fault by two stages. First, the value of fault resistance is calculated by an equation based on the fault current and voltage at the PDs place. Then, by obtaining the value of fault resistance, the distance of fault can be calculated by using voltage and current equations based on the PDs measured values.

This paper is organized as follows: In section 2, the challenges and requirements of the fault location methods in DC Microgrids are presented. The proposed scheme and calculation of the fault resistance and location is discussed in section 3. The proposed scheme is simulated in Digsilent, and the results are presented in section 4. Finally, the conclusion is discussed in section 5.

II. Challenges in Fault Location of DC Microgrids

The basic requirements of the fault location methods for DC Microgrids are accuracy, cost, reliability and the functionality of the algorithm during the topology changes. Before explaining the proposed protection scheme, these basic requirements are discussed in the following sections.

A. Accuracy

Fault location methods which utilize steady state fault current data in their calculations are not fast, because the fault current needs a few milliseconds for transient behavior of capacitors and diodes of the system. On the other hand, due to the short lines of DC Microgrids, and low line resistance, the error of fault locating in DC Microgrids is normally higher than power grids. The accuracy of the fault location is calculated by percentage error defined as [19]:

$$\%Error = \frac{\text{Actual Location- Calculated Location}}{\text{Total Length of the Faulted Line}} \times 100 \quad (1)$$

Typically, from the relay location, the resistance of a fault with a fault resistance and a farther fault without fault resistance is the same. Therefore, the fault resistance increases the error of the fault location. Thus, calculation the fault resistance enhance the accuracy of the algorithm.

B. Cost and reliability

Using communication links in the DC Microgrid protection increases the overall cost of the system. Therefore, online method for evaluating the fault location and resistance which does not require communication links is essential for reducing the cost of DC Microgrid protection scheme. Thus, the localized protection methods require less time and data.

On the other hand, in the ring systems, fault current contributed from both sides of the fault location, and contribution of the fault current decreases by the faults occurred as a farther location from the corresponding bus. Therefore, for increasing the reliability of the system, the protection system should monitor the data from both sides of the fault location. However, to process the data utilizing a communication link may cause a delay, and increases the cost. Also, due to the communication link failure, using the communication link reduce the reliability of the system.

C. functionality during the topology changes

Usually, a protection scheme cannot be designed for a fixed DC Microgrid. Because, in real situations, the system characteristics such as loads and resources may changes. Therefore, a protection scheme must be robust against changes in the system. On the other hand, the fault resistance is not fixed. Hence, the value of fault resistance should be a variable in fault location calculations. An protection system must has a structure which is immune against conditions change of the system. The idea of this type of protection schemes in DC Microgrids boils down to proper system impedance calculation.

III. Proposed Fault Location Scheme

The analytical model of the DC Microgrid during the fault is derived for designing a fault location scheme. This model is described based on Fig. 1, which shows location of the fault and two PDs. The derived scheme accompanied by the local measurements at battery place is used to calculate the fault resistance and location. Two PDs can be applied at the end of one element, in this model they connected to the battery place.

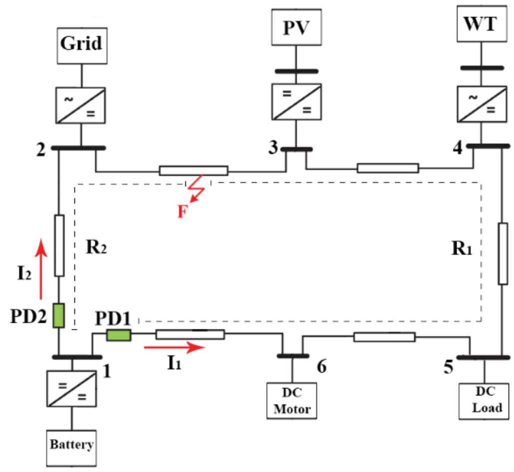

Fig. 1. Model of case study for the proposed method

The equations of the voltage of the line based on the distance from the PD place, as shown in Fig. 1., is written as:

$$\begin{cases} V_{R1} - R_1 I_1 - R_f(I_T) - L_1 \dfrac{dI_1}{dt} = \mathrm{V}_1(\mathrm{D}_1) \\ V_{R2} - R_2 I_2 - R_f(I_T) - L_2 \dfrac{dI_2}{dt} = \mathrm{V}_2(\mathrm{D}_2) \end{cases} \quad (2)$$

