Fault-Location Scheme for Power Distribution System with Distributed Generation

Shamam Alwash, Vigna K. Ramachandaramurthy, Nadarajah Mithulananthan

Institutions: Universiti Tenaga Nasional, University of Queensland

Published on: 01 Jun 2015 - IEEE Transactions on Power Delivery (IEEE)

Topics: Fault indicator, Stuck-at fault and Power-system protection

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPWRD.2014.2372045, IEEE Transactions on Power Delivery

Fault Location Scheme for Power Distribution System with Distributed Generation

S. F. Alwash, *Member, IEEE*, V. K. Ramachandaramurthy, *Senior Member, IEEE*, and N. Mithulananthan, *Senior Member, IEEE*

***Abstract*-- This paper presents a novel fault location scheme for unbalanced power distribution system in the presence of the distributed generation (DG). The proposed scheme first identifies the possible fault locations using a new formulation of impedance-based method. The new formulation overcomes the requirement of fault type identification by using only one fault location equation. The proposed equation is applicable to all shunt fault types. From the possible fault locations, the exact fault location is then identified by matching the measured voltage at the substation bus and each DG unit bus with calculated ones. The proposed scheme is applicable for all DG types without the need for their individual parameters. The balanced and unbalanced laterals and the capacitive effect of distribution line are also considered. The proposed scheme was evaluated and tested on a modified IEEE 34-bus distribution system using PSCAD/EMTDC software.**

***Index Terms*-- Distributed generation, fault location, power distribution faults, power system protection.**

I. INTRODUCTION

THE deregulation and privatization of power systems have forced electrical utilities to keep the supply and the service continuity indices within the required standards, albeit credible fault and contingencies continue to happen. Faults in power distribution systems are considered the main contributor to the supply interruption and responsible for poor service continuity indices [1]. The most effective way to improve these indices is by employing efficient fault location (FL) techniques that can minimize the inspection and service restoration times, and thus, reduce outage time and improve the service continuity. Moreover, locating temporary fault can also help in preventing future permanent fault that could bring more damage to equipment [2]. Accordingly, many FL techniques have been developed and deployed in distribution systems [3]. Most of these techniques are designed for radial networks with a single direction of the power flow. However, the assumption of unidirectional power flow is changing as a result of Distributed Generation (DG) units integration. The penetration of DG units changes the radial characteristics of distribution systems to non-radial and multi-source systems. This new feature of the distribution systems affects the accuracy of the traditional FL methods. Hence, there is a need for a FL method that can be implemented in distribution systems in the presence of DG units.

Recently, some FL methods based on a modification or a re-coordination of the existing protective devices have been proposed for distribution system in the presence of DG units [4-8]. The objectives of these methods are correct identific-ation and isolation of the faulted area. However, the exact FL is not attempted.

Methods for determining the exact FL in distribution systems with DG units using artificial neural network (ANN) are presented in [9-12]. In these methods, simulations for various types and locations of faults are carried out to generate databases, which are then used to train ANN. These methods suffer from inaccuracy due to the continuous variations of loads and source impedance [13].

A FL method based on matching the calculated and measured voltage changes at all source buses in the distribution feeder is presented in [14]. In this method, the calculation process of the voltage changes assumes that the pre and during fault voltage at each load bus are equal. Hence, in the case of low fault resistance, the error may be very high.

Impedance-based FL methods using symmetrical-component or phase-component approach are proposed in [15]-[19]. In these methods, a FL equation has been derived for each fault type to identify the possible fault locations in the distribution system with considering only the synchronous generator type of DG unit. In addition, these methods use short line model, which neglect the capacitive effect of the overhead distribution lines. However, the capacitive effect can significantly affect the accuracy of the FL method [20].

An improvement on impedance-based FL method related to the capacitive effect consideration and the number of FL equations is presented in [20]. The method was formulated for a traditional distribution system where the presence of DG is not considered. The method uses two FL equations based on the identification of fault type. The first equation is used for ground fault types, whereas, the second equation is used for line-to-line fault. The three-phase fault without connection to ground is not considered in the two equations and the identification of fault type is required. However, it is difficult

This work was supported in part by Ministry of High Education and Scientific Research, Iraq, and in part by Power Quality Research Group, Universiti Tenaga Nasional, Malaysia.

Shamam F. Alwash is with the Power Quality Research Group, Universiti Tenaga Nasional, Selangor, Malaysia, and with University of Babylon, Babylon ,Iraq (e-mail: shamamalwash@ieee.org).

Vigna K. Ramachandaramurthy is with the Power Quality Research Group, Universiti Tenaga Nasional, Selangor, Malaysia (e-mail: vigna@uniten.edu.my).

Nadarajah Mithulananthan is with School of Information Technology and Electrical Engineering at the University of Queensland, Australia (e-mail: mithulan@itee.uq.edu.au).

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPWRD.2014.2372045, IEEE Transactions on Power Delivery

to obtain accurate fault type identification in the distribution systems [21]. In [22], a single FL equation has been derived for all possible fault types where the identification of fault type is not required. However, the method does not consider the exact fault point, the capacitive effect and the presence of DG in the distribution system.

Considering the aforementioned limitations of current FL methods, in this paper, a comprehensive FL scheme for unbalanced power distribution system in the presence of any possible DG type is proposed and examined. The proposed scheme identifies the FL using two steps. In the first step, a new impedance-based method is utilized to identify all possible fault locations using a novel FL equation, which is applicable for all single and compound faults types. The balanced and unbalanced laterals and the capacitive effect of distribution line are also considered. In the second step, the exact FL among the multiple candidate locations is determined based on matching the measured voltage at the substation bus and each DG unit bus with calculated ones.

This paper is organized as follows: Section II presents the methodology of the proposed FL scheme. Sections III and IV formulate the proposed impedance-based FL method and the proposed exact FL method, respectively. The case study is presented in Section V, whereas the results are presented in Section VI. Section VII presents the conclusions and contributions of this paper.

II. PROPOSED SCHEME

The proposed scheme assumes that the pre fault and during fault voltages and currents measured at the substation bus and the terminal of each DG unit are available as synchronized phasors using digital fault recorders and GPS means [23, 24]. The proposed scheme also assumes that all the system data is given except the load power demand at each load bus.

