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A Fault Area Location Method in Distribution Network with DG

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Abstract

To precisely locate the grounded fault area in distribution network with DG, a new grounded fault area location algorithm based on three-phase impedance model and fault features in distribution network with DG is proposed in this paper. This method establishes three-phase impedance model if the distribution network with DG, analyzes and extracts the fault characteristics on the basis of the three phase impedance model of distribution network with DG. According to the characteristic of the feature value in the fault point, this method traverses all the nodes and gets the fault associated nodes. The method proposed in this paper was tested in a sixty nodal distribution system with six DG's, the result of the method verifies that the method can precisely locate the grounded fault area in distribution network with DG.

Keywords: *distribution network with DG, fault section location, three phase impendence model, energy characteristic*

1. Introduction

Distribution network is an important part of power system and it is closely associated with the customers. The security of a power distribution network is of great significance to the long-term stable operation of power system. Distribution network topological structure is complex and the environment varies. It is prone to failure. Therefore, the power distribution network fault diagnosis has been the focus study point [1-7]. Fault area location is the basis of the fault location.

For the distributed network with distributed generators, the fault area location has become a indispensable step in the fault location of distribution network. Literature [8] proposed an adaptive matrix distribution network fault location algorithm on the basis of FTU fault partition matrix algorithm. According to the direction of the current into the FTU, it determines whether distributed power is input and whether there are other circumstances. And then preliminary fault area is determined and located. Then on the basis of topology and FTU over-current, the adaptive fault matrix formation was formed to confirm the fault area. Such methods require some measure unit (FTU). The investment cost is high. Literature [9] proposed an improved matrix algorithm based on the former fault area localization algorithm. The method add he orientation to the parameters of network matrix and information matrix. And it set only one positive direction for the multiple power supply network. Literature [10] improved the fault judgment matrix according to relationship between over-current direction in fault nodes and the load flow direction. The fault information matrix combined with the network structure matrix finished the improvement. The method searched the parent node to determine the fault node. This kind of algorithm can location the smallest area, however it is greatly influenced by system topology structure so it is lack of robustness. Literature [11] proposed an area location method based on wavelet transform. The method applied wavelet transform to analysis the singularity variation of the original signal. It looked for the fault characteristic that can be used to locate the fault area so as to determine the fault point. This kind of intelligent algorithm depends on experience, the selection of parameters not enough accuracy.

In order to solve the problems previously mentioned, three-phase impedance model of the distribution network was established in this paper. The fault feature of the fault phase current was extracted when fault occurred. Finally a new fault area location method was proposed by using the fault current characteristic. This method has been verified in a sixty nodal distribution system with six DG's.

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2. The Impedance Model

1) The main power supply and DG thevenin equivalent model

From the thevenin theorem, the main power supply and DG equivalent impedance model can respectively be equivalent to an ideal voltage source with internal resistance. Each phase current and voltage can be simultaneously measured in the main feeder and each DG access points (this is feasible under the condition of existing technology). Then the positive sequence, negative sequence and zero sequence current and voltage can be calculated. By adopting the power equivalent model in literature [12], the positive sequence, negative sequence and zero sequence equivalent impedance of the DG can be set according to the theory of the asymmetry electricity network.

$$Z_{S1}=\frac{\dot{V}_L-\dot{V}_{F1}}{\dot{I}_{F1}-\dot{I}_L},\ Z_{S2}=-\frac{\dot{V}_{F2}}{\dot{I}_{F2}},\quad Z_{S0}=-\frac{\dot{V}_{F0}}{\dot{I}_{F0}} \tag{1}$$

Here, Z_{S1}, Z_{S2} and Z_{S0} is positive sequence impedance, negative sequence impedance and zero sequence impedance of DG respectively. $\dot{V}_L$, $\dot{I}_L$ is the positive sequence voltage and current of the branch that DG accesses before the fault. $\dot{V}_{F1}$, $\dot{V}_{F2}$, $\dot{V}_{F0}$ and $\dot{I}_{F1}$, $\dot{I}_{F2}$, $\dot{I}_{F0}$ is the positive sequence, negative sequence and zero sequence voltage and current values when fault occurred. The three-phase asymmetrical impedance model of the DG is as follows:

$$Z_{abc}=\begin{bmatrix} Z_{Sa} & Z_{Sab} & Z_{Sac} \\ Z_{Sba} & Z_{Sb} & Z_{Sbc} \\ Z_{Sca} & Z_{Scb} & Z_{Sc} \end{bmatrix}=\frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} {Z_S}^{(0)} & 0 & 0 \\ 0 & {Z_S}^{(1)} & 0 \\ 0 & 0 & {Z_S}^{(2)} \end{bmatrix}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \tag{2}$$

There, $a=e^{j2\pi/3}$.