Where V_R is the voltage of the PD place, I_1 and I_2 are the measured currents at PDs place, I_T is the sum of I_1 and I_2, R_1 and R_2 are measured resistance form PDs place, R_f is fault resistance, $V_1(D)$ and $V_2(D)$ are voltage at the fault place, and D_1 and D_2 are the distance of the fault from PDs place. In these equations, the values of the D_1, D_2, and R_f are unknowns. Therefore, the aim of the proposed method is obtaining these variables.

On the other hand, R_1, R2, L_1 and L_2 are shown in terms of resistance and inductance per meter in (3):

$$\begin{cases} R_1 = R_L D_1 \\ R_2 = R_L D_2 \\ L_1 = L_L D_1 \\ L_2 = L_L D_2 \end{cases} \quad (3)$$

Where R_L and L_L are the value of resistance and inductance of cables per meter. In addition, at the fault location, the values of the $V_1(D_1)$ and $V_2(D_2)$ are zero. Thus, the values of the fault distances in terms of fault resistance is calculated as

$$\begin{cases} D_1(R_f) = \dfrac{V_1 - R_f I_T}{L_L \dfrac{dI_1}{dt} + R_L I_1} \\ D_2(R_f) = \dfrac{V_2 - R_f I_T}{L_L \dfrac{dI_2}{dt} + R_L I_2} \end{cases} \quad (4)$$

On the other hand, because D_1 and D_2 are calculated from two opposite direction, sum of these values is constant and equal to the length of ring lines. Therefore, the D_T is defined as:

$$D_1 + D_2 = D_T \quad (5)$$

Moreover, the only unknown of the (5) is the fault resistance, and it is calculated by:

$$R_f = \frac{L_L \dfrac{dI_1}{dt}(A) + L_L \dfrac{dI_2}{dt}(B) - L_L D_T \dfrac{dI_1}{dt}\dfrac{dI_2}{dt}}{I_T(C) + R_L I_T^2} \quad (6)$$

Where,

$$\begin{cases} A = V_2 - R_L I_2 D_T \\ B = V_1 - R_L I_1 D_T \\ C = L_L(\dfrac{dI_1}{dt} + \dfrac{dI_2}{dt}) \end{cases} \quad (7)$$

Therefore, the value of fault resistance is calculated by (6), and then, the location of the fault is calculated by using (4). In summary, the computational steps of proposed method are:

1. Find the $D(R_f)$ in terms of fault resistance.
2. Substituting of the $D(R_f)$ in the (6).
3. Find the value of fault resistance.
4. Substituting the fault resistance value into $D(R_f)$.

IV. Simulation Results

The simulations have been done to validate the proposed scheme and calculate the fault resistance and location. The case study and its components are discussed in this section, briefly. And then, different scenarios are analyzed to show the accuracy of the protection scheme.

A. *Test system*

A low voltage 600 V DC Microgrid is simulated in the Digsilent, as shown in Fig. 1. Two types of converters are considered for loads and resources, AC/DC and DC/DC. Whereas DC/DC converters are connected to PV, battery and load, and AC/DC converters are connected to WT, AC load, and grid. Component ratings are given in the Table I.

TABLE I. Rating of DC Microgrid components

System component	Rating
DC grid voltage	600 V
Battery	Internal R=0.0125 Ohm, Number of Cells=125 Internal L=0.025 mH, Battery Rating= 70 Ah
PV	V_{mp}= 31.73, I_{mp}=8.98, 15 kW
WT	10 kW
Load	Constant load, 20 kW
Motor	4.5 kW
Cable parameters	R=0.028 Ohm/km, L=0.1 mH/km, Copper