The pre fault data are used to estimate the load power demand at each load bus using the same procedures of the load power demand estimation method presented in [25], with modification to consider the presence of DG units. The basic idea of this method is to utilize a load flow approach to update normal loads values based on the measured pre-fault total power, which is supplied from all sources including the substation bus. The algorithm of this method shall be suppressed in this paper due to the space limitations.

Once the load power demand at each load bus is known, the bus impedance matrix can be determined for the distribution feeder [26]. Each line section in the feeder is modeled by using pi section model. The loads which are included in bus impedance matrix are modeled as constant impedance loads. Impact of the other load types and the load variation on the FL estimates will be discussed in the results and discussion section.

The measured currents at each source bus are treated in the proposed scheme as current injections. Hence, the source impedance of these units is not included in the bus impedance matrix. The advantage of this formulation is that the proposed scheme is not affected by the type of DG unit and its interface.

The bus impedance matrix and during fault voltages and currents measured at each source bus are then used in the proposed impedance-based FL method and the proposed exact FL method to identify the FL.

III. PROPOSED IMPEDANCE-BASED METHOD

In the following subsections, a new formulation of impedance-based FL method for unbalanced distribution systems in the presence of DG units is explained in detail.

A. Proposed FL Equation

Consider a simple distribution system with DG units, as shown in Fig. 1, which shows a faulty line section between buses i and j. The fault at point F can be of any possible shunt fault type. The fault point divides the faulty line section into two segments. These segments are marked as segment-p and segment-q, which are upstream and downstream of the fault point, respectively. Each segment is modeled by using "pi model" to take into account the capacitive effect of distribution line.

Using the sending-end voltages and currents of the segment-p, the voltage at the fault point $[V_F]$ can be calculated as in (1) [27]:

$$[V_F]=[d_{(\alpha)}][V_{s-p}]-[b_{(\alpha)}][I_{s-p}] \tag{1}$$

where;

$$[d_{(\alpha)}]=[U]+0.5\alpha^2[Z][Y_{sh}] \tag{2}$$

$$[b_{(\alpha)}]=\alpha[Z] \tag{3}$$

$[V_{s-p}]$ 3PH sending-end voltages of the segment-p (in volts)
$[I_{s-p}]$ 3PH sending-end currents of the segment-p (in amps)
$[Z]$ line series impedance matrix (in ohms)
$[Y_{sh}]$ line shunt admittance matrix (in ohms^{-1})
$[U]$ 3×3 unit matrix.
α per-unit fault distance

The dissipated apparent power in the fault is given by (4):

$$S_F=[V_F]^t[I_F]^* \tag{4}$$

Substituting (1) into (4) yields:

$$S_F=[V_{s-p}]^t[I_F]^*+0.5\alpha^2[V_{s-p}]^t[Z][Y_{sh}][I_F]^* - \alpha[I_{s-p}]^t[Z][I_F]^* \tag{5}$$

Considering a resistive fault, the dissipated reactive power is equal to zero. Splitting the imaginary part of (5) and equalizing it to zero yields:

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPWRD.2014.2372045, IEEE Transactions on Power Delivery

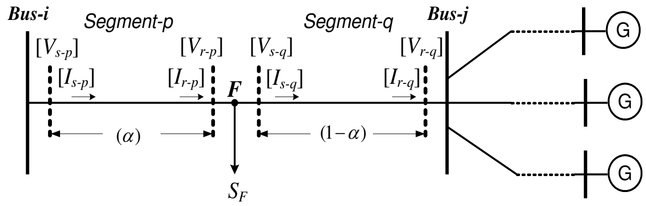

Fig. 1. A simple distribution system with DG units.

$$0=\mathrm{Im}\{[V_{s-p}]^t[I_F]^*+0.5\alpha^2[V_{s-p}]^t[Z][Y_{sh}][I_F]^* -\alpha[I_{s-p}]^t[Z][I_F]^*\} \tag{6}$$

Equation (6) can be rearranged as a second-order polynomial with respect to a per-unit fault distance (α) as in (7):

$$X_0+X_1\cdot\alpha+X_2\cdot\alpha^2=0 \tag{7}$$

where;

$$X_0=\mathrm{Im}\{[V_{s-p}]^t[I_F]^*\} \tag{8}$$

$$X_1=\mathrm{Im}\{-[I_{s-p}]^t[Z][I_F]^*\} \tag{9}$$

$$X_2=\mathrm{Im}\{0.5[V_{s-p}]^t[Z][Y_{sh}][I_F]^*\} \tag{10}$$

Equation (7) represents a general FL equation that can be used for all possible shunt fault types in a three-phase, two-phase and single-phase distribution line section. Moreover, shunt fault types can be single-fault types such as a single-phase-to-ground, phase-to-phase, double-phase-to-ground, three-phase and three-phase-to-ground faults, or compound-fault types such as a single-phase-to-ground fault combined with phase-to-phase fault for the remaining phases.

In this paper, the proposed scheme represents all the line section parameters by three-phase matrices in order to avoid the use of multiple FL algorithms in the unbalanced distribution feeder. For any phase which fails to exist, the corresponding row and column in the matrix equation will contain null-entries. By solving (7) for each line section, all possible fault locations are obtained. The sending-end voltages and currents of the analyzed line section, the line parameter and the fault current are used to calculate the coefficients of (7). Since the fault current and the sending-end voltages and currents are also unknown, a formulation for estimating these values should be used, and subsequently presented in subsections III.B and III.C, respectively.

