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DETECTING THE FAULT SECTION IN THE DISTRIBUTION NETWORK WITH DISTRIBUTED GENERATORS BASED ON OPTIMAL PLACEMENT OF SMART METERS

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Abstract: ***One of the most important issues in employing distribution networks is detecting the fault location in medium-voltage distribution feeders. Due to the vastness of distribution networks and growing distributed generation (DG) sources in this network, detection is difficult with the common methods. The aim of this paper is to present a method based on voltage distributed meters in a medium-voltage distribution network (by smart meters installed along the feeder) in order to detect the fault location in the presence of DG sources. Due to vastness of distribution network and cost of installing smart meters, it is not economically possible to install meters in all the Buses of the network. That's why in this article, combination of genetic and locating algorithms and fault-based on voltage drop has been used to suggest a method to optimize the meter locations. In order to evaluate the efficiency of the method suggested, first we determine the optimal number and location of the meters and then we apply the fault that has been simulated in different Buses of the sample network, using PSCAD/EMTDC software. After results analysis, the fault location is estimated by MATLAB. Simulation results show that the fault locating method by optimal number of meters has good efficiency and accuracy in detecting faults in different spots and in different resistance ranges.***

Keywords: Fault location, optimal placement, feeder smart meters, distributed generation sources

1. INTRODUCTION

Power distribution network is a part of the huge energy delivery network which, while being complicated, provides services to a huge number of consumers and covers vast geographical areas. In order to reduce the energy outage (considering the network's faults), protective relays are widely used in the distribution network. One of the useful plans which increases services to the customers is the ability to quickly detect and separate the faults [1]. Recent advances in metering and communication systems have made power companies look for efficient solutions to improve the monitoring and automation of distribution systems. These advances include two-sided communications of a metering system, data management system and real-time access to information such as consumption, voltage drop and power exit [2-3]. Therefore, smart feeder and consumer meters can achieve potential applications beyond measurement for expense account purposes. For example in [4], using smarts meters that have been initially installed in the distribution system has been suggested as an affordable solution for monitoring and automation of distribution systems. Smart meters are smart sensors that can be installed across the distribution system, from sub-transmission substations to the consumer location. Of these types of devices, we can name digital protective relays, digital fault recorders, smart meters, and power quality meters [5]. One of the important applications of these meters in related to fault management; because the fault outcome in the distribution network will lead to reliability and power quality problems such as voltage drops, transient or continual outages, and high operational costs. In this regard, one of the main topics is fault management of fault locating methods [5]. Because logical fault locating methods with high-accuracy can lead to reduced cost and time for retrieving energy sources. In traditional distribution systems and after a fault occurs, system operators usually use methods such as switching operations or subscribers' contacts to estimate the fault location [6]. These methods are rudimentary and based on trial and error which usually take time and reduce the lifespan of electric equipment by connecting and disconnecting the sub-current of the short connection. Automatic methods are another type of fault location methods. These methods are generally divided into two main categories of impedance methods and methods based on traveling waves [7]. Impedance-based methods are among the most applicable methods in fault locating; their most important problem is estimation of several spots in the network (especially in distribution networks) as the fault location. On the other hand, the most important problem with the methods based on traveling waves is their requirement to use metering devices with extremely high sampling rate [8].

Another type of method uses the measured voltage and current in the substation, distributed voltage and current metering across the network and network's electric parameters to estimate the fault location. Therefore, data collected by smart metering devices can be used for fault location in distribution networks. Fault locating algorithms presented in [9-12], and also the method presented in this article are of this type. In [19-23], the artificial neural network is used to detect the faulted section and fault location.

Considering the vastness of distribution networks and the multiplicity of spots candidate for installment of smart metering devices, optimal placement of this equipment is very important. Most of the methods suggested so far have mentioned the issue of optimal placement of metering devices for visibility of system condition and only a few articles have mentioned the issue of visibility of fault location [13-15]. That's why in this article, a method for optimal placement of meters has been suggested for fault location visibility using the combination of the fault locating algorithm (presented in the next section) and the genetic algorithm which will be discussed in the following sections.

