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Fault Location of Distribution Network Containing Distributed Generations

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Abstract

It makes the topology of distribution network more complex to contain a lot of distribution generations (DGs) in it. For this reason, a fault location approach suitable to the distribution network containing DGs is proposed. Firstly, according to the results of power flow calculation, a database of voltage sag is established; then the power quality information is acquired by power quality monitors and correlation analysis on collected nodal voltage data and voltage sag data of the established database is performed; and then the node with the matching extent value most close to 1 is determined as the fault point. Simulation results of IEEE 33-bus system show that the proposed approach is effective and using the proposed approach the misjudgment can be prevented. Finally, the results of the analysis on the influences of different load models, transition resistances, connection and disconnection of DGs on the proposed approach show that the proposed approach possesses better robustness and reliability.

Keywords: *distribution network, distributed generation (DG), fault location, power quality monitor, correlation analysis, voltage sag*

1. Introduction

In recent years, along with the gradually depletion of the conventional energy such as oil, coal, natural gas particularly on earth, the distributed generations (DG) which are represented by solar energy, wind energy, fuel cell, cogeneration and other forms of distributed power supply have been attracting more and more attention and taken as an ideal way of comprehensive utilization of existing resources by the electric power utilities in many countries and researchers around the world. However, a great of DGs being connected into the distribution network makes the conventional distribution network become multiple power sources configurations from single power source, which makes the power quality of distribution network, power flow and fault levels take great changes, thus directly affects the fault location of distribution network and relay protection [1-2]. The scale and configuration of modern power distribution network are large and complicated, with the improvement of distribution network automation, a variety of intelligent electrical appliances such as feeder terminal unit (FTU), remote terminal unit (RTU) have been used, the failure in such distribution network would produce huge amounts of alarm information, the connection and quit of many DGs makes the data more complex and variable, which further increased the difficulty for the operators in quickly handling the failure. So the study on both the rapid analysis and process of the uploaded data signals and the distribution network fault location has great significance in isolating the fault, restoring power service, improving power supply reliability, ensuring the quality of user power supply, etc. About distribution network fault, domestic and foreign scholars put forward a variety of fault diagnosis methods [3-10]: traditional matrix method is simple, but the fault tolerance is not high, if the real-time information distortion or information is not intact, it is easy to cause misjudgment; the artificial intelligence method has good fault tolerance, but needs relatively complex model building, and fault location efficiency is not high either; up today, most of the algorithms in fault location are limited to simple radiant operation mode of the single power supply, for complex distribution system containing DG, they lack applicability. Therefore, it is necessary to study more adaptable distribution network fault location method.

At present, the power quality monitoring(PQM) devices [11] are developing into the monitoring system that continuously measures the PQ at multiple points. These monitoring systems will provide such functions as high-speed communication with an Internet network and

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statistical analysis through uninterrupted measurements and display with a web browser. It collects, compares, and analyzes the information that has gathered at lots of monitoring sites. In this paper, based on the system voltage sag characteristics, the changes of the powerflow when the faults occurs and the information collected by the power quality monitors, the faults in the distribution network with DGs can be detected and located instantly through correlation analysis in order to improve the adaptability of distribution network fault location.

2. Correlation Analysis

Correlation analysis is an important method of signal processing, the essence of which is judging the similarity of two signals in time domain. At present, the applications of the correlation analysis in power system are mainly concerned in fault line selection, fault phase selection, transient differential protection and induction motor fault diagnosis, etc.

From a statistical point of view ,correlation analysis is the characterization of correlation degree between two or more variables , assume that x(t)、y(t) are two finite energy real signal waveform, the linear similarity degree of two waveform can be described by the correlation coefficient ρ [12-14].

$$\rho=\frac{\int_{-\infty}^{\infty}x(t)y(t)\mathrm{d}t}{\sqrt{\int_{-\infty}^{\infty}x^2(t)\mathrm{d}t}\sqrt{\int_{-\infty}^{\infty}y^2(t)\mathrm{d}t}} \qquad (1)$$

The correlation coefficient after discretization is:

$$\rho_{xy}=\frac{\sum_{n=0}^{N-1}x(n)y(n)}{\sqrt{\sum_{n=0}^{N-1}x^2(n)\sum_{n=0}^{N-1}y^2(n)}} \qquad (2)$$

The matching degree of correlation analysis is defined as:

$$\rho'=|\rho_{xy}|=|\sum_{n=0}^{N-1}x(n)y(n)[\sum_{n=0}^{N-1}x^2(n)\sum_{n=0}^{N-1}y^2(n)]^{-\frac{1}{2}}| \qquad (3)$$

Theoretically in Equation (3) the time should be infinite, while doing correlation analysis, the Equation (3) is still effective in finite length data window, and correlation analysis matching degree ρ' value interval is among [0, 1].If ρ' = 1, the two waves exist in positive linear relationship; If ρ′ =-1, then there is a negative linear relationship between two waves. If ρ'=0, the two waves have no relationship.