According to Equation (1) and (2), the positive sequence, negative sequence and zero sequence equivalent impedance of DG can be calculated by a set of voltage and current data variation of the DG measurement point before and after the fault. And then the asymmetrical impedance model of DG is acquired.

2) The three-phase impedance model of the double winding transformer

The primary's current and voltage (expressed in p or ABC) can be associated with the secondary's current and voltage (expressed in s or ABC) according to the double winding transformer's connection mode [13]. So the three-phase admittance matrix of the transformer can be set.

$$\begin{bmatrix} I_p \\ I_s \end{bmatrix}=\begin{bmatrix} Y_{pp} & Y_{ps} \\ Y_{sp} & Y_{ss} \end{bmatrix}\begin{bmatrix} V_p \\ V_s \end{bmatrix} \tag{3}$$

Taking $Y_g-\Delta$ transformer as example, Y is the standard value of the transformer admittance.

$$\begin{bmatrix} I_A \\ I_B \\ I_C \\ -I_a \\ -I_b \\ -I_c \end{bmatrix}=y\begin{bmatrix} 1 & 0 & 0 & \frac{-1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & 0 \\ 0 & 1 & 0 & 0 & \frac{-1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \\ 0 & 0 & 1 & \frac{1}{\sqrt{3}} & 0 & \frac{-1}{\sqrt{3}} \\ \frac{-1}{\sqrt{3}} & 0 & \frac{1}{\sqrt{3}} & \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ \frac{1}{\sqrt{3}} & \frac{-1}{\sqrt{3}} & 0 & -\frac{1}{3} & \frac{2}{3} & -\frac{1}{3} \\ 0 & \frac{1}{\sqrt{3}} & \frac{-1}{\sqrt{3}} & -\frac{1}{3} & -\frac{1}{3} & \frac{2}{3} \end{bmatrix}\begin{bmatrix} V_A \\ V_B \\ V_C \\ V_a \\ V_b \\ V_c \end{bmatrix} \tag{4}$$

3) The three-phase impedance model of the feeder line

For the distribution network feeder [14], the line length is not very long. The feeder lines adopts three-phase π equivalent model in this article. The asymmetric impedance model of unit length line is as follows.

$$Z_{Labc}=\begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ba} & Z_{bb} & Z_{bc} \\ Z_{ca} & Z_{cb} & Z_{cc} \end{bmatrix} \tag{5}$$

Z_{aa},Z_{bb} and Z_{cc} are respectively the self-impedance of the ABC phases, Z_{ab},Z_{ba},Z_{bc},Z_{cb},Z_{ca} and Z_{ac} are respectively the mutual impedance between ABC phases.

4) The three-phase impedance model of the load

This paper only studies the simple constant impedance load and constant power load. The admittance matrixes of the load in each node are established to reflect the unbalanced load of node [14]. So each phase's load admittance matrix can be expressed as:

$$Y_{LDi,i} = \frac{P_i - jQ_i}{|V_i^2|}\Omega^{-1} \tag{6}$$

Here, i=a,b,c_i , P_i is each phase's active power (Mw) , Q_i is each phase's reactive power of each phase (MVAR), V_i is each phase's voltage (kV) of the load node.