2. FAUT LOCATION METHODS BASED ON SMART METERS

The fault locating methods presented in this article are based on the monitoring ability of feeder meters and short connection equations. The main idea of the suggested method for fault locating is employing this ability; in a way that voltage drop information could be measured for calculating the fault location index which shows the nearest Bus to the fault location. In the case of fault detection in the network, meters will be sampled prior and during the fault occurrence in order to provide an effective amount of voltage. The equation model of fault locating is presented in the following [14].

Using the amount of voltage measured by the feeder meters, we can calculate the voltage deviation by the following:

$$\Delta V_i^{(abc)} = V_i^{(abc)p} - V_i^{(abc)f} \qquad (1)$$

In which, the subscript I refers to the feeder meter installed in the Bus number i.

$V_i^{(abc)p}$ and $V_i^{(abc)f}$ are respectively the voltages measured before and during the fault and the superscripts a,b,c show voltage deviation is phases a,b,c. If a fault occurs in Bus k, the fault current in each phase can be estimated by the following equation using the voltage deviation measured by the meter i:

$$I_{fault,ik}^{(abc)} = \left(Z_{ik}^{(abc)}\right)^{-1} . \Delta V_i^{(abc)} \qquad (2)$$

In which the ik 3*3 sub-matrix is from the impedance matrix of the 3-phased Bus system and the fault current calculated by measuring the voltage of meter i, considering the fault in Bus number k. It should be noted that in order to improve the method's accuracy, the low-voltage section of the distribution network is modeled by load and is embedded in the system's impedance matrix. Load estimation can be done using common load curves or, based on the obtained information, by the consumers' smart meters.

Therefore, if the meter N exists in the network. N is the fault current estimation with the assumption that Bus k has a fault. If the fault actually occurs in the Bus k, all the estimated currents should have the same amount that is close to the actual one. On the other hand, if the fault occurs on any other BUS, the fault will be present on the fault current that is estimated based on the measurements of each meter i. In addition, the fault calculated by different meters might be different from each other.

Based on the above explanations, the fault locating index δ_k can be used based on the detection of the real bus in which the fault has occurred. This index is calculated by summing the difference between N (the estimated fault current) and the average of estimated currents, considering that bus k has a fault, using the equation (3):

$$\delta_k = \sum_{ph}^{a,b,c} \sum_{i=1}^{Nfm} \left| I_{fault,ik}^{ph} - I_{fault}^{ph} \right| \qquad (3)$$

In which $I^{ph}_{fault,ik}$ is the fault current calculated for phase ph by measuring the voltage by feeder meter in bus I and I^{ph}_{fault} is the average of all the calculated fault currents by voltage measurement of all the meters for bus k. As it was previously mentioned, if the bus understudy has a fault, all the estimated currents are practically similar. Therefore, the bus related to the smallest fault index is selected as the bus with the fault.

When only the voltage amount is used, there is no need for synchronization and because all the meters are sampled simultaneously by the same fault incidence, the complexity and costs will decrease.

To be summarized, the following steps explain the method application to locate the fault location, after a fault is detected:

- 1 - Forming the network's impedance matrix, considering the loads and distributed generation sources.
- 2 - Obtaining the voltage before and during the fault by feeder meter by bus i.
- 3 - Estimation of the fault current of $I^{ph}_{fault,ik}$ for each bus in the system using the measurements of feeder meters and Zbus matrix.
- 4 - Calculating the average of fault current of I^{ph}_{fault}.
- 5 - Calculating the current fault index of δ_k for each bus k.
- 6 - Showing the bus related to the minimum δ_k .