B. *Fault in components*

A DC Microgrid, where loads and resources are connected at both ends of a cable, and the system has ring configuration considered to test the proposed scheme. The length of each segment is 200 m, and the unknown parameters of the proposed method are fault resistance and location. In this part, the fault is assumed to occur at resources and loads with different fault resistances. A fault has occurred at PV with 400 m distance from PD1. And, in this case, a fault resistance with different values from 0 to 3 Ohm is considered. It is observed that the amount of the error of fault changes from 0% to 0.82%. The values of error in terms of the calculated location of a fault in PV are depicted in Fig. 2. It is observed that the calculation error of the fault location nonlinearly increases as the fault resistance increases. This is because, first, the value of the fault resistance adds to the line length between fault location and PD. However, this effect minimized due to the using two directional method. Moreover, because of giving the absolute value of error in Fig. 2, by increasing the fault resistance, the value of error increases from a negative value to positive values. The negative values mean the error in (1) is negative, in other words, the value of calculated location is higher than the actual location. In continue, different values of the fault resistance are taken into account. Then the fault location and resistance are accurately calculated by (4) and (6). The results for various components are given in Table II and III, respectively.

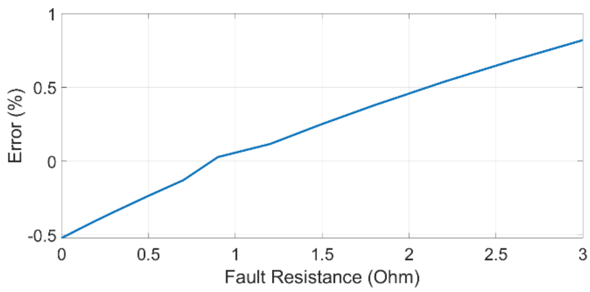

Fig. 2. The error of fault in PV in terms of fault resistance variation

TABLE II. CALCULATED FAULT LOCATION IN COMPONENTS

Component	Fault resistance (Ohm)	Actual fault distance (m)	Calculated fault distance (m)	Error%
PV	1.50	400	401.00	0.25%
WT	0.30	600	593.00	1.16%
DC Motor	0.90	1000	1051.2	5.12%

TABLE III. CALCULATED FAULT RESISTANCE IN COMPONENTS

Component	Actual fault resistance	Calculated fault resistance	Error%
PV	0.30	0.2875	4.17%
WT	0.30	0.2823	5.9%
DC Motor	0.30	0.2809	6.37%

C. Fault in lines

Fault in line is simulated for different fault locations and resistances. The error of fault distance calculation for different fault resistances and locations is presented in Table IV. It is noticed that the error increases as the fault resistance increase, but, the error of fault distance calculation is under 5%. In addition, the absolute error of fault distance calculation based on the actual fault resistance and location is shown in Fig. 3. By increasing the distance and fault resistance, the error will increase because the effect of the inductance of the cable decreases as the fault resistance increase. In this method, due to the using two directional PD in a DC Microgrid ring, the contribution of the fault current from other end is considered.

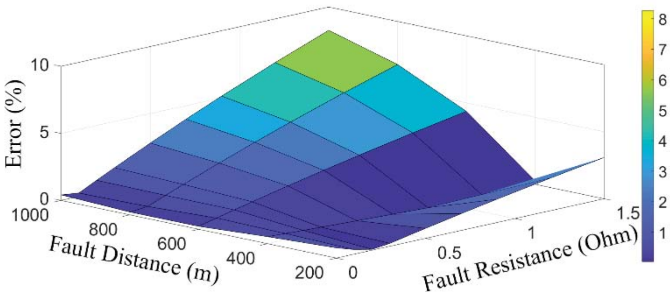

Fig. 3. The absolute error of fault location calculation

TABLE IV. The Error of fault distance for fault in the cable

Actual fault distance (m)	Fault resistance (Ohm)	The error of fault distance (%)
150	0.2	0.13%
450	0.25	0.65%
700	0.3	1.28%
900	0.4	2.04%
1050	0.5	2.85%

D. Considering variation in DC Microgrid

In a real situation, the value and mode of the active power of resources are variable. Therefore, a protection scheme cannot be implemented or design for a fix situation. Thus, the proposed method is tested in different scenarios. In the first scenario, DC Microgrid protection is compared in islanded and grid-connected mode. The second scenario compares the connect and disconnect mode of DC Motor. The results of these scenarios are given in Table V. The results prove that the proposed protection method can protect the system during variation of DC Microgrid topology and operation mode, and, the errors of fault distance calculation in different modes in each scenario are almost same.

