Identification method of the feeder-transformer relationship in active distribution network based on power restoration information matrix

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Abstract. In order to solve the problem of identification and verification of topological relationship between feeder and distribution transformer in distribution network, a new identification method of feeder-transformer relationship in active distribution network based on power restoration information matrix is proposed. Firstly, the identification model of feeder-transformer relationship is established through the distribution network feeder-transformer information matrix. Then, through the identification model of feeder-transformer relationship, the real-time power restoration information matrix (RRIM) and standard power restoration information matrix (SRIM) are established to describe the power restoration distribution transformer under real-time and standard conditions. Finally, the feeder-transformer relationship error information matrix is established through the difference between RRIM and SRIM to describe the name information of distribution transformer with misconnection and leakage on a feeder. The case analysis shows that this method can identify the feeder-transformer relationship of distribution network based on the topology information of DMS and real-time distribution transformer power restoration information. The method is simple and reliable, can better meet the actual needs of the site, and has good popularization value.

1. Introduction

Accelerating the development of clean energy is the key link to achieve the goals of "carbon peak" and "carbon neutralization". The distribution network is the main consumer of distributed generation. It is the basis of building intelligent active distribution network to realize the observable, measurable, controllable and adjustable distribution network.

The distribution management system (DMS) can realize the data collection, monitoring, control, analysis and management of the distribution network. It has been widely deployed in the State Grid and China Southern Power Grid [1-3]. It effectively supports the daily work of dispatching, automation, and operation and maintenance personnel. Good graphics and models are the basis for the optimization analysis of the DMS. The current DMS diagram is drawn manually through the production management system (PMS). However, due to the large number of distribution transformer equipment and frequent daily changes, the diagram and model of distribution transformer are not updated in time, which is far from the actual operation status on site, and the diagram and reality are
inconsistent. It has seriously affected the monitoring and analysis application of distribution network. It has affected the accuracy of line loss analysis of distribution network. It has affected the safety of fault isolation and power transfer of distribution network. Therefore, it is of great significance to accurately identify and verify the connection relationship between distribution transformer and feeder.

A feeder-transformer relationship verification method based on distribution network operation data is proposed in reference [4-5]. This method classifies the distribution transformers with similar voltage fluctuations on the low-voltage side of the distribution transformer to the same feeder through the reduction of the three-phase voltage in the distribution transformer station area. An identification method of station area topology relationship of low-voltage distribution network based on voltage fluctuation similarity of smart meter and spatial coordinate distance is proposed in reference [6-7]. This method determines the relationship between the distribution transformer and the meter through the fluctuation law of the voltage of the low-voltage intelligent meter and the total voltage in the station area. A reverse identification method of the distribution network feeder-transformer relationship based on the measurement data of the smart meter is proposed in reference [8]. Based on the voltage fluctuation correlation between smart meter and medium voltage bus, the relationship between feeder and distribution transformer is identified by combinatorial optimization method. The above methods have achieved good results in solving the subordinate relationship between distribution network feeders and distribution transformers. However, none of the above methods consider the existing graphics and model status of the DMS, which has certain limitations and is not conducive to the rapid and accurate identification and verification of the feeder-transformer relationship. Therefore, based on the graphic model data of the DMS, it is of great practical significance to study the identification and verification of the feeder-transformer relationship of the distribution network.

Firstly, the identification model of feeder-transformer relationship in distribution network is established. Then, the general idea of feeder-transformer relationship verification based on distribution transformer power restoration information is discussed. Finally, the detailed method of feeder-transformer relationship identification in active distribution network is given.

2. Establishment of distribution network feeder-transformer information matrix model

The power restoration is required after the completion of fault emergency repair and planned maintenance of distribution network. By closing and transmitting power, the temporary operation mode of the distribution network is restored to the normal operation mode before the failure and planned maintenance. When the switch is closed for power transmission, the distribution transformer downstream of the switch will transition from a power failure state to a live state. The distribution transformer power restoration information will be sent to the DMS master station system by the intelligent fusion terminal. Then the distribution transformer associated with switch is identified.

As shown in Figure 1, Bus1 and Bus2 are 10kV buses of substation. The Feeder1~Feeder4 are 4 feeders. The S1~S4 are feeder substation outlet switches. The F1~F9 are branch switches with remote control function. The B1~B14 are sectional switches with three remote functions. The G1 and G2 are distributed generators. The P1 and P2 are distributed power grid connection switches. The T1 ~ T48 are distribution transformers, the D1 ~ d48 are drop out fuses, and the L1 ~ L3 are interconnection switches.

When the branch switch F1 is closed, the distribution transformer T2~T5 will transition from a power failure state to a live state. The power restoration alarm information of each distribution transformer is sent to the DMS master station system by the intelligent fusion terminal. Then the distribution transformer associated with switch F1 is T2 ~ T5.