In the first step, as it was previously mentioned, all the loads and distributed generation sources need to be modeled and embedded in the impedance matrix. In this article, the constant impedance model is used to model the loads in order to improve the efficiency of fault locating method, considering the loads in system's impedance matrix. Also, PQ (real and reactive power) model (DG model as the PQ bus) is used to model distributed generation sources and DG modeling as the PQ bus is done by using negative load model [16].

3. SUGGESTED METHOD FOR OPTIMAL PLACEMENT OF SMART METERS IN ORDER TO MAKE THE FAULT LOCATION VISIBLE

In the suggested method for optimal placement, the combination of genetic optimization algorithm and fault locating algorithm based on smart meters (which were previously mentioned) is used. In this method, we employ the fault location algorithm to evaluate each particle produced by the genetic algorithm and considering the number of meters in that particle and its

effectiveness on fault location algorithm, a cost is allocated to that particle. This method receives the network information, connected loads and installation points of measurement tools as input and then applies the fault locating algorithm and compares the original fault location with the location achieved by the locating algorithm to calculate the costs of locations suggested for installation of meters. In this method, fault locating cost will be calculated per fault occurrence in each network bus and the total cost of each particle consists of total fault locating costs in each network bus plus the number of meters used in the suggested particle.
Performance steps for the suggested method are as the following:

- 1 - Receiving the network information (impedance of lines, distances between buses, loads and etc.)
- 2 - Receiving the particle or suggested locations for installation of meters and calculating the number of meters used in the particle; NOM (Number of Meter)
- 3 - Fault occurrence in all the network buses and applying the fault locating algorithm
- 4 - Comparing the response of the fault locating algorithm (pf) with the real fault location (rf). If the response doesn't match the real location, then cost(j,i)=1; otherwise, cost(j,i)=0
- 5 - Total particle cost is calculated by the following equation:

$$Tcost(j) = NOM + \sum_{i=1}^{M} cost(j,i) \quad (4)$$

4. NETWORK INFORMATION

The network under study is the medium-voltage 33 bus distribution network of [17]. The network is a 12.66 kV network and the total load connected to it is 3715 kW and 2300 kVar. The single linear network model is demonstrated in Figure 1.

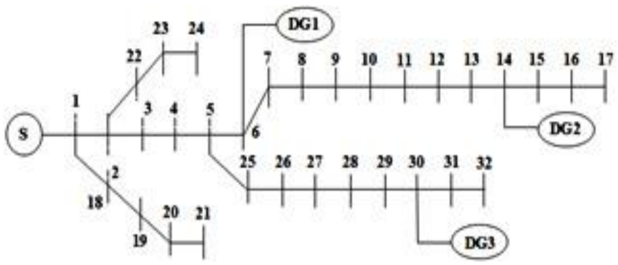

Figure 1. The medium-voltage 33 bus distribution network [17].

Table 1. Results of optimization of location, size and power factor of distributed generators [18]

DG number	Optimal power factor	Optimal location and size (kVA)	Ploss (kW)	Loss reduction (%)
No DG	-	-	211.2	-
DG1	0.82	Bus 6 3107	67.9	67.85
DG2	0.82	Bus 14 2195.1098	44.39	78.98
DG3	0.82	Bus 30 1098.768, 1098	22.29	89.45

Reference [18] has presented a method based on advanced analysis, in order to optimize the size and location of distributed generators in the medium-voltage 33 bus distribution network. The aim of this optimization is to minimize the losses across the system. A quick technique has also been used in this method to obtain the optimal power factor of distributed generators. Table 1 shows the results of this optimization in which the optimal number, location, size and power factor of distributed generators have been determined.

As it is obvious from Table 1, the presence of three DGs in buses 6, 14 and 30 of the sample network will lead to the most loss reduction. In this condition, approximately 65% of the system's total load will be provided by these three DGs. The results of Table 1 have also been used in this article and DGs are put in buses 6, 14 and 30 as a PQ model.