The commonly recognized view is that if ρ<0.3 there is no correlation and 0.3≤ρ<0.5 is for low degree corelation;0.5≤ρ<0 is for moderate corelation;0.8≤ρ<1 for high degree correlation.

3.Fault Location for Complex Distribution Networks

3.1. Fault Location Algorithm Process

Voltage sag is referred to as the power voltage RMS value abruptly dropped to 90% ~ 10% of the rated voltage amplitude in a short time, the typical duration was 0.5 ~ 30 wave cycle [15]. The primary cause of voltage sag is certain branch current transient increase in the system.Short-circuit faults, switch operation, the on-and-off of transformer and capacitor set, sudden cut of DG and large induction motor starting, etc can cause voltage sag [16]. When a fault occurs in the feeder, voltage sags propagate presenting different magnitudes and phase angle for each feeder node. The nearer the node is to the point of the fault, the greater magnitude the voltage sag. Based on the above characteristics, the power quality (PQ) monitor installation at the root nodes samples the data information of different DGs in and out of network operation, according to the network topology data, the pre- and during-fault powerflow data can be obtained, the database of root nodes voltage sags are built up through the simulation of each node fault online,then the voltage amplitude correlation matching degree of root node is calculated and by comparing with the database ,the optimum matching point is extracted, so the point of fault can be determined. The steps of the fault location algorithm is shown in Figure 1.

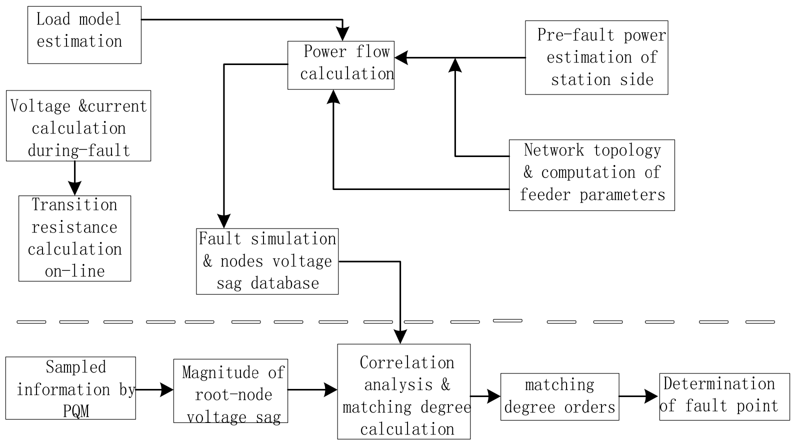

Figure 1. Flow Chart of Fault Location

The function above the dotted line: 1) to calculate pre-fault data of each feeder such as voltage, current and powerflow etc.(including DGS in or out of the network); 2) to establish the database of specified nodes voltage sag by simulating different nodes faults, calculate the transition resistance.The function below the dotted line is to analyze the correlation between the magnitude of the specified nodes voltage sag and the relevent data groups in the voltage sags database and sort the matching degree sequence, the node matching degree which is nearest to 1 is certainly the faulted point.

3.2. Data Acquisition of the Feeders and Synchronization

The proposed algorithm uses voltage and current measurements at the feeder root nodes as well as the voltage measurements at the nodes which DGs are installed along the feeder. Pre-and during-fault voltage and current phasors must be recorded at the feeder root nodes. The during-fault voltage sag magnitudes aquired at root nodes (where the power qualty mornitors are installed) are used by the algorithm in order to find the faulted point.

Since the data recorded by FTU and the PQM is multifarious and disorderly, and the time which DGs are interconnected is random, in order to reflect the same fault event, all the data must be strictly synchronized. For this purpose, GPS means is used to provide the uniform high-accuracy clock for the whole distributed networks needed mornitoring to make sure that all the recorded data is strictly synchronized, the data on both sides can also be communicated in real time by the fiber communication channel [17].