5) The formation of system's three-phase admittance matrix

Based on the system topology structure, line parameters and load parameters, the three-phase unbalanced node admittance equation for a distribution network with DG can be built as Equation (7).

$$\begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{1n} \\ Y_{21} & Y_{22} & \cdots & Y_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ Y_{n1} & Y_{n2} & \cdots & Y_{nn} \end{bmatrix}_{3n\times 3n} \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_n \end{bmatrix}_{3n\times 1} = \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_n \end{bmatrix}_{3n\times 1} \tag{7}$$

Here, n is the node number of the distribution system, and m is the distributed generator number of the distribution system. The node admittance matrix of the system is:

$$Y_{abc3n\times 3n}=\begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{1n} \\ Y_{21} & Y_{22} & \cdots & Y_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ Y_{n1} & Y_{n2} & \cdots & Y_{nn} \end{bmatrix}_{3n\times 3n} \tag{8}$$

The unbalanced three-phase node impedance equation of the power system is shown as following.

$$\begin{bmatrix} Z_{11} & Z_{12} & \cdots & Z_{1n} \\ Z_{21} & Z_{22} & \cdots & Z_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ Z_{n1} & Z_{n2} & \cdots & Z_{nn} \end{bmatrix}_{3n\times 3n} \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_n \end{bmatrix}_{3n\times 1} = \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_n \end{bmatrix}_{3n\times 1} \tag{9}$$

The node impedance matrix of the system is:

$$Z_{abc3n\times 3n}=\begin{bmatrix} Z_{11} & Z_{12} & \cdots & Z_{1n} \\ Z_{21} & Z_{22} & \cdots & Z_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ Z_{n1} & Z_{n2} & \cdots & Z_{nn} \end{bmatrix}_{3n\times 3n} \tag{10}$$

The node impedance matrix is the inverse matrix of the node admittance matrix.

$V_i=\begin{bmatrix}V_{ia}\\V_{ib}\\V_{ic}\end{bmatrix}$ and $I_i=\begin{bmatrix}I_{ia}\\I_{ib}\\I_{ic}\end{bmatrix}$ in Formula (7) and Formula (9) are respectively the voltage and the injection current at noad i.

Thus, the three-phase impedance model of the distribution network with DG has been established. The three-phase impedance model takes the asymmetry of the distribution network in consider.

3. The Fault Area Location Method in Distribution System with DG

3.1. The Fault Feature Analysis of the Distribution Network with DG based on Three Phase Impedance Model

Assuming that the DGs are located in nodes $BS(1), BS(2),\ldots, BS(m)$, the falut occurred in noad j and the voltage and the injection current of each power supply can be synchronously measured. The measured voltage and current signals before the fault are $\dot{V}_{BS}(1),\dot{V}_{BS}(2)\ldots\dot{V}_{BS}(m)$ and $\dot{I}_{BS}(1),\dot{I}_{BS}(2)\ldots\dot{I}_{BS}(m)$. The measured voltage and current signals when the fault occurred are $\dot{V}_{BS}'(1),\dot{V}_{BS}'(2),\ldots,\dot{V}_{BS}'(m)$ and $\dot{I}_{BS}'(1),\dot{I}_{BS}'(2),\ldots,\dot{I}_{BS}'(m)$. The voltage of the fault point before fault, noted as $\dot{V}_j^{oc}$, can be calculated by the system node fault equation.

$$\dot{V}_j^{oc}=\sum_{k=1}^{m}Z(j,k)\,\dot{I}_{BS}(k) \tag{11}$$

From Equation (11), when short circuit current $\dot{I}_{fj}$ is injected into a node, it will generate fault component voltage, noted as $\Delta\dot{V}$, at each node as shown in (12).

$$\begin{bmatrix}\Delta\dot{V}_1\\ \vdots\\ \Delta\dot{V}_i\\ \vdots\\ \Delta\dot{V}_n\end{bmatrix}=\begin{bmatrix}Z_{11} & \ldots & Z_{1i} & \ldots & Z_{1n}\\ \vdots & \ldots & \vdots & \ldots & \vdots\\ Z_{i1} & \ldots & Z_{ii} & \ldots & Z_{in}\\ \vdots & \ldots & \vdots & \ldots & \vdots\\ Z_{n1} & \ldots & Z_{ni} & \ldots & Z_{nn}\end{bmatrix}\begin{bmatrix}0\\ \vdots\\ -\dot{I}_{fi}\\ \vdots\\ 0\end{bmatrix} \tag{12}$$