5. SIMULATION RESULTS

In this part and in order to analyze the performance of the fault locating method with the optimal number of meters, first we apply the optimal placement algorithm on the sample network and determine the installation points of meters. After determining the optimal number and location of meters, the fault location method will be tested on the network in different conditions including different values for fault resistance and different fault types.

Assumptions in these simulations include:

- The medium-voltage part of the distribution network will be studied and the network does not have loops.
- The network understudy has been simulated in PSCAD software and the meters have been simulated in buses with meters.
- Loads connected to the network have been considered as constant impedance model.
- The faults apply to all the system buses in order to execute the optimal placement algorithm as a single-phase fault to the ground with the fault resistance of 5 Ω.
- The measurements of PSCAD will be analyzed in MATLAB.

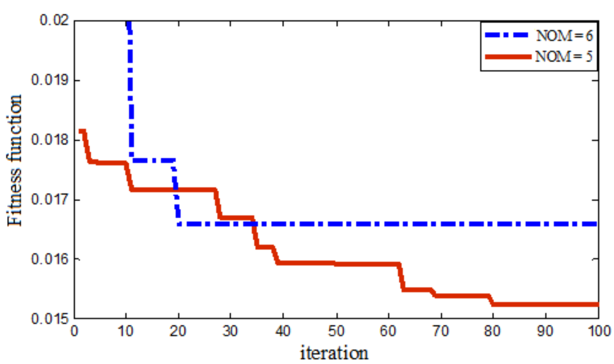

Figure 2. Optimization results of smart meters number with genetic algorithm.

Considering all the above assumptions, the optimization results are shown in Table 2. As you can see in Figure 2, the fitness function value (equation 4) was better for 5 smart meters than 6, although it should be noted that 4 smart meters may also be less cost, but detecting the fault section become more difficult so the best case is the 5 smart meters in the network.

Table 2. Optimal number and locations for installation of meters

The optimal number of measurements	5
The location of measurements	17-19-21-24-30

In the following, the fault location method will be tested in various conditions on the sample network with an optimal number of meters. For this purpose, the fault is separately applied in each stage to one of the network buses and in that stage, a fault index will be obtained for all the network buses and the bus with the minimum fault index is the bus with the fault.

By placing meters in buses 30, 24, 21, 19 and 17, first we apply the fault location method with a 3-phase fault to the ground on the network and its results are shown in Table 3.

Table 3. Lines Information of Medium Voltage Test Network

Location of fault	1	2	3	4	5	6	7	8
Suggested location	1	2	3	4	5	5	7	8
Error	-	-	-	-	-	√	-	-
Location of fault	9	10	11	12	13	14	15	16
Suggested location	9	10	11	12	12	14	15	15
Error	-	-	-	-	√	-	-	√
Location of fault	17	18	19	20	21	22	23	24
Suggested location	17	18	19	20	21	22	23	24
Error	-	-	-	-	-	-	-	-
Location of fault	25	26	27	28	29	30	31	32
Suggested location	25	26	27	28	29	30	31	30
Error	-	-	-	-	-	-	-	√

According to Table 3, it can be seen that the fault location method with the optimal number of meters in the presence of DG has shown good efficiency and among all the system buses, it only estimated four buses wrong which makes the total error only 12.5 percent.

As it was stated, in the fault location algorithm, the bus with the minimum fault index will be considered as the bus with the fault. In this article and in order to better show the fault index values for the detection of faulty bus, we divide 1 by all the fault index values and therefore in the following figure, the bus Tcost(j) with the highest fault index will be known as the faulty bus.

Since most of the faults occurring in the distribution systems are single-phase short connection faults to the ground, in order to analyze the efficiency of fault locating method with the optimal number of meters against fault type and resistance, the fault location method has been applied with fault resistances of 1, 30, 60 and 15j+1 ohm on the network, despite the presence of single-phase fault to the ground. Simulation results for all the assumptions are exactly like the results of Table 3 in which the fault locating algorithm with the optimal number of meters, estimates 4 buses wrongly: buses 6, 13, 16 and 32. For example, fault index values for a single-phase fault to the ground with the resistance of 0.5j+1 ohm are shown in Figure 3.