B. Fault Current Equation

For the line section in Fig. 1, the currents of segment-*p* and segment-*q* both participate in feeding the fault. Accordingly, the fault current can be calculated as in (11):

$$[I_F]=[I_{r-p}]-[I_{s-q}] \tag{11}$$

The receiving-end current of the segment-*p* can be determined as in (12):

$$[I_{r-p}]=-[C_{(\alpha)}][V_{s-p}]+[d_{(\alpha)}][I_{s-p}] \tag{12}$$

where;

$$[C_{(\alpha)}]=\alpha[Y_{sh}]+0.25\alpha^3[Y_{sh}][Z][Y_{sh}] \tag{13}$$

For the line section in Fig. 1, the receiving-end current of segment-*q*, which represents the current of bus-*j*, can be determined by using (14):

$$[I_{r-q}]=[Z_d]_j^+\cdot[V_{r-q}]-[I_G]_j-[Z_d]_j^+\sum_{k=1,\ k\neq j}^{N}[Z_T]_{j,k}[I_G]_k \tag{14}$$

where (+) denotes pseudo-inverse which is used to avoid the inverse problem of the singular matrix in the case of the single-phase and two-phase line sections [28]. $[I_G]_k$ is the measured current of the DG unit connected at bus-*k*. $[Z_d]_j$ represents the driving point impedance at bus-*j* and $[Z_T]_{j,k}$ represents the transfer impedance between buses *j* and *k*. The driving point and transfer impedances are determined from the modified bus impedance matrix. The driving point impedances are the diagonal elements of the modified bus impedance matrix whereas the transfer impedances are the off-diagonal elements. For this case, the bus impedance matrix is modified by separating the subsystem downstream of the j^{th} bus from the rest of the system. This is done by removing the series impedance and shunt admittance of the analyzed line section (*i-j*) from the original bus impedance matrix.

Using Kirchoff's voltage and current laws, the three-phase voltages and currents at the receiving-end of the segment-*q* are given by (15) and (16), respectively [27]:

$$[V_{r-q}]=[d_{(1-\alpha)}][V_F]-[b_{(1-\alpha)}][I_{s-q}] \tag{15}$$

$$[I_{r-q}]=[d_{(1-\alpha)}][I_{s-q}]-[C_{(1-\alpha)}][V_F] \tag{16}$$

Using (1) and (14)-(16), $[I_{s-q}]$ can be written as in (17):

$$[I_{s-q}]=[A_3]^+[A_1][V_{s-p}]-[A_3]^+[A_2][I_{s-p}] -[A_3]^+[I_G]_j-[A_3]^+[Z_d]_j^+\sum_{k=1,\,k\neq j}^{N}[Z_T]_{j,k}[I_G]_k \tag{17}$$

where;

$$[A_1]=([Z_d]_j^+[d_{(1-\alpha)}]+[C_{(1-\alpha)}])[d_{(\alpha)}] \tag{18}$$

$$[A_2]=([Z_d]_j^+[d_{(1-\alpha)}]+[C_{(1-\alpha)}])[b_{(\alpha)}] \tag{19}$$

$$[A_3]=[d_{(1-\alpha)}]+[Z_d]_j^+[b_{(1-\alpha)}] \tag{20}$$

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPWRD.2014.2372045, IEEE Transactions on Power Delivery

Equations (12) and (17) represent the contributions of the upstream and downstream system to the fault currents in the presence of DG, respectively.

C. Voltage and Current Estimation

For the first line section which is connected to substation bus, the sending-end voltages and currents are given. So the process for estimating the sending-end voltages and currents at the next section should be performed using those of the upstream line section.

For the line section-*k* which is located between bus-*i* and bus-*j*, as shown in Fig. 2, the bus-*i* voltages can be obtained from the sending-end voltages and currents of upstream line section (line section-*u*) using the following equation:

$$[V]_i = [d_{(1)}][V_s]_u - [b_{(1)}][I_s]_u \tag{21}$$

where $[V_s]_u$ and $[I_s]_u$ are the sending-end voltages and currents of the line section-u. $[d_{(1)}]$ and $[b_{(1)}]$ are determined by substituting α=1 in (2) and (3), respectively.

The sending-end voltages of the line section-*k* can then be calculated using (22):

$$[V_s]_k = [T]_k [V]_i \tag{22}$$

where $[T]_k$ is 3×3 diagonal matrix, and its values can be determined as follows:

$T_{p,p}$= 1 if the phase-p exists in the line section-k, otherwise it equals to zero. p =1, 2 and 3.

The sending-end currents of the line section-*k* can be calculated by subtracting the load and laterals currents connected to the incoming bus (bus-*i*) of the line section-*k* $[I_{Lt}]_i$ from the receiving-end current of the upstream line section (line section-*u*) as shown in (23):

$$[I_s]_k = [T]_k ([I_r]_u - [I_{Lt}]_i) \tag{23}$$

The receiving-end current of the line section-*u* can be calculated using (24):

$$[I_r]_u = [d_{(1)}][I_s]_u - [C_{(1)}][V_s]_u \tag{24}$$

In order to determine the currents $[I_{Lt}]_i$ which represent the load and lateral currents of bus-*i*, the bus impedance matrix is modified by separating the load and laterals of bus-*i* from the rest of the system. This can be achieved by removing the series impedance and shunt admittance of all line sections connected to bus-*i* except those of the laterals. By separating the load and laterals subsystem from the rest of the system as shown in Fig. 3, the reference bus for this subsystem is bus-*i* and the current $[I_{Lt}]_i$ can be determined using (25):

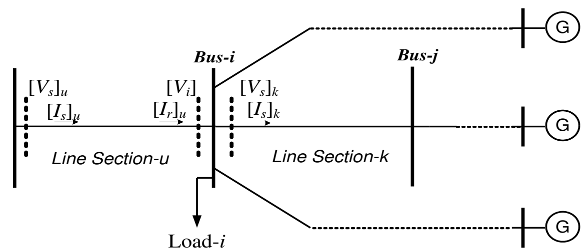

Fig. 2. Distribution feeder with distributed generation units.