When short-circuit current Ifj is injected into node j, the fault component voltage, generated by Ifj, at each power measurement point is:

$$\Delta\dot{V}_i=-Z_{ij}\cdot\dot{I}_{fj}\quad(i=1,2,\ldots,m) \tag{13}$$

The fault voltage component at measurement point i can be obtained by the difference between voltage value before fault and the value in fault.

$$\Delta\dot{V}_i=V_{BS}'(i)-V_{BS}(i)\quad(i=1,2,\ldots,m) \tag{14}$$

When the fault occurred in node j, The fault current can be calculated as Equation (15) by the fault voltage component in source measurement point, noted as I_{fj}.

$$\dot{I}_{fj}(i)=Y(i,j)(\dot{V}'_{BS}(i)-\dot{V}_{BS}(i)),(i=1,2,\ldots,m) \quad (15)$$

The fault current generated by all power supplies is:

$$I_{fj}=(Z(j,j)+R_g)^{-1}\cdot V_j^{oc} \quad (16)$$

R_g is fault grounding resistance.

The error between the fault current of the fault phase calculated by each power supply and the fault current of the fault phase calculated by all power supplies is defined as fault characteristic value in this paper.

The fault characteristic value, noted as E(j), is defined as following:

$$E(j)=\sum_{i=1}^{m}|I_{fj}(i)-I_{fj}| \quad (17)$$

According to the electrical network theory, the fault current of the fault phase calculated by each power supply is equal to the fault current of the fault phase calculated by all power supplies fault current. Thus, the fault characteristic value at the true fault point is zero.

3.2. Fault Section Location

If the neutral point of the power system is directly grounded, the fault current is large. The fault current characteristics can be extracted to locate the fault area.

The distribution network with neutral point directly grounded is taken as the object of study in this paper. The distribution network with DG is modeled by using three phase impedance model. The fault feature of the distribution network with DG based on three phase impedance model is analyzed and extracted with the arithmetic represented in 3.1.

The fault associated node is the node with the smallest fault feature. Thus, the fault area is located by the fault associated nodes.

Assume the fault occurred in *B(1)*, the fault current in fault node is calculate by using Equation (15) and Equation (16). And the fault feature value of node 1 is calculated by using Equation (17). Then assuming fault occurred in $B(2),B(3),\ldots,B(n)$, the fault characteristic value $E(1),E(2),\ldots,E(n)$ is respectively calculated.

The node fault characteristic value which is closest to the actual fault location on is the smallest. By confirming the two minimum of the error, the fault area is just between the two nodes. In this way, the fault area is located. However, in some cases, this process may misjudge the fault area. In order to avoid this problem, three fault associated nodes are used to locate the fault area in this paper. The flow chart of the fault area location is shown in Figure 1.

4. Simulation and Analysis

4.1. The Simulation Model

The fault area location method based on the three phase impendence matrix and the fault feature is tested in a sixty-node distribution system with six distributed generator. The system's neutral point is grounded directly. The topology of the system is shown in figure 2. Load parameter is described in the literature [15]. System's total load is 2.5 MVA. System's line Numbers and DG unit capacity and access point are shown in literature [15]. In this paper, the three phase node admittance matrix established in this paper can capture any possible imbalance and the grounding capacitance. And cables and overhead lines can also use the matrix model.

The voltage and current waveforms of each DG substation power supply and the terminal are recorded. The waveform was transferred to MATLAB when fault occurs and was transformed into synchronous phasor by full wave Fourier transformation.