As it was determined, change in fault type and fault resistance does not impact the efficiency of fault location algorithm.

6. COMPARING THE PRESENTED METHOD WITH SIMILAR METHODS

As it was stated in the introduction, a category of fault location methods is based on measurements in substation and along the system and algorithms suggested in [9-12] and the method presented in this article are of this type and therefore, here we compare these methods.

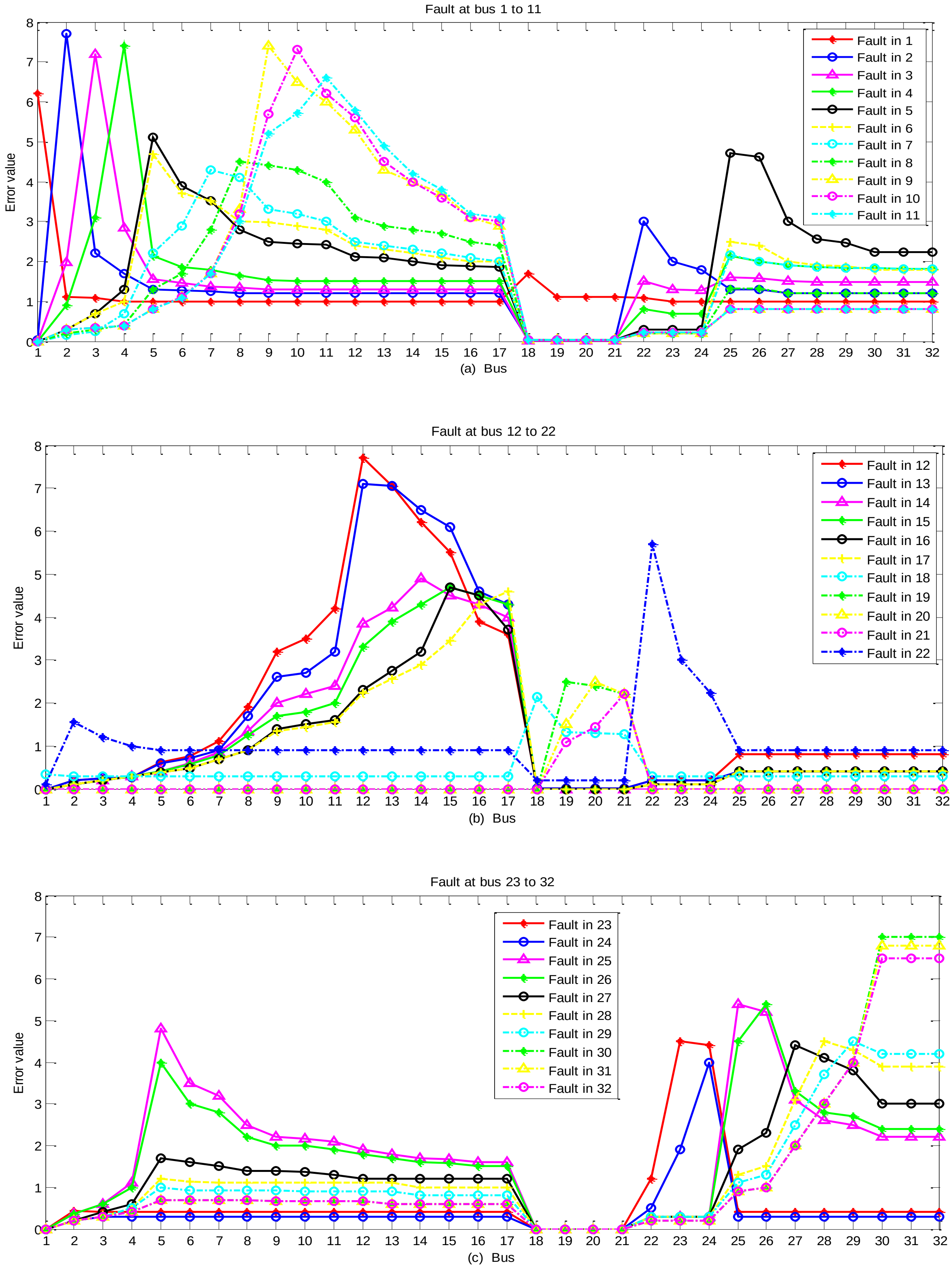

Figure 3. Fault indices values with optimal number of meters in the presence of DG and single-phase fault occurrence to the ground with the fault resistance of 15j+1 ohm: a) fault application is buses 1 to 11, b) fault application is buses 12 to 22, c) fault application in buses 23 to 32.

For the method presented in this article, the calculations are significantly fewer than the method suggested in [10] (because of not being repetitive). System parameters are used in both algorithms. Nonetheless, the method suggested in [10] runs the load distribution multiple times, whereas the present study only uses a simple equation.

The fault location method used in [11] uses voltage phasor which is distributed measured across the feeder (to find the fault location). The fault locating process in this method uses the connection theory, a method for fault resistance estimation and also load estimation. That's why the number of calculations will be plenty in this method and fault resistance will have a higher influence on the results compared to the method presented in this article. Also, the method used in [11] needs GPS information which is commonly unavailable in distribution networks.

Reference [12] has used a method similar to the method presented in this article to find the fault location; the difference is that in this method, simultaneous voltage and current measurements are used in the junction of distributed generators and substation which leads to increased costs and complexity.

7. CONCLUSION

In this article, a method was presented for fault locating based on the optimal placement of smart meters in medium-voltage distribution networks with distributed generators. For optimal placement of meters, genetic algorithm is used as the optimal placement algorithm and in order to evaluate the particles produced by the genetic algorithm, fault location method based on smart meters is used.