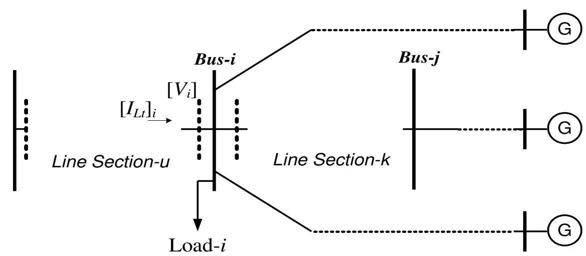

Fig. 3. Distribution feeder with separation of the load and laterals connected to bus-i from the rest of the system.

$$[I_{Lt}]_i = [Z_d]_i^{+}[V_i] - [I_G]_i - [Z_d]_i^{+} \sum_{k=1,\, k\neq i}^{N} [Z_T]_{i,k}[I_G]_k \tag{25}$$

Substituting (24) and (25) in (23) yields:

$$\begin{aligned}[I_s]_k = [T]_k (& [d_{(1)}][I_s]_u - [C_{(1)}][V_s]_u \\ & - [Z_d]_i^{+}[V_i] + [I_G]_i + [Z_d]_i^{+} \sum_{k=1,\, k\neq i}^{N} [Z_T]_{i,k}[I_G]_k)\end{aligned} \tag{26}$$

Equations (22) and (26) are used to estimate the voltages and currents at the sending-end of the line section-*k*, respectively.

D. Proposed Impedance-Based Fault Location Algorithm

The proposed impedance-based FL algorithm is described as follows:

Step 1) Start from the first line section (k = 1).

Step 2) If $k \neq 1$, determine the sending end voltages and currents of the k^{th} line section using (22) and (26), respectively.

Step 3) Determine an initial fault current using (27):

$$[I_F] = [I_{s-p}] - [I'_{s-p}] \tag{27}$$

where $[I_{s-p}]$ and $[I'_{s-p}]$ are the measured currents at the sending-end of the segment-p during the fault and before the fault, respectively.

Step 4) Solve the FL equation to determine the per-unit fault distances (α_1) and (α_2), respectively, using (28) and (29):

$$\alpha_1 = \frac{-X_1 - \sqrt{X_1^2 - 4 \cdot X_2 \cdot X_0}}{2 \cdot X_2} \tag{28}$$

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPWRD.2014.2372045, IEEE Transactions on Power Delivery

$$\alpha_2 = \frac{-X_1 + \sqrt{X_1^2 - 4 \cdot X_2 \cdot X_0}}{2 \cdot X_2} \tag{29}$$

where X_0, X_1 and X_2 are determined by using (8), (9) and (10), respectively.

Step 5) Check the convergence of α_1 and α_2 by using (30) and (31), respectively:

$$\left|\alpha_1(i) - \alpha_1(i+1)\right| \le \delta \tag{30}$$

$$\left|\alpha_2(i) - \alpha_2(i+1)\right| \le \delta \tag{31}$$

where δ and i are a threshold value and the iteration number, respectively.

Step 6) If α_1 and α_2 converge, go to Step 7. Otherwise, update the fault current by using the determined per-unit fault distances (α_1) and (α_2), respectively, in (11), and return to Step 4.

Step 7) If α_1 or α_2 is not within the analyzed line section length, go to Step 8. Otherwise, save the correct per-unit fault distance and save the corresponding fault current and the number of analyzed line section.

Step 8) If the analyzed section is not the last section, update k ($k = k+1$) and return to Step 2.

Step 9) If multiple candidate locations are obtained, determine the exact FL, as subsequently explained in Section IV.

IV. Proposed Exact Fault Location Method

In this method, the exact FL among multiple candidate locations is identified using voltage matching rules. The method works by generating error index for each candidate based on matching the measured voltages at the substation bus and each DG unit bus with calculated ones. The candidate FL with lowest error index will be considered as the most likely fault point. The algorithm of this method is described in detail as follows:

Step 1) For each FL candidate, the bus impedance matrix of the given distribution system is modified to create a new bus (bus-N+1) at a fault point [26]. By injecting the fault current $[I_F]$ which is determined from the proposed impedance-based FL algorithm in the new bus (fault point) and by treating the measured currents at each source bus as current injections, the voltages at the substation bus and each DG unit bus can be calculated using (32):

$$[V_{sc}]_i = [Z_d]_i [I_G]_i - [I_F][Z_T]_{i,N+1} + \sum_{k=1,\, k \ne i}^{N} [Z_T]_{i,k} [I_G]_k \tag{32}$$

Step 2) The error index for candidate FL is then determined using (33):

$$Error = \sum_{i=1}^{m} norm([V_{sc}]_i - [V_{sm}]_i) \tag{33}$$

Where, m is the number of sources in the system including the substation source. $[V_{sc}]_i$ and $[V_{sm}]_i$ are the calculated and measured voltages at i^{th} source bus, respectively.

Step 3) If the error index for all candidates is determined, classify the error indices and organize them in ascending order. Otherwise, go back to step 1.

V. Case Study

In order to evaluate the performance of the proposed FL scheme, a modified version of IEEE 34-bus test feeder, as shown in Fig. 4, was simulated with PSCAD/EMTDC [29]. The original IEEE 34-bus feeder is an actual feeder located in Arizona [30]. It is very long and contains a three-phase main feeder, multiple three-phase and single-phase laterals, unbalanced distributed and spot loads, shunt capacitors and two step voltage regulators. As a result of modification, the distributed loads and the low voltage circuit were aggregated as spot loads and modeled as constant impedances with lagging power factor of 0.89. The voltage regulators were removed, since the tap setting of voltage regulators is unknown and the proposed scheme assumes that all system data are given except the loads which are estimated in this scheme. In order to consider the presence of DG units in the distribution feeder, two fixed speed wind generators are added, as shown in Fig. 4. The data for the two generators are described in [31].

All possible shunt fault types were simulated in different location on the distribution feeder to test and evaluate the proposed scheme. The fault resistance varied from zero to 25 Ω according to the fault type [32]. For each test case, the pre fault and during fault voltage and current waveforms were measured at each source bus assuming that the measurement equipment has an ideal manufacturing tolerance. A sampling rate of 256 samples per cycle was used. Full cycle Discrete Fourier transform in PSCAD/EMTDC software was used to calculate the fundamental voltage and current phasors which is then exported to MATLAB environment [33] for FL estimation. Pre fault phasors were calculated one cycle before the inception of the fault. This margin is used to avoid fluctuations and overlap of the pre fault and during fault data. During fault, phasors were calculated at the third cycle after the fault inception.