3.3. Load Modeling

Usually, loads connected at a distribution feeder present significant random and uncertainty. Based on their complex power demand. These loads can be three, two or single-phase. In this paper, the Polynomial static load models with constant power, constant current and constant impedance which is called comprehensive load model (CLM) are formed in certain ratio as follows:

$$\begin{cases} P = P_0[a_p(\frac{U}{U_0})^2 + b_p(\frac{U}{U_0}) + c_p] \\ Q = Q_0[a_q(\frac{U}{U_0})^2 + b_q(\frac{U}{U_0}) + c_q] \end{cases} \quad (4)$$

$$\begin{cases} a_p + b_p + c_p = 1 \\ a_q + b_q + c_q = 1 \end{cases} \quad (5)$$

Where U is voltage applied to the load, P、Q are the corresponding active and reactive power respectively at U;U_0 is the load nominal voltage, P_0、Q_0 are the corresponding rated active and reactive power respectively.a,b,c define the ratios of each type of load occupied in the power. p,q are the subscript signs of active and reactive power respectively. Each coefficient reflects the static characteristic of load, its value is different for different load group, the coefficients are the parameter identification objects of load model.

3.4. Power Flow Calculation

Large amounts of DGs access to the distribution network further aggravate the original asymmetry of it, which makes the conventional power flow algorithm of three-phase distribution network unsuitable. After the connection of DGs, the accuracy of the power flow calculation has a great influence on the accuracy of fault location. Literature [18] proposed a fast algorithm which can caculate the loop network power flow containing DGs but is unfit for three-phase unbalanced power flow caculation; In view of the complex distribution network with DGs, literature [19] proposed an improved power flow algorithm, which performances better in dealing with loop and unbalanced three-phase power flow calculation containing DGs. In this paper, an improved back/forward sweep algorithm[19] is used to calculate power flow of the distribution network containing DGs.

3.5. Voltage Sag Analysis During-Fault

A simple configuration of power distribution network is shown in Figure 2, if the fault occurred at point b, the voltage sag (RMS value) reflected at node a is:

$$U_{\mathrm{ab}} = U_{\mathrm{a}} + \Delta U_{\mathrm{ab}} \quad (6)$$

$$\Delta U_{\mathrm{ab}} = -Z_{\mathrm{ab}} I_{\mathrm{b}} \quad (7)$$

Where U_{a} is pre-fault voltage at a. ΔU_{ab} is voltage variation between pre-fault and during-fault; I_{b} is the fault current, Z_{ab} is line impedance between node a and b.

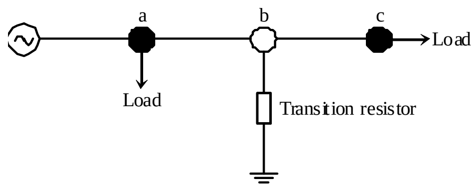

Figure 2. Structure of Simple Distribution Network

In practical calculation, in order to accurately extract the transient voltage sag values, the Kalman filtering method [20] is used to extract the voltage sag eigenvalue; it is suitable for the short-term voltage sag disturbance analysis with rapid voltage changes.

3.6. Simulation Test

In order to verify the effectiveness of the proposed algorithm, an IEEE33 node system [21] is used to simulate the fault and analysize it. The types of DG, installation location and capacity are shown in Table 1, the detailed parameters of the system are refered to literature [21].

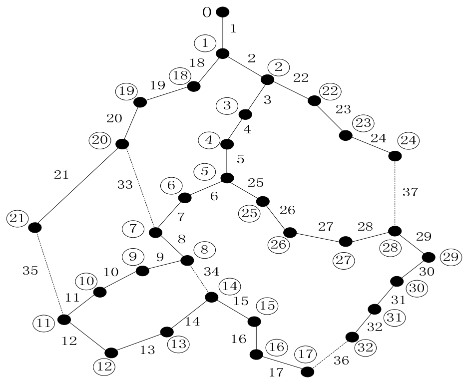

Figure 3. IEEE 33-bus System

Table 1. Location, Type and Capacity of DG

Nodes	Types of DG	Capacity
6	Double-fed wind machines	P=100 kW, Q=100 kvar
12	Photovoltaic cell	P=300 kW, I=10 A
24	Fuel cells	P=100 kW, U=12.66 kV
29	Constant speed type asynchronous motor	P=200 kW, s=0.033

PS: *P,Q* are the active power and reactive power of DG respectively, *I* is the rated current, *U* is the rated voltage, s is the slip speed.