TABLE V. THE RESULTS OF PROPOSED PROTECTION METHOD FOR DIFFERENT SCENARIOS

Scenario	Actual fault location (m)	Calculated fault location (m)	Error (%)
Scenario 1			
Islanded mode	200	201.4	0.70%
Grid-connected mode	200	198.4	0.81%
Scenario 2			
DC Motor-connected	1000	977.0	2.30%
DC Motor-disconnected	1000	977.1	2.29%

E. Comparison with existing schemes

The qualitative and quantitative performance of the proposed scheme is compared with other methods [20-23] based on the cost, accuracy, and need of communication link. Table VI shows the comparison of these five methods. All methods are compared on the basis of the error in fault location at the same distance. It is an undeniable fact that the cost of the proposed scheme is much lower than [20,23], due to the implementing local PDs. The suggested method in [21] is only effective for fault with low resistance. Therefore, it cannot detect HIFs, but, in terms of error for different fault locations, as shown in Table VI, the error of the proposed method is much lower than [22]. Also, the proposed method is further compared with the scheme of [23] in terms of accuracy for fault locating in different resistance and locations. As shown as Fig. 1., faults with different resistances and locations are analyzed. The transient behaviors of current are utilized to calculate the fault resistance and location by two PDs. Errors of the fault location calculation using [23] and proposed scheme are given in the Table VI. The technique of [23] is only capable to locate faults which are close to the PD. Due to considering the only single source and passive loads, by increasing the fault resistance and distance of fault, the error of fault calculation will increase.

TABLE VI. COMPARISON OF THE FAULT LOCATION METHODS

Parameters	[20]	[21]	[22]	[23]	Proposed Method
Require Communication Link	No	No	No	No	No
Require external unit	No	Yes	Yes	No	No
Maximum error of fault location	12%	7.8%	7%	20%	5%
Cost	Low	High	High	Low	Low

V. CONCLUSION

Due to the fast isolation of fault and less available data, DC Microgrid fault location is a challenging task. In addition, unlike the conventional systems, the bidirectional fault current is taken into account for protection of the DC Microgrid by a localized method. In this paper, the current transients during the fault are used to design a localized fault location and resistance calculation scheme, without using communication links. A mathematical equation of the current and voltage behavior is derived to calculate the fault resistance and location. The proposed method calculates the fault resistance and location without using any communication link. The location of component and line faults are obtained with an error less than 5%. In addition, the proposed method is applicable to DC Microgrid with ring configuration for locating faults with different fault resistances. Moreover, the proposed scheme can protect the DC Microgrids during changing the topology and operation mode. Therefore, the effectiveness of the proposed algorithm is shown by simulation results and compared with other existed algorithms.

REFERENCES

[1] Kalesar, Babak Mohamadi, et al. "Effect of Angles of Harmonic Components of Back to Back Converter of Distributed Generation Resources on Current Behavior of Distribution Networks." 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe). IEEE, 2018.

[2] Teymouri, Armin, S. Hamid Fathi, and Faramarz Karbakhsh. "An advanced hysteresis controller to improve voltage profile of power system with PV units: A smart grid power exchange framework." 2015 30th International Power System Conference (PSC). IEEE, 2015.

[3] Bayati, Navid, Amin Hajizadeh, and Mohsen Soltani. "Protection in DC microgrids: a comparative review." IET Smart Grid 1.3 (2018): 66-75.

[4] T. Kaipia, P. Salonen, J. Lassila, and J. Partanen, “Application of low voltage dc-distribution system - a techno-economical study,” in Proc. 19th Int. Conf. Elect. Distrib., May 2007.

[5] Bayati, Navid, Amin Hajizadeh, and Mohsen Soltani. "Accurate Modeling of DC Microgrid for Fault and Protection Studies." 2018 International Conference on Smart Energy Systems and Technologies (SEST). IEEE, 2018.

