STATE ESTIMATION AND AUXILIARY FAULT ANALYSIS OF DISTRIBUTION NETWORK BY THE LOAD MONITOR SYSTEM

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ABSTRACT

This paper proposes a state estimation method for the distribution network based on the load monitor system. According to the data gathered from the load monitor system, all operational information of the distribution network can be estimated by the proposed state estimation algorithm. The algorithm is realized by the method of least square and solved by the Newton iteration method. From the calculation result, the operator can get more information from the network and help analyze and decide. Also, the load monitor system can be further used to assist the judgement of the disconnection fault of the distribution line. According to the voltage variation curve gathered from the load monitor and combing the connection mode of transformer, the phase and location of the disconnection fault in distribution line can be judged quickly and easily, so the time to repair the fault can be shortened a lot.

INTRODUCTION

Power system state estimation is a method which uses the redundance of the data from the measurement to improve the precision of the measurement and estimate the operational state of the system [1]. With the development of intelligent grid, the gather of the distribution network data has been spread and expanded. In many cities of China, the load monitor system has been widely used in the distribution network. The load monitor system can inspect the voltage, current, active power and reactive power of the load in the distribution network and transfer these data to the power reschedule center. According to these data, the power operator can master the condition of the load in the distribution network and make some deep analysis.

Based on the data gathered from the load monitor system, the state estimation method for the distribution network is proposed. This method uses the data from the load monitor system, such as the voltage, current, active power and reactive power of the pole-mounted transformers and compacted transformers. The voltage and angle of all nodes in the distribution network can be estimated by the least square algorithm. Also, when there existing single-line disconnection fault in network, according to the voltage variation curve drawn by the load monitor system, the phase and location of the disconnection line can be judged. So the time to find and repair the fault can be shortened and the reliability of the distribution network can be increased.

1 LOAD MONITOR SYSTEM

Load monitor system is composed by the load monitor device (UI meter) installed in the low-voltage side of distribution transformers, data transfer system and terminal server in power company [2]. The data gathered by the UI meter is transferred by the GPRS wireless network to the internet and received by the terminal server in the power company. The UI meter can gather the information of voltage, current and power of the distribution transformers in real time and send them in a uniform format to the terminal server. The configuration of the load monitor system is illustrated in Fig.1.

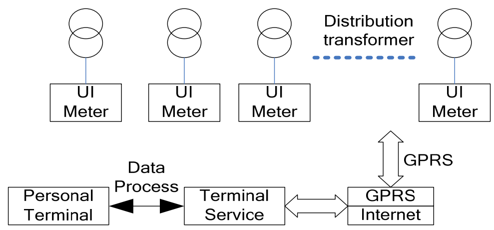

Figure 1. Load monitor system

The working principle of UI meter is illustrated in Fig.2:

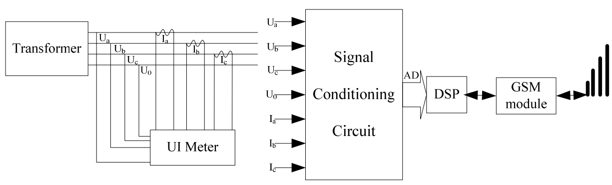

Figure 2. Working principle of UI meter

From Fig.2, it can be seen that the UI meter firstly gathers the voltage and current in the low-voltage side of the distribution transformers and then sends them into the signal conditioning circuit. After A/D transformation in this circuit, the data is then sent into the DSP. Required indices will be calculated in the DSP. Lastly, these indices will be sent into terminal data server in power company by GSM module. The required indices are as follows: phase current, phase voltage, power factors, active power, reactive power, active electric quantity, reactive electric quantity.

2 MATHEMATIC MODEL OF STATE ESTIMATION

There are mainly two kinds of mathematic models for the state estimation calculation. One is the model based on Newton method, the other is the model based on the measurement transformation technology [3-5]. The model based on the measurement transformation technology has higher calculating speed. However, this model needs the measurement of both active power and reactive power and can't use the measurement of voltage. Also, this model has bad convergency characteristic. So the model based on the Newton method is used. This model has better convergency characteristic and is more stable.
The nonlinear measuring equation for state estimation is as follows:

$$z = h(x) + v \tag{1}$$

The least square state estimation is to solve state variable ***x*** to minimize the following objective function:

$$J(x) = [z - h(x)]^T R^{-1} [z - h(x)] \tag{2}$$

Where z is the measuring data; x is the state vector; $h(x)$ is the measuring function; v is the measuring error; R^{-1} is the weighted matrix and $1/\delta_i^2$ is its diagonal elements； $1/\delta_i^2$ is the variance of the *i*th measurement.
The optimal condition to minimize $J(x)$ is as follows:

$$\frac{\partial J(x)}{\partial x} = 0 \tag{3}$$

After solving equation (3) under given state x^l, the new state vector can be gotten:

$$x^{l+1} = x^l + \Delta x^l \tag{4}$$

$$\Delta x^l = \left[H(x^l)^T R^{-1} H(x^l) \right]^{-1} H^T(x^l) R^{-1} r(x^l) \tag{5}$$

$$\text{Where: } H(x^l) = \frac{\partial h(x^l)}{\partial x^l},\ r(x^l) = z - h(x^l) \tag{6}$$

For the initial state x^0, the condition for convergency is: $\max\left|\Delta x_i^l\right| \le \varepsilon_x$ or $\left|J(x^l) - J(x^{l+1})\right| < \varepsilon_J$, where ε_x and ε_J are all relative small positive values.

3 STATE ESTIMATION CONSIDERING LOAD MONITOR SYSTEM

After installing load monitor system, the measuring data z that can be gathered from the distribution line are as follows:

1) The voltage and current of root node of the feeder line in substation.
2) The voltage, current, active and reactive power of pole-mounted transformers and compacted transformers equipped with load monitor devices.
3) The active and reactive power of some user substations.

Set the voltage amplitude and angle in all nodes as the state vector x. Suppose V_i is the voltage amplitude of node *i*, θ_i is the angle of node *i*, $G_{ij} + jB_{ij}$ is the admittance of branch *ij*. Then the relationship between measuring data and state vector is as follows:

$$P_i^e = V_i \sum_{j \in i} V_j (G_{ij} cos\theta_{ij} + B_{ij} sin\theta_{ij}) \tag{7}$$

$$Q_i^e = V_i \sum_{j \in i} V_j (G_{ij} sin\theta_{ij} - B_{ij} cos\theta_{ij}) \tag{8}$$

$$V_i^e = V_i \tag{9}$$

$$I_i^e = \sqrt{I_{ir}^2 + I_{ix}^2} \tag{10}$$

where $I_{ir} = \sum_{j=1}^{n} (G_{ij} V_j \cos\theta_j - B_{ij} V_j \sin\theta_j)$, and

$$I_{ix} = \sum_{j=1}^{n} (B_{ij} V_j \cos\theta_j + G_{ij} V_j \sin\theta_j)$$

In above equations, P_i^e, Q_i^e, V_i^e and I_i^e are measuring data of active power, reactive power, voltage amplitude and current amplitude respectively. Such measuring data constitutes measuring vector z. The measuring function vector $h(x)$ is equation (7)-(10). By solving the partial derivative of measuring function to state vector, the Jacobi matrix $H(x)$ in (6) can be gotten.
The process of the state estimation algorithm considering load monitor system is as follows:

1) Set the time to estimate and get all measuring data z from the load monitor system in this time.
2) Initialize voltage amplitude and angle of all nodes in the distribution network as the voltage $[V_0, \theta_0]$ in the root node. Set *i*=0.
3) Substitute voltage V_i into equation (7)-(10) and solve the distance between measuring data and measuring function: $r(V_i, \theta_i) = z - h(V_i, \theta_i)$.
4) Solve all elements in the Jacobi matrix $H(V_i, \theta_i)$ under the voltage $[V_i, \theta_i]$.
5) Solve the voltage increment $[\Delta V_i, \Delta\theta_i]$ by equation (5).
6) If $\max_{i=1,n} \left|\Delta V_i, \Delta\theta_i\right| \le \varepsilon$, output results of state estimation and terminate; otherwise, go to 7).
7) Set $[V_{i+1}, \theta_{i+1}] = [V_i, \theta_i] + [\Delta V_i, \Delta\theta_i], i = i+1$, go to 3).

During the solving process of algorithm, the voltage amplitude in the root node of distribution line is invariant and the voltage angle is always 0. ε is set as a relative small positive value. The value of the voltage, current and power in the low-voltage side of the transformer has been conversed into the value in high-voltage side.