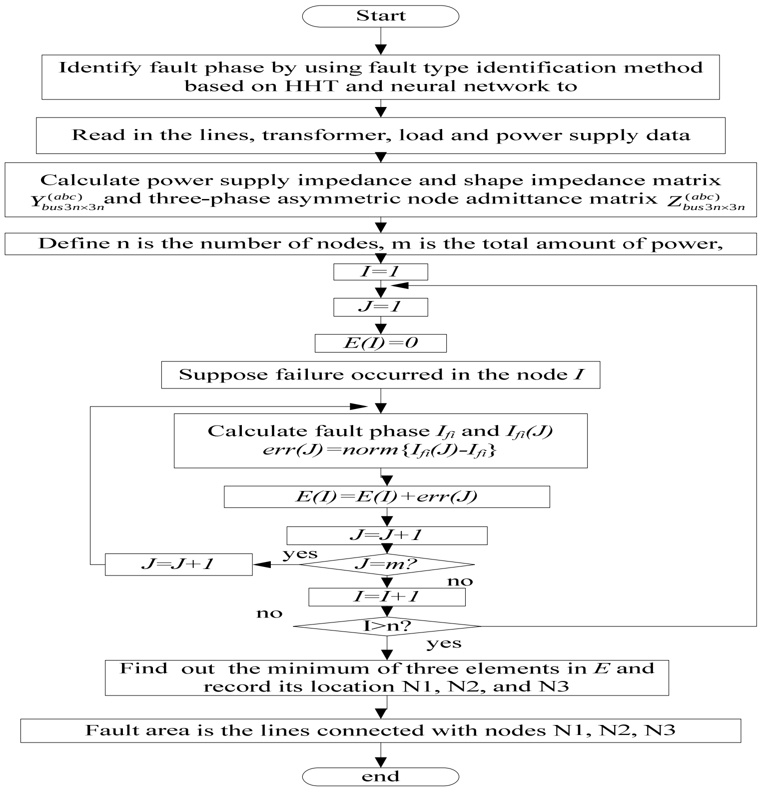

Figure 1. The Flow Chart of the Fault Area Location based on the Three-phase Impedance Model

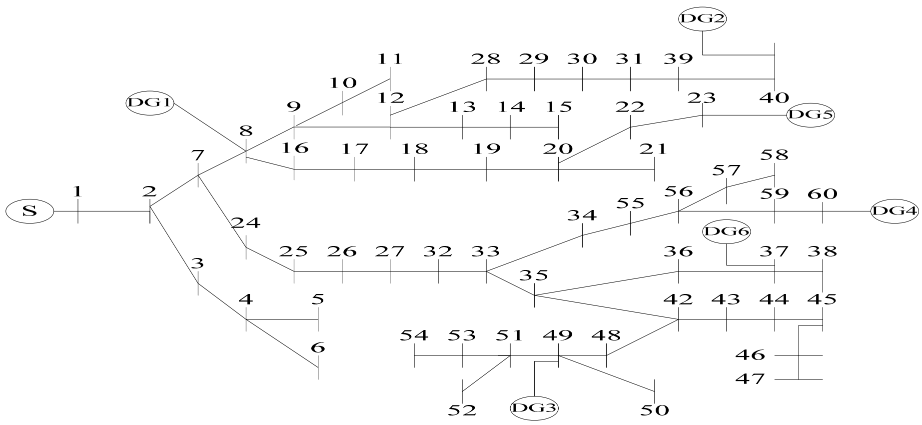

Figure 2. The Topology of the Sixty-node Distribution System with Six Distributed Generator

4.2. Simulation Examples based on Three Phase Impedance Model

When the neural point of the system's main power source is direct grounded, the short-circuit current will be large when fault occurs. In this case, the three-phase impedance model can be used to locate the fault area. The simulation examples in different fault conditions are addressed as following.

Example 1. The one-phase ground fault happens on line 1, the grounding resistance is 100Ω. According to the definition of fault feature value, the fault feature values of all the nodes are shown in Figure 3. The fault associated nodes searched are 1, 2 and 3. The method can locate the Fault area accurately.

Example 2. The two-phase ground fault happens on line 8, the grounding resistance is 10Ω. According to the definition of fault feature value, the fault feature values of all the nodes are shown in Figure 4.

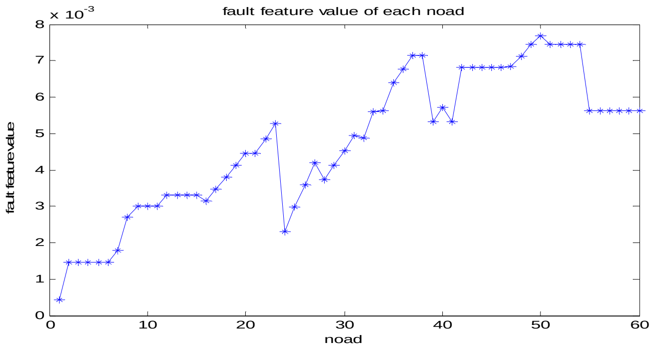

Figure 3. Fault Characteristic Value of each Node when Line 1 Occurs Single-phase Ground Fault