The pre fault voltage and current phasors were used to estimate the load power demand at each load bus and subsequently the load bus impedance while the FL was estimated using the phasors during fault. The estimated FL accuracy was measured by the percentage error calculated as follows:

$$\%\ \text{Error} = \left| \frac{\text{Actual FL - Estimated FL}}{\text{Total Length}} \right| \times 100 \tag{34}$$

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPWRD.2014.2372045, IEEE Transactions on Power Delivery

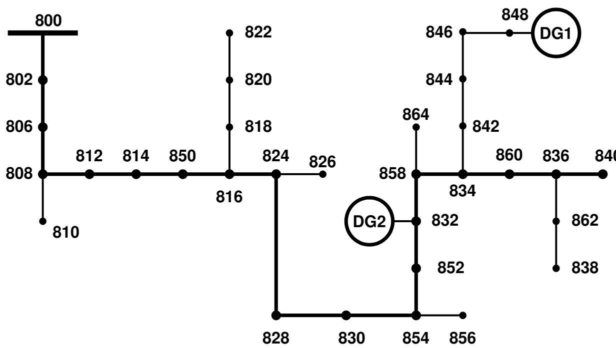

Fig. 4. Single line diagram of the modified IEEE 34-bus test feeder with DG units.

VI. TESTS RESULTS AND DISCUSSION

In this section, the accuracy of the proposed scheme is tested under the effects of fault resistance, fault distance, load variation and load model. The ability of the scheme to find the FL for all possible shunt fault types is verified. Robustness of the proposed scheme to identify the exact FL is also performed. The proposed scheme is compared with other FL methods to verify the superiority of the proposed work.

A. Accuracy Tests

1) Effect of fault resistance: Several tests were conducted to evaluate the accuracy of the proposed scheme under the variation of fault resistance. Table I shows the maximum and average errors for fourteen type of faults simulated at the sending, middle and receiving points of each line section in the network presented in Fig. 4. The fault resistances were assumed to be 0, 10 and 25 Ω. It can be seen from the results presented in Table I that the FL errors for the cases of zero fault resistance is very small and the errors increase with increasing fault resistance. However, the highest difference between the average FL errors for the cases of 0 Ω and 25 Ω was 0.04% which is not significant. It is also noteworthy that the highest FL error obtained from all mentioned cases was 0.10%. These results show good accuracy for a large and unbalanced distribution feeder.

2) Effect of fault distance: To analyze the effects of the fault distance variation on the accuracy of FL estimates, simulations of different fault types and fault resistances were carried out in different locations on the main distribution feeder. Fig. 5 shows the obtained results for an A-g fault with fault resistances of 10 and 25 Ω. It can be seen from Fig. 5 that the FL error increases when the fault distance increases. However, for a long distribution feeder, the maximum errors for the two mentioned cases were 0.08% and 0.1%, respectively. This result shows that the proposed scheme is not significantly affected by the fault distance.

3) Effect of Load Variation: In order to demonstrate the accuracy of the proposed FL scheme under the effect of the load variations, another simulation was carried out by taking into account random loading for each load bus.

The load factor of each load bus was randomly selected from a normal distribution with mean value equal to one and standard deviation equal to 0.2, as shown in Fig. 6. Fig. 7 shows the estimated FL errors for an A-g fault located in different location on the main distribution feeder with a fault resistance of 25 Ω. It can be seen from Fig. 7 that the accuracy of the proposed scheme does not significantly deteriorate due to individual load variations. The results of this case show a maximum error of 0.13%, whereas the maximum error for the case of no load variation is 0.1%.

4) Effect of Load Model: Generally, loads in distribution systems vary with time depending on consumer type, weather and state of economy. Due to the availability of measurements at only source buses, it is difficult to know the load type at the fault instant. Hence, development of a fault location method which considers the exact type of load is not useful with these limitations. Therefore, the majority of analytical fault location methods such as impedance-based methods assume the load type in the load modeling. The most commonly used model is constant impedance model [3].

TABLE I
MAXIMUM AND AVERAGE ERRORS

Fault Type	Average Error [%]			Maximum Error [%]		
	R_F = 0 Ω	R_F = 10 Ω	R_F = 25 Ω	R_F = 0 Ω	R_F = 10 Ω	R_F = 25 Ω
A-g	0.01	0.04	0.05	0.03	0.08	0.10
B-g	0.01	0.03	0.04	0.03	0.08	0.09
C-g	0.02	0.03	0.04	0.03	0.09	0.10
AB	0.01	0.05	-	0.03	0.09	-
BC	0.02	0.05	-	0.04	0.08	-
CA	0.01	0.03	-	0.02	0.06	-
AB-g	0.01	0.02	0.04	0.01	0.03	0.07
BC-g	0.01	0.02	0.03	0.01	0.03	0.06
CA-g	0.01	0.02	0.04	0.01	0.03	0.07
ABC	0.01	0.01	-	0.01	0.02	-
ABC-g	0.01	0.02	0.03	0.01	0.02	0.04
AB & C-g	0.01	0.01	0.02*	0.01	0.02	0.05*
BC & A-g	0.01	0.02	0.03*	0.02	0.03	0.05*
CA & B-g	0.01	0.01	0.02*	0.01	0.02	0.04*

*The phase-to-phase fault resistance is 10 ohm.

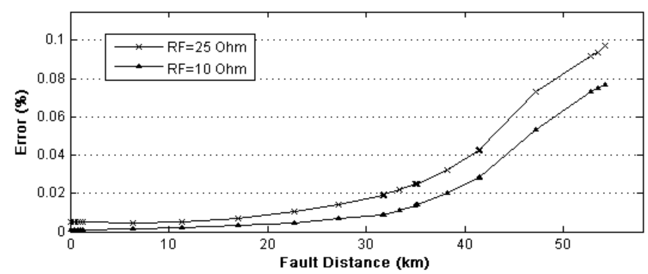

Fig. 5. Fault location error for the case of single-phase-to-ground faults with R_F = 10 and 25 Ω.