4 TEST AND RESULTS

This paper takes a real 10KV distribution line as an example to verify the validity of the algorithm. The network is illustrated in Fig.3. This distribution line is a feeder line of one 35KV substation. This distribution line is combined by both the overhead line and cable and its length is 12 kilometers. There are 13 Buses in all along this distribution line. Bus 1 is the root node in the 35KV substation. Bus 2, 4, 6, 10, 11 are nodes with pole-mounted transformers. Bus 7, 9 are nodes with compacted transformers. Bus 5, 12 are nodes with user transformers. Bus 13 is one node with load switch. After installing the load monitor device in the distribution line, a lot of information such as the current, voltage and power of the pole-mounted transformers and compacted transformers can be gotten. With such information, the state estimation calculation can be done to get all operational data along the distribution line. Then the voltage amplitude and angle in the node of the user transformers and load switches will be gotten.

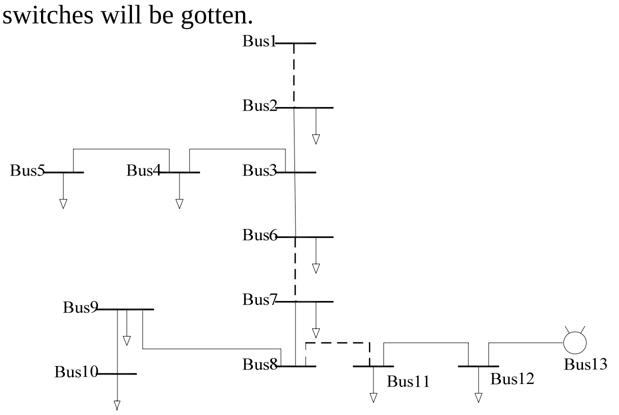

Figure 3. Network of distribution line

The proposed state estimation algorithm is used to estimate the operational state of the network. During the calculation, the voltage amplitude in Bus 1 is assigned as 10.35KV and the voltage angle in Bus 1 is assigned as 0. In order to validate the correctness of the estimation results, the accuracy results solved by the power flow program is compared. Comparison results of some typical measuring data are listed in Tab.1. These typical measuring data are gathered from the node of root, pole-mounted transformers, compacted transformers, user transformers and load switch.

Table 1. Comparison of state estimation results

Measure Parameter	Practical Value	Measure Value	Estimation Value	Measure Error(%)	Estimation Error (%)
P1	3855.6	3903.1	3875.15	1.23	0.50
Q1	677.1	685.96	671.263	1.30	0.86
I1	218.31	217.71	218.578	0.27	0.12
V2	10.288	10.373	10.3411	0.82	0.51
$\theta 2$	-0.101	Null	-0.1017	Null	0.12
P2	180.0	180.69	179.153	0.38	0.47
Q2	20.0	19.981	20.2111	0.09	1.05
I2	10.16	10.053	10.1589	1.04	0.01
P5	600.0	591.82	598.781	1.36	0.20
Q5	100.0	100.91	100.364	0.91	0.36
V5	10.131	Null	10.082	Null	0.48
V7	10.040	9.9236	10.1229	1.15	0.82
$\theta 7$	-1.106	Null	-1.0927	Null	1.21
P7	350.0	349.07	349.117	0.26	0.25
Q7	50.0	50.463	49.7732	0.92	0.45
I7	20.33	20.557	20.1376	1.12	0.94
V13	9.919	Null	9.94569	Null	0.26
$\theta 13$	-1.601	Null	-1.6022	Null	0.03

From table 1, it can be seen that the estimation results is more precise than the measuring results. So the state estimation has the effect of filtering. In this test, the practical value is calculated by the power flow program. The measuring value is the sum of practical value and random error. The random error is subject to normal distribution and its expected value is zero. For the state that hasn't be measured, it can also be estimated by the state estimation program, such as the voltage of user Bus 5 and load switch Bus 13, the voltage angles of all nodes. These estimating results can help the operator analyze and make decision.

5 AUXILIARY FAULT ANALYSIS

Single-phase disconnection fault is a common kind of faults in the distribution network. The address and phase of disconnection fault is difficult to find some times. However, the above problem can be well solved by the load monitor system. There are mainly two kinds of connection modes for the transformers widely used in 10KV distribution network in China. One kind of connection mode is Y/Y_0, the other is $\triangle/Y_0$. When single-phase disconnection fault happens, the voltage waves in the low-voltage side of these two kinds of transformers are illustrated in Fig.4 and Fig.6. In these figures, the yellow, blue and red curves represent the voltage of A, B and C phase in the low-voltage side of transformer respectively. The abscissa represents the time and the ordinate represents voltage amplitude.