The more of the number of power quality monitors (PQM) installed, the higher of the precision of the algorithm in this paper, but when the mornitoring points reach a certain number, location accuracy will reach the limit value owing to the intrinsic characteristics of power distribution feeders. As a rule of thumb, the installation points should be able to detect the variations of the voltages and currents of each feeder, in this example, the nodes at 2, 5, 11, 19, 28 were installed the PQ monitors. When the fault occurred at the point where a DG is connected, the DG will be cut off the network instantly and the fault can be easily located by the PQ monitor, so this kind of faults will be ignored in this paper. Because the operation of DG is at random, therefore the normal operation data of the network with DG or without should be recorded and transmitted to the database for storage. Here, the load model used for simulation is the comprehensive load model as depicted in section 3.2. The most common faults are single-phased at site, so in this paper, only single-phase faults are simulated and analyzed. Assume that a fault occurred at node 25 for phase A, the transition resistance is 2Ω, the duration time is 0.2s, the results of the voltage sags at nearby nodes are calculated and shown in Figure 4, the results comparison between estimation and simulation(obtained by PSS/E software) is listed in Table 2.

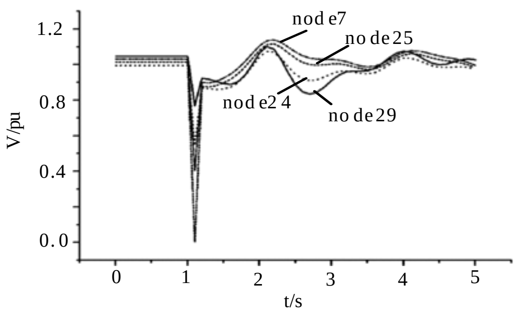

Figure 4. Calculation Result of Voltage Sag

Table 2. Comparison Analysis of the Results of Voltages Sag at 1.2s

nodes	estmation values /pu	simulation values /pu
29	0.75	0.74
14	0.53	0.52
25	0.02	0.01
7	0.41	0.42

According to Figure 4 and Table 2, the magnitude of the voltage sag at node 25 is the largest, the other nodes' simulation and analysis results of the voltage sag are roughly the same as the estimated results of the algorithm, which shows the voltage sag analysis model is conformed to the actual situations. (PS: the estimated values are calculated according to the algorithm, yet the simulation values are obtained by PSS/E software).

When the fault occurred at node 28, the DG' breaker at node 29 tripped off, which indicated that the faulted point which is too close to DG installation position may affect the operation of the DG. Further assume that faults occur at other nodes, database of voltage sag is built up by collecting the values of voltage sag through the power quality monitor after 33-node failure is simulated .Still assume that node 25 occurs a short circuit fault, compare the real-time acquisition of the power quality monitor of voltage sags with the voltage sag groups in the database and make the correlation matching degree calculation, the result is shown in Figure 5.

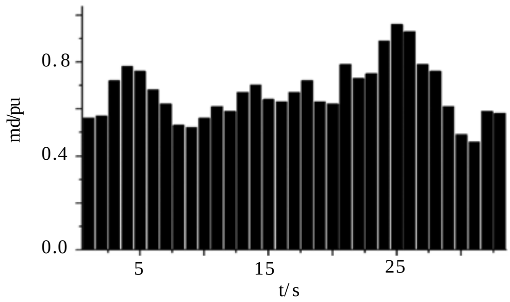

Figure 5. Matching Degree Result at Node 20 when Fault

The Figure 5 shows that the calculation correlation matching degree at node 25 is 0.98, most close to 1, so by the matching results ,the node 25 can be inferred as the point of failure, which is consistent with the facts.

4. Applicability Analysis on the Algorithm
4.1. Influence of the Load Model on the Algorithm

Environmental factors, load fluctuation, DG access and exit, distribution transformer connection mode, and so on will affect the fault location results.in order to verify the algorithm has better applicability and robustness, let's take IEEE33 node system as an example, selecting different load model, transition resistance, DG interconnection and exit to evaluate the algorithm' applicability in this paper.