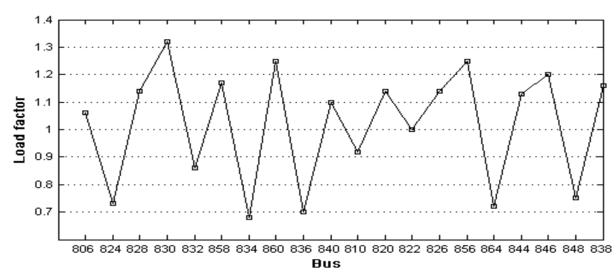

Fig. 6. Random load factor.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPWRD.2014.2372045, IEEE Transactions on Power Delivery

As mentioned in Section V, the loads were modeled as constant impedance. In order to show the accuracy of the proposed scheme against the variations of the load model, a polynomial load model with 20% of constant power, 25% of constant current and 55% of constant impedance has been adopted to represent the loads connected to the feeder. The obtained results for an A-g fault with fault resistance of 25 Ω are presented in Fig. 8. It can be seen from the results presented in Fig. 8 that the accuracy of the proposed scheme is not significantly affected by the exact load model. The maximum FL error for this case is 0.17%, whereas the maximum error for the case of constant impedance load model is 0.1%. The deference between the maximum errors of the two cases is 0.07% which is very small.

B. Ability Tests

Results presented in Table I show that the proposed FL scheme has the ability to locate all possible shunt fault types including single-fault and compound-fault types. Beside the ability, the accuracy of the proposed scheme is not affected by the accuracy of the fault type identification, since the identification of fault type is not required.

C. Robustness Tests

Robustness of the proposed FL scheme to identify the exact FL has been analyzed for cases with normal load, load variation and load model variation. The results show that the exact FL was indicated by the first position in the FL ranking with an accuracy of 95%. The remaining 5% of the test cases show the same minimum location error index for two possible fault points.

Table II presents the ranking results for different fault in the middle of sections 846-848 and 836-862 with fault resistance of 10 Ω and different load cases. It can be seen from Table II that the proposed scheme has accurately identified the exact FL among the multiple candidate locations for the faults in line section 846-848. For faults in line section 836-862, the exact FL and one other candidate location have been chosen among four locations as the most possible fault locations since both locations have the same lowest error index.

D. Comparison Tests

To verify the superiority of the proposed scheme over other FL methodologies, a comparison between the proposed scheme and the methods proposed by Bretas [15] and Nunes [16-18] is presented. These methods are chosen as they are best impedance-based methods developed for distribution systems with DG units.

The two methods mentioned above were implemented in MATLAB software. The proposed processes in this paper for determining the fault current were used for all methods. The capacitive effect was, however, not considered as it is the case in Bretas and Nunes's methods. In the implementation of Bretas's method, the mutual impedance of distribution lines was also not considered since the method is formulated for balanced systems.

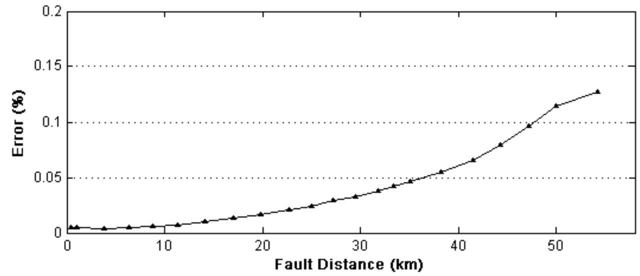

Fig. 7. Fault location error for the case of individual load variations.

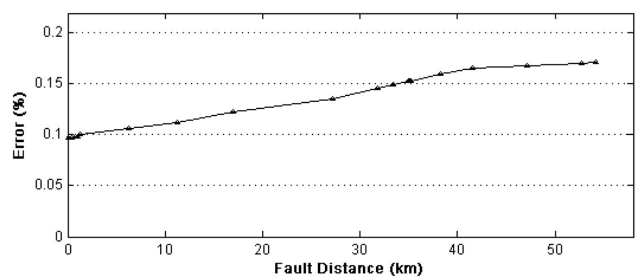

Fig. 8. Fault location error for the case of compound load type.

TABLE II
RANKING RESULTS FOR THE POSSIBLE FAULT LOCATIONS

Case	Fault type	Faulty line section	Line sections that include the possible fault locations/ Ranking error index	Line sections that include the most possible locations
Normal load	A-g	846-848	846-848 / 55 836-840 / 715 836-862 / 715 818-820 / 1.2E04	846-848
Individual load change	BC		846-848 / 49 836-840 / 681	846-848
Load type change	ABC-g		846-848 / 48 836-840 / 826 818-820 / 2.6E04	846-848
Normal load	AB-g	836-862	836-862 / 42 836-840 / 42 844-846 / 626	836-862 836-840
Individual load change	AB&C-g		836-862 / 53 836-840 / 53 844-846 / 888	836-862 836-840
Load type change	ABC		836-862 / 50 836-840 / 50 844-846 / 846 818-820 / 2.8E04	836-862 836-840

Table III shows the comparison of the two mentioned methods and the proposed method for a single-phase-to-ground fault at five locations with fault resistances of 0 and 25 Ω. It can be seen from Table III, the accuracy of Bretas and Nunes's methods is moderate and it dramatically decreased with increasing fault distance and fault resistance.

On the other hand, the accuracy of the proposed method is high and the effects of fault distance and fault resistance are very low. For the fault placed at a fault distance of 6.3 km from the substation with fault resistance of 25 Ω, the obtained error is 0.005%, whereas in the case of Bretas and Nunes's methods, the errors are 0.727% and 0.466%, respectively.

The main difference between the methods mentioned above and the proposed method is the line model and the consideration of unbalanced characteristics. Bretas and Nunes's

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPWRD.2014.2372045, IEEE Transactions on Power Delivery

TABLE III
FAULT ERROR COMPARISON

Fault Distance (km)	Fault Location Error (%)					
	$R_F = 0\ \Omega$			$R_F = 25\ \Omega$		
	Proposed Method	Nunes's Method	Bretas's Method	Proposed Method	Nunes's Method	Bretas's Method
0.4	0.001	0.005	0.016	0.005	0.410	0.415
1.05	0.001	0.013	0.044	0.005	0.417	0.431
6.3	0.001	0.014	0.333	0.005	0.466	0.727
17	0.003	0.015	1.575	0.008	0.601	2.02
27.2	0.006	0.022	3.718	0.014	0.776	4.238

methods use the short line model where the capacitive effect is not considered. This model can provide good accuracy for locating the fault in the short distribution lines. However, it is not suitable for long distribution feeder [20]. Moreover, Bretas's method neglects the mutual impedance effect of the distribution line by assuming the loads are balanced and the distribution lines are perfectly transposed. From the practical view, this assumption is not valid and decreases the accuracy of FL estimate as shown in the results presented in Table III.