Research findings are summarized as the following:

- In order to locate faults using an algorithm based on smart metering devices, there is no need for meters to be installed in every place in the network and by installing an optimal number of them in optimal locations, the fault location can be detected with good accuracy.
- The fault location algorithm with the optimal number of meters in the presence of distributed generation sources shows robust performance.
- The fault type and fault impedance value doesn't have any influence on the performance of fault location algorithm and in all the fault types, fault location algorithm with the optimal number of meters has shown good and robust performance.

8. REFERENCES

[1] Mak, S.T., 1999, June. Synergism between intelligent devices and communication systems for outage mapping in distribution networks. In Paper presented at CIRED'99, 15eme Congres International des Reseaux Electriques de Distribution.

[2] Gungor, V.C., Sahin, D., Kocak, T., Ergut, S., Buccella, C., Cecati, C. and Hancke, G.P., 2011. Smart grid technologies: Communication technologies and standards. IEEE transactions on Industrial informatics, 7(4), pp.529-539.

[3] Popa, M., 2011, June. Data collecting from smart meters in an Advanced Metering Infrastructure. In 2011 15th IEEE International Conference on Intelligent Engineering Systems(pp. 137-142). IEEE.

[4] Luan, W., 2010, October. Low cost feeder monitoring solution in support of utility operations. In Proc. CIGRE Conf. Power Syst.

[5] Kezunovic, M., 2011. Smart fault location for smart grids. IEEE Transactions on Smart Grid, 2(1), pp.11-22.

[6] Estebsari, A., Pons, E., Bompard, E., Bahmanyar, A. and Jamali, S., 2016, June. An improved fault location method for distribution networks exploiting emerging LV smart meters. In 2016 IEEE Workshop on Environmental, Energy, and Structural Monitoring Systems (EESMS) (pp. 1-6). IEEE.

[7] Trindade, F.C. and Freitas, W., 2017. Low voltage zones to support fault location in distribution systems with smart meters. IEEE Transactions on Smart Grid, 8(6), pp.2765-2774.