[6] Salomonsson, Daniel, Lennart Soder, and Ambra Sannino. "Protection of low-voltage DC microgrids." IEEE Transactions on Power Delivery 24.3 (2009): 1045-1053.

[7] Park, Jae-Do, et al. "DC ring-bus microgrid fault protection and identification of fault location." IEEE transactions on Power delivery 28.4 (2013): 2574-2584.

[8] Yu, Ming, et al. "DC short circuit fault analysis and protection of ring type DC microgrid." Power Electronics and Motion Control Conference (IPEMC-ECCE Asia), 2016 IEEE 8th International. IEEE, 2016.

[9] Mohanty, Rabindra, and Ashok Kumar Pradhan. "Protection of smart DC microgrid with ring configuration using parameter estimation approach." IEEE Transactions on Smart Grid 9.6 (2018): 6328-6337.

[10] Meghwani, A., S. C. Srivastava, and S. Chakrabarti. "A non-unit protection scheme for DC microgrid based on local measurements." IEEE Transactions on Power Delivery 32.1 (2017): 172-181.

[11] L. Tang and B. Ooi, “Locating and isolating DC faults in multi-terminal DC systems,” IEEE Trans. Power Del., vol. 22, no. 3, pp. 1877–1884, Jul. 2007.

[12] da Silva, Chrystian Dalla Lana, et al. "A continually online trained impedance estimation algorithm for transmission line distance protection tolerant to system frequency deviation." Electric Power Systems Research 147 (2017): 73-80.

[13] Iurinic, Leonardo Ulises, et al. "Distribution systems high-impedance fault location: A parameter estimation approach." IEEE Transactions on Power Delivery 31.4 (2016): 1806-1814.

[14] M. Shukr, D. W. P. Thomas, and P. Zanchetta, "VSCHVDC transmission line faults location using active line impedance estimation," in IEEE International Energy Conference and Exhibition (ENERGYCON), 2012, pp. 244-248.

[15] M. J. Mousavi and K. L. Butler-Purry, “A novel condition assessment system for underground distribution applications,” IEEE Trans. Power Syst., vol. 24, no. 3, pp. 1115–1125, Aug. 2009.

[16] Bayati, Navid, Amin Hajizadeh, and Mohsen Soltani. "Impact of Faults and Protection Methods on DC Microgrids Operation." 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe). IEEE, 2018.

[17] S. D. A. Fletcher, P. J. Norman, S. J. Galloway, P. Crolla, and G. M. Burt, “High speed differential protection for smart DC distribution system,” IEEE Trans. Smart Grid, vol. 5, no. 5, pp. 2610–2617, Sep. 2014.

[18] J. D. Park, J. Candelaria, L. Ma, and K. Dunn, “DC ring-bus microgrid fault protection and identification of fault location,” IEEE Trans. Power Del., vol. 28, no. 4, pp. 2574–2584, Oct. 2013.

[19] Kang, Ning, Jiaxiong Chen, and Yuan Liao. "A fault-location algorithm for series-compensated double-circuit transmission lines using the distributed parameter line model." IEEE Transactions on Power Delivery 30.1 (2015): 360-367.

[20] Yang, J., Fletcher, J.E., OReilly, J.: ‘Short-circuit and ground fault analyses and location in VSC-based DC network cables’, IEEE Trans. Ind. Electron., 2012, 59, (10), pp. 3827–3837

[21] Mohanty, R., Balaji, U.S.M., Pradhan, A.K.: ‘An accurate noniterative faultlocation technique for low-voltage DC microgrid’, IEEE Trans. Power Deliv.,2016, 31, (2), pp. 475–481

[22] Christopher, E., Sumner, M., Thomas, D., et al. ‘Fault location in a zonal DC marine power system using active impedance estimation’, IEEE Trans. Appl. Ind., 2013, 49, (2), pp. 860–865

[23] Feng, X., Qi, L., Pan, J.: ‘A novel fault location method and algorithm for DC distribution protection’, IEEE Trans. Ind. Appl., 2017, 53, (3), pp. 1834–1840