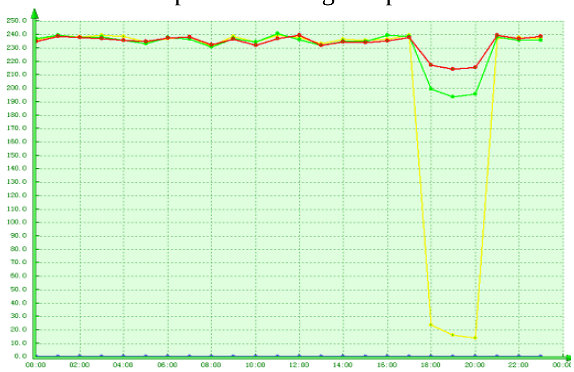

Figure 4. Voltage curves in the low voltage side of Y/Y_0 transformer

From Fig.4, it can be seen that, for the Y/Y_0 transformers, when single-phase disconnection fault happens, the voltage of the disconnection phase will fall down to 0 and the voltage of the other two phases will fall just a little.

Such conclusion can also be drawn from the principle of Y/Y_0 transformer in Fig.5. When one phase disconnects, the other two phases will form a loop circuit directly. The current of the other two phases will fall down to 0.866 time of its original value and have opposite direction. So the inductive voltage of these two normal phases will fall a little. But the inductive voltage of the disconnection value will be zero. Above all, for the Y/Y_0 transformer, when the voltage wave of the load monitor is like Fig.4, it can be concluded that the phase whose voltage is about zero is the disconnection phase.

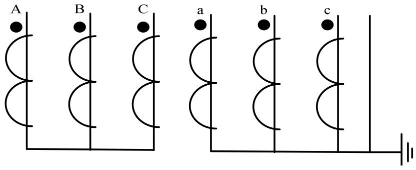

Figure 5. Winding diagram of Y/Y_0 transformer

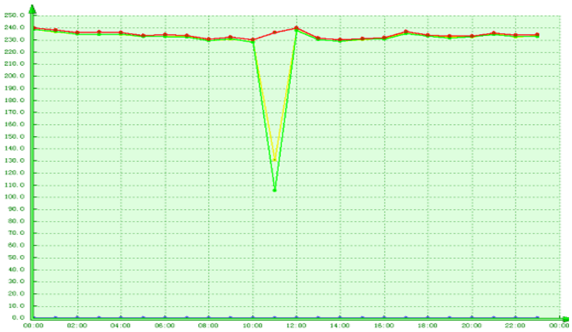

Figure 6. Voltage curves in the low voltage side of △/Y_0 transformer

From Fig.6, it can be seen that, for the △/Y_0 transformers, when single-phase disconnection fault happens, the voltage of the one phase doesn't change and the voltages of the other two phases will fall down to about half of their original values. Such conclusion can also be drawn from the principle of △/Y_0 transformer in Fig.7. When one phase disconnects, the other two phases will form a loop by two parallel circuits. The reactance of one circuit doesn't change. So the current and its inductive voltage in this circuit also don't change. The reactance of the other circuit scaled up to two times of its original value. So the current in the other circuit falls into half of its original value and the inductive voltage of these two phases will fall into half of their original values. Above all, for the △/Y_0 transformer, when the voltage wave collected by the load monitor system is similar to that in Fig.6, the disconnection phase can be judged according to the connection mode of the transformer.

Above all, it can be seen that single-phase disconnection fault happens, the disconnection phase can be judged according to the voltage wave in the load monitor device and the connection mode of transformer. Furthermore, the location of disconnect phase can be judged according to the voltage waves of two adjacent load monitor devices. So the load monitor system can help find the phase and location of the single-phase disconnection phase and save the time of elimination.

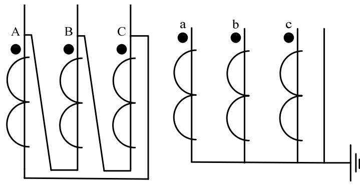

Figure 7. Winding diagram of △/Y_0 transformer

6 CONCLUSIONS

This paper makes good use of the data gathered by the load monitor system and uses the state estimation algorithm to estimate the operational state of the distribution network. By the state estimation algorithm based on the Newton method, the measuring data can be filtered and the state of line and node in the distribution network can be gotten. When single-phase disconnection fault happens, the phase and location of the disconnection phase can be judged by both the connection mode of transformer and the voltage wave collected by the load monitor system.

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Biography

Peng Wu received Ph.D. degree in electrical engineering from Shanghai Jiao Tong University, ShangHai, China, in 2009. He is currently working in Songjiang Power Supply Company, Shanghai Municipal Electrical Power Company. Now he is engaged in the power rescheduling work of distribution network.