The mentioned load model in section 2 is comprehensive load model (CLM), the model has reflected the field operation more accurately, in order to illustrate this, we use the constant impedance load model (CILD) to analyze and compare. The model is as follows:

$$S = S_0 (\frac{U}{U_0})^2 \tag{8}$$

Where S_0 is the rated complex power, S is the power of the constant impedance load model.

Let a single-phase fault occur at node 25 ,the fault location results under two load models are shown in Figure 6.

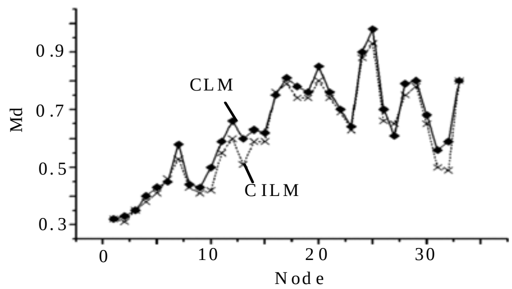

Figure 6. Fault Location Result with Different Load Model

According to Figure 6, the value of the matching degree (Md) drops a little when the constant impedance load model (CILM) is used ,but it does not affect the determination of the fault location result, since the matching degree at node 25 is still the biggest.

4.2. Influence of the Transition Resistance

Setting the transition resistance as 0.1,2,15,200Ω respectively, still let a phase A fault occur at node 25,by simulation analysis, the location results under 4 circumstances are shown in Figure 7.

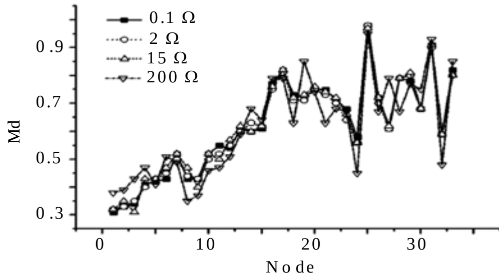

Figure 7. Fault Location Result with Different Transition Resistance

According to Figure 7, when a fault occurrs, the correlation matching degrees vary a little with different transition resistance owing to the variation of the fault currents, of course, the existence of DG is sure to cause some influence on the fault currents, however, no matter the transition resistance is large or small, it does not affect the correlation matching degree analysis, so the algorithm has stronger ability to resist the influence of transition resistances.

4.3. Influence of the DG' Connection

If the fault occurred at node 25, shift the DG from node 29 to node 26, the fault location result is shown in Figure 8.

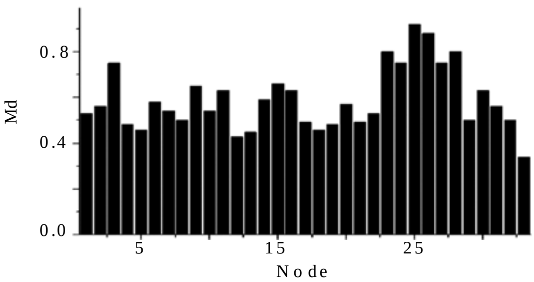

Figure 8. Fault Location Result when DG in and out the Network

According to the figure, when the DG is disconnected from the network, the fault location result is out of question; when the DG is connected, owing to the DG's voltage support, the voltage sag magnitude at node 26 is relatively smaller, so the correlation matching degree at 25 is slightly reduced, yet it does not affect the fault location result.

If the observed and measured voltage data is missed or failed to be received for various reasons, an alternative method of adding fault current information as a compensation criterion can be used to prevent misjudgment, i.e whether the fault current is continuous or not is considered as the judgment criterion .When only a single fault occurs at a feeder, the discontinuous current zone is definitely the fault zone [22].

5. Conclusion

A new fault location algorithm is proposed by using correlation matching degree and voltage sag characteristics in a complex distribution network containing several DGs in this paper. The key factor that affects the algorithm is the accuracy and completeness of the node voltage sag database which can be guaranteed by repeatedly simulations. If the power flow calculation is more accurate, DGs' connection and exit will not affect the accuracy of the fault location. As the intelligent distribution network is further improved, DGs will be realized the true sense of "plug and play", yet this will also increase the complexity of fault location, the method in this paper can provide reference for intelligent distribution network fault location. In addition, how to achieve the optimal allocation of intelligent monitors in order to make the configuration of the monitoring points are smallest but with high measurement redundancy, is an urgent need for further study.

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