[8] Chen, P.C., Malbasa, V., Dong, Y. and Kezunovic, M., 2015. Sensitivity analysis of voltage sag based fault location with distributed generation. IEEE Transactions on Smart Grid, 6(4), pp.2098-2106.

[9] Baldwin, T., Kelle, D., Cordova, J. and Beneby, N., 2014, March. Fault locating in distribution networks with the aid of advanced metering infrastructure. In 2014 Clemson University Power Systems Conference (pp. 1-8). IEEE.

[10] Pereira, R.A.F., da Silva, L.G.W., Kezunovic, M., and Mantovani, J.R.S., 2009. Improved fault location on distribution feeders based on matching during-fault voltage sags. IEEE Transactions on Power Delivery, 24(2), pp.852-862.

[11] Lotfifard, S., Kezunovic, M., and Mousavi, M.J., 2011. Voltage sag data utilization for distribution fault location. IEEE Transactions on Power Delivery, 26(2), pp.1239-1246.

[12] Brahma, S.M., 2011. Fault location in power distribution system with penetration of distributed generation. IEEE transactions on power delivery, 26(3), pp.1545-1553.

[13] Liao, Y., 2009. Fault location observability analysis and optimal meter placement based on voltage measurements. Electric Power Systems Research, 79(7), pp.1062-1068.

[14] Trindade, F.C., Freitas, W. and Vieira, J.C., 2014. Fault location in distribution systems based on smart feeder meters. IEEE transactions on Power Delivery, 29(1), pp.251-260.

[15] Farag, H.E., El-Saadany, E.F., El Shatshat, R. and Zidan, A., 2011. A generalized power flow analysis for distribution systems with high penetration of distributed generation. Electric Power Systems Research, 81(7), pp.1499-1506.

[16] Teng, J.H., 2008. Modelling distributed generations in three-phase distribution load flow. IET generation, transmission & distribution, 2(3), pp.330-340.

[17] Baran, M.E. and Wu, F.F., 1989. Network reconfiguration in distribution systems for loss reduction and load balancing. IEEE Transactions on Power delivery, 4(2), pp.1401-1407.
[18] Hung, D.Q. and Mithulananthan, N., 2013. Multiple distributed generator placement in primary distribution networks for loss reduction. IEEE Transactions on industrial electronics, 60(4), pp.1700-1708.
[19] Dashtdar, Masoud. "Fault Location in Distribution Network Based on Fault Current Analysis Using Artificial Neural Network." *Journal of Electrical & Computer Engineering* 1 (2018): 18-32.
[20] Dashtdar, Masoud, Rahman Dashti, and Hamid Reza Shaker. "Distribution network fault section identification and fault location using artificial neural network." In *2018 5th International Conference on Electrical and Electronic Engineering (ICEEE)*, pp. 273-278. IEEE, 2018.
[21] Dashtdar, Majid, Masoud Dashtdar. "Fault Location in the Transmission Network Based on the Analysis of the Recorded Current by the Relay Using a Discrete Wavelet Transform." 2rd International Conference on Electrical Engineering, Mechanical Engineering, Computer Science and Engineering. (2019).
[22] Majid Dashtdar, Masoud Dashtdar, Fault Location in the Transmission Network Using a Discrete Wavelet Transform, American Journal of Electrical and Computer Engineering. Vol. 3, No. 1, 2019, pp. 30-37. doi: 10.11648/j.ajece.20190301.14.
[23] Al-Fuhaidy, Farouk Abduh Kamil, Faisal Saif Alkamali, Khaled Abdullah Al-Soufy, Tianjin Feng, Uma Devi Sankarasubbu, Senthil Kumar Suburaj, Majid Dashtdar, et al. "DFT-Based OFDMA System with Phase Modulation for Broadband Communication." *American Journal of Electrical and Computer Engineering* 3, no. 1 (2019): 1-9.