This observation led to the conclusion that the proposed method presents great improvements to the FL accuracy by considering the characteristics of the distribution system.

Besides the consideration of distribution system characteristics, the proposed impedance-based method uses only one FL equation that is applicable for all fault types occurrence in single phase, two phase and three phase line sections. Hence, the identification of fault type is not required. Only the fundamental values of voltages and current measured at the substation and each DG unit bus are required for the proposed method. The currents measured at each DG unit bus are treated as current injection to consider the participation of each DG unit to the fault current. This idea avoids the modeling effort to represent the behavior of the generation unit and its interface during the fault conditions. Hence, the proposed method is applicable to any DG unit type and has similar behavior for different types.

On the other hand, Bretas and Nunes's methods use FL equation for each fault type. The identification of fault type is required. Therefore, the accuracy of these methods not only depends on the FL methodology but it also depends on the accuracy of the adopted fault classification method. These methods are formulated for three-phase distribution systems with a synchronous generator unit. Due to the complexity to obtain FL equations for different fault type configurations, these methods are formulated in [15-17] for single-phase to ground fault and in [18] for three-phase to ground fault. These papers did not consider all possible fault types.

Finally, impedance-based methods such as the methods presented in [15-18] determine the FL that is given by the fault distance. Due to the tree topological structure of distribution systems, multiple fault locations are frequently obtained. In practice, other techniques and devices, such as fault indicators, and information from protection devices may be used to determine the exact FL or the most likely FL. However, the proposed scheme in this paper identifies the exact FL among multiple candidate locations using only the available measurements at the substation bus and each DG unit bus.

It is important to note that the conventional methods that use fault indicators [34] to identify the exact FL require seven fault indicators for the test case in this paper. On the other hand, the proposed method shows an accuracy of 95% without using any additional device. However, this accuracy is subjected to the number and location of DG units. In order to improve the accuracy of the proposed method to 100%, it only requires one fault indicator that can be installed in the line section 836-862.

The preceding discussion demonstrates the superiority of the proposed scheme in terms of the accuracy and the ability to identify the location of all possible fault type occurring in the unbalanced distribution systems in the presence of DG units.

VII. CONCLUSION

This paper presented a novel FL scheme to identify the exact FL using new impedance-based and voltage matching methods. The proposed impedance based method is used to identify all possible fault locations using single FL equation which is applicable for all shunt fault types. The exact FL among the multiple candidate locations is then determined using the proposed voltage matching method. The proposed scheme covers all the unbalanced conditions of the distribution systems such as the untransposed lines, the asymmetrical line impedances and the single-phase laterals and loads. The capacitive effect of distribution lines and the presence of DG in the distribution system were also considered.

A modified IEEE 34-bus distribution system with two fixed-speed wind turbines was used to test and evaluate the proposed scheme. Test results verified the accuracy and robustness of the proposed scheme to identify the exact location under the effects of fault resistance, fault distance and load uncertainty. The superiority of the proposed scheme over other FL methodologies was also verified. Thus, the proposed scheme is promising for practical application.

REFERENCES

[1] S. Kazemi, M. Fotuhi-Firuzabad, and R. Billinton, "Reliability assessment of an automated distribution system," *IET Generation, Transmission and Distribution*, vol. 1, no. 2, pp. 223-233, March 2007.

[2] C. K. Tan, and V. K. Ramachandaramurthy, "Novel wide-area fault location and predictive maintenance technique for distribution system," IEEJ Transactions on Electrical and Electronic Engineering, vol. 7, no. 2, pp. 152-160, March 2012.

[3] J. Mora-Florez, J. Melendez, and G. Carrillo-Caicedo, "Comparison of impedance based fault location methods for power distribution

systems," *Electric Power Systems Research*, vol. 78, no. 4, pp. 657-666, Apr. 2008.

[4] S. Chaitusaney, and A. Yokoyama, "Prevention of reliability degradation from recloser–fuse miscoordination due to distributed generation," *IEEE Trans. Power Delivery*, vol. 23, no. 4, pp. 2545-2554, Oct. 2008.

[5] S. M. Brahma, and A. A. Girgis, "Microprocessor-based reclosing to coordinate fuse and recloser in a system with high penetration of distributed generation," in *Proc. IEEE Power Eng. Soc. Winter Meeting*, 2002, vol. 1, pp. 453–458.

[6] S. M. Brahma, and A. A. Girgis, "Development of Adaptive protection scheme for distribution systems with high penetration of distributed generation," *IEEE Trans. Power Delivery*, vol. 19, no. 1, pp. 56-63, Jan. 2004.

[7] A. F. Naiem, Y. Hegazy, A. Y. Abdelaziz, and M. A. Elsharkawy, "A classification technique for recloser fuse coordination in distribution systems with distributed generation," *IEEE Trans. Power Delivery*, vol. 27, no. 1, pp. 176-185, Jan. 2012.

[8] K. Tuitemwong, and S. Premrudeepreechacharn, "Expert system for protection coordination of distribution system with distributed generators," *International Journal of Electrical Power and Energy Systems*, vol. 33, no. 3, pp. 466-471, March 2011.

[9] H. Zayandehroodi, A. Mohamed, and H. Shareef, "Determining exact fault location in a distribution network in presence of DGs using RBF neural networks," in *proc. 2011 IEEE International Conference on Information Reuse and Integration (IRI)*, pp. 434-438.

[10] S. A. M. Javadian, A. M. Nasrabadi, M. R. Haghifam, and J. Rezvantalab, "Determining fault's type and accurate location in distribution systems with DG using MLP neural networks," in *proc. 2009 IEEE Int. Conf. on Clean Electrical Power*, pp. 284-289.