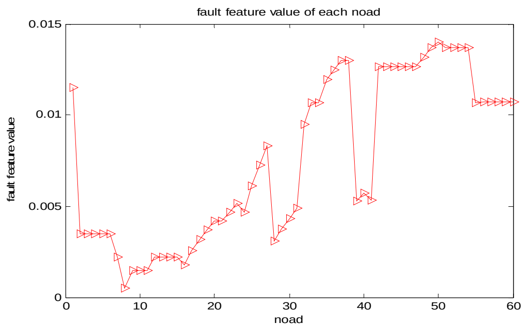

Figure 4. Fault Characteristic Value of each Node when Line 8 Occurs Two-phase Ground Fault

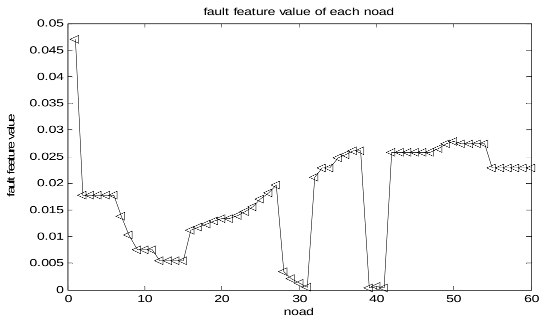

Figure 5. Fault Characteristic Value of each Node when line 39 Occurs Three-phase Ground Fault

The fault associated nodes searched are 8, 9 and 10. The method can locate the Fault area accurately.

Example 3. The three-phase ground fault happens on line 39, the grounding resistance is 50Ω. According to the definition of fault feature value, the fault feature values of all the nodes are shown in Figure 5.

The fault associated nodes searched are 39, 40 and 41. The method can locate the fault area accurately.

Example 4. Different fault conditions were set to all the lines. The fault area was searched by the method proposed in this paper. The results are shown in Table 1 (as space is limited, only parts of the locating results were listed).

Example 5. The number of distributed generator reduced, and single phase ground, two phase ground and three phase fault were set in all branch. The fault area was searched by the method proposed in this paper. The section determination accuracy with different number of DG is shown in Table 2.

Through a large number of simulation examples, it can be seen that the proposed fault section locating method based on three phase impedance model for a distribution network with DG has higher accuracy. This method was verified efficient in the neutral directly grounded distribution network with DG.

Table 1. The Result of Fault Area Location

Fault condition	Fault line	section	Associated nodes	Whether accurate
AG	2	2-3	2、3、4	yes
BG	16	16-17	16、17、18	yes
CG	24	24-25	24、25、26	yes
AG	31	27-31	30、29、31	yes
BG	48	48-49	48、49、51	yes
ABG	6	2-7	7、2、3	yes
BCG	12	12-13	12、13、14	yes
ACG	17	17-18	18-17-19	yes
ACG	21	20-22	22、20、21	yes
BCG	26	26-27	26、27、32	yes
ABCG	32	32-33	32、33、34	yes
ABCG	40	39-41	39、41、31	yes
ABCG	42	42-43	42、43、44	yes
ABCG	50	49-51	49、51、53	yes
ABCG	52	51-53	49、51、53	yes

Table 2. Section Determination Accuracy with Different Number of DG

DG number	The accuracy under different number of DG
1	93.33%
2	95%
3	98.33%
4	100%
5	100%
6	100%

5. Conclusion

Fault location in distribution systems with large amounts of DG can greatly affect the operation of the power distribution system. The method proposed in this paper is efficiently solved the fault area location problem. The method uses the measuring technique that can be fulfilled at present. It has a solid theoretical foundation and it is verified in a 60 nodes distribution system with six generators. The simulation results show that the proposed fault area location method based on three phase impedance model in the distribution network with DG is effective. Even when the number of the DG is small, the method is also accurate. In the simulation example, the accuracy of the fault area location is above 93.33%. The more DGs are employed, the method is more robust. When DGs number is above 4, the accuracy of the method is equal to 100%. In addition, the method proposed in this paper is not affected by the variations of the system topology, system operational states, fault time and the grounding resistance.

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