[11] S. A. M. Javadian, M. R. Haghifam, S. M. T. Bathaee, and M. F. Firoozabad, "Adaptive centralized protection scheme for distribution systems with DG using risk analysis for protective devices placement," *International Journal of Electrical Power and Energy Systems*, vol. 44, no. 1, pp. 337-345, Jan. 2013.

[12] M. Zayandehroodi, A. Mohamed, H. Shareef, and M. Farhoodnea, "A novel neural network and backtracking based protection coordination scheme for distribution system with distributed generation," *International Journal of Electrical Power and Energy Systems*, vol. 43, no. 1, pp. 868-879, Dec. 2012.

[13] M. M. Saha, J. Izykowski, and E. Rosolowski, *Fault Location on Power Networks*, London: Springer, 2009.

[14] S. M. Brahma, "Fault location in power distribution system with penetration of distributed generation," *IEEE Trans. Power Delivery*, vol. 26, no. 3, pp. 1545-1553, July 2011.

[15] A.S. Bretas, and R.H. Salim, "Fault Location in Unbalanced DG Systems using the Positive Sequence Apparent Impedance," in *proc.* 2006 *IEEE Transmission and Distribution Conference and Exposition: Latin America*, pp.1-6.

[16] J.U.N. Nunes, and A.S. Bretas, "An extended fault location formulation for unbalanced distribution feeders with distributed generation," in *2010 Proceedings of the International Symposium, Modern Electric Power Systems (MEPS)*, pp.1-6.

[17] J. U. N. Nunes, and A. S. Bretas, "A impedance-based fault location technique for unbalanced distributed generation systems," in *proc. 2011 IEEE Trondheim PowerTech*, pp. 1-7.

[18] J.U.N. Nunes, and A.S. Bretas, "Impedance-based fault location formulation for unbalanced primary distribution systems with distributed generation," in *proc. 2010 International Conference on Power System Technology (POWERCON)*, pp.1-7.

[19] D. Penkov, B. Raison, C. Andrieu, J. P. Rognon, and B. Enacheanu, "DG impact on three phase fault location. DG use for fault location purposes," in *proc. 2005 Int. Conf. on Future Power Systems*.

[20] R. H. Salim, K. C. O. Salim, A. S. Bretas, "Further improvements on impedance-based fault location for power distribution systems," *IET Generation, Transmission and Distribution*, vol. 5, no. 4, pp. 467-478, April 2011.

[21] B. Das, "Fuzzy logic-based fault-type identification in unbalanced radial power distribution system," *IEEE Trans. Power Delivery*, vol. 21, no. 1, pp. 278-285, Jan. 2006.

[22] S. F. Alwash, and V. K. Ramachandaramurthy, "Novel fault location method for overhead electrical distribution systems," *IEEJ Transactions on Electrical and Electronic Engineering*, vol. 8, no. S1, pp. S13-S19, Sep. 2013.

[23] IEEE Guide for Monitoring, Information Exchange, and Control of Distributed Resources Interconnected with Electric Power Systems, IEEE Std. 1547.3, Nov. 2007.

[24] J.-A. Jiang, Y.-H. Lin, J.-Z.Yang, T.-M. Too, and C.-W. Liu, "An adaptive PMU based fault detection/location technique for transmission lines PART II: PMU implementation and performance evaluation," *IEEE Trans. Power Delivery*, vol. 15, no. 4, pp. 1136–1146, Oct. 2000.

[25] R. A. F, Pereira, L. G. W. Silva, M. Kezunovic, and J. R. S. Mantovani, "Improved fault location on distribution feeders based on matching during-fault voltage sags," *IEEE Trans. Power Delivery*, vol. 24, no. 2, pp. 852-862, Apr. 2009.

[26] J. J. Grainger, and W. D. Stevenson, *Power system analysis*. New York: McGraw-Hill, 1994.

[27] W. H. Kersting, *Distribution System Modeling and Analysis*, Boca Raton, FL: CRC, 2002.

[28] A. Ben-Israel and T. N. Greville, *Generalized Inverses: Theory and Applications*, Verlag New York: Springer, 2003.

[29] PSCAD/EMTDC User's manual, Manitoba HVDC Research Centre Inc., Winnipeg, 2005.

[30] W. H. Kersting, "Radial distribution test feeders," in *Proc. IEEE Power Eng. Soc. Winter Meeting*, 2001, vol. 2, pp. 908–912.

[31] R.C. Dugan and W. H. Kersting, "Induction machine test case for the 34-bus test feeder-description," in *Proc. IEEE Power Eng. Soc. General Meeting*, 2006.

[32] J. L. Blackburn, *Protective Relaying Principles and Applications*. New York: Marcel Dekker, 1998.

[33] The Mathworks, Inc. Natick, MA, 2010. Matlab Help Manual.

[34] R. Das, "Determining the location of faults in distribution systems," PhD Thesis, University of Saskatchewan, Saskatchewan, Saskatoon, 1998.

Shamam Alwash (M'13) received his B.Sc. degree in Electrical Engineering from University of Babylon, Iraq, in 2000 and his M.Sc. degree in Electrical Power Engineering from University of Technology, Iraq, in 2004. He was with the Department of Electrical Engineering, University of Babylon, Iraq. Currently, he is pursuing his Ph.D. at University Tenaga Nasional, Malaysia. His research interests include power quality, renewable energy, power system protection and automation.

Vigna K. Ramachandaramurthy (SM'12) completed his PhD at UMIST, UK in 2001. He is presently a professor and heads the Power Quality Research Group in University Tenaga Nasional, Malaysia. He also leads several research and consultancy projects. His main research interests are power system studies, power system protection, power quality, renewable energy integration and grid impact of distributed generation.

Nadarajah Mithulananthan (SM'10) received his Ph.D. in Electrical and Computer Engineering from University of Waterloo, Canada in 2002. He worked as an electrical engineer at Generation Planning Branch of Ceylon Electricity Board in Sri Lanka and as a researcher at Chulalongkorn University, Bangkok, Thailand. He also served as an associate professor at Asian Institute of Technology, Bangkok, Thailand. He is currently with School of Information Technology and Electrical Engineering at the University of Queensland, Australia. His main research interests are renewable energy integration and grid impact of distributed generation, electric vehicle charging and energy storage systems.