The distribution network feeder-transformer information matrix (FTIM) is established to describe the topological connection relationship between all feeders and distribution transformers in the entire distribution network, specifically:
Where, each line represents all distribution transformers associated on a feeder. The $f_{ij}$ is the name of the j-th distribution transformer connected to the i-th feeder. If the distribution transformer does not exist, the value is -1. The $i=1, 2, 3, \ldots, n$. The $n$ is the number of feeders in the distribution network. The $j=1, 2, 3, \ldots, m$. The $m$ is the maximum number of distribution transformers connected to the feeder.

$$\text{FTIM} = \begin{bmatrix}
    f_{11} & f_{12} & \cdots & f_{1j} & \cdots & f_{1m} \\
    f_{21} & f_{22} & \cdots & f_{2j} & \cdots & f_{2m} \\
    \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
    f_{i1} & f_{i2} & \cdots & f_{ij} & \cdots & f_{im} \\
    \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
    f_{n1} & f_{n2} & \cdots & f_{nj} & \cdots & f_{nm}
\end{bmatrix}$$

(1)

3. Identification method of feeder-transformer relationship in active distribution network

The topological connection relationship between all feeders and distribution transformers in the DMS system is described by the distribution network feeder-transformer information matrix FTIM. When the switch is closed for power transmission, the connected distribution transformer will restore power supply, and each distribution transformer will send the power restoration alarm information to the DMS master station system. If the distribution transformer of power transmission and restoration alarm information is inconsistent with the feeder associated distribution transformer in the FTIM, it indicates that there is an error in the topological connection relationship between the feeder and the distribution transformer in the DMS. Based on this principle, the feeder-transformer relationship of distribution network can be identified and verified.

Multiple switches need to be operated during fault handling and planned maintenance and power restoration. In order to realize the identification of line transformer relationship in distribution network, it is necessary to close all relevant switches on a feeder. Then DMS master station system can identify and verify the feeder-transformer relationship of the feeder according to the received distribution transformer restoration information.
The real-time power restoration information matrix (RRIM) is established to describe the actual situation of the power restoration alarm signal sent by the distribution transformer to the DMS master station after the feeder switch is closed and the power supply is restored in the real-time state. The specific description is as follows:

\[
RRIM = \begin{bmatrix}
    r_{11} & r_{12} & \cdots & r_{1j} & \cdots & r_{1m} \\
    r_{21} & r_{22} & \cdots & r_{2j} & \cdots & r_{2m} \\
    \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
    r_{ij} & r_{ij} & \cdots & r_{ij} & \cdots & r_{ij} \\
    \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
    r_{nj} & r_{nj} & \cdots & r_{nj} & \cdots & r_{nm}
\end{bmatrix}
\]

Where, the \( r_{ij} \) is the restoration information value of the j-th distribution transformer connected to the i-th feeder. If the power restoration alarm information of \( f_{ij} \) is received by the DMS master station system, the value of \( r_{ij} \) is 1. If the power restoration alarm information of \( f_{ij} \) is not received by the DMS master station system, the value of \( r_{ij} \) is 0. If \( f_{ij} \) does not exist, the value of \( r_{ij} \) is -1.

The standard power restoration information matrix (SRIM) is established to describe the standard status of the power restoration alarm signal of the DMS master station based on the DMS topology relationship after the feeder switch is closed and the power supply is restored under the expected state. The specific description is:

\[
SRIM = \begin{bmatrix}
    s_{r11} & s_{r12} & \cdots & s_{r1j} & \cdots & s_{r1m} \\
    s_{r21} & s_{r22} & \cdots & s_{r2j} & \cdots & s_{r2m} \\
    \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
    s_{rj1} & s_{rj2} & \cdots & s_{rjj} & \cdots & s_{rjm} \\
    \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
    s_{rn1} & s_{rn2} & \cdots & s_{rnj} & \cdots & s_{rnm}
\end{bmatrix}
\]

Where, \( s_{rj} \) is the standard restoration information value of the j-th distribution transformer connected to the i-th feeder. If the power restoration alarm information of \( f_{ij} \) should be received by the DMS master station system, the value of \( s_{rj} \) is 1. If the power restoration alarm information of \( f_{ij} \) shouldn’t be received by the DMS master station system, the value of \( s_{rj} \) is 0. If \( f_{ij} \) does not exist, the value of \( s_{rj} \) is -1.

The standard real-time difference information matrix (SRDM) is established to describe the difference between the SRIM and the RRIM. Specifically:

\[
SRDM = \text{SRIM} - \text{RRIM} = \begin{bmatrix}
    d_{m11} & d_{m12} & \cdots & d_{m1j} & \cdots & d_{m1m} \\
    d_{m21} & d_{m22} & \cdots & d_{m2j} & \cdots & d_{m2m} \\
    \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
    d_{mj1} & d_{mj2} & \cdots & d_{mjj} & \cdots & d_{mjm} \\
    \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
    d_{mn1} & d_{mn2} & \cdots & d_{mnj} & \cdots & d_{mnm}
\end{bmatrix}
\]

Wherein, \( d_{mj} \) is the standard real-time information difference of the j-th distribution transformer connected to the i-th feeder, which has three values of 0, 1 and -1.

The feeder-transformer relationship error information matrix (FTEM) is established to describe the name information of distribution transformer with misconnection and leakage on a feeder. Specifically:

\[
FTEM = \begin{bmatrix}
    t_{e11} & t_{e12} & \cdots & t_{e1k} & \cdots & t_{ein} \\
    t_{e21} & t_{e22} & \cdots & t_{e2k} & \cdots & t_{e2n}
\end{bmatrix}
\]

Where, \( t_{ej} \) is the restoration information of the j-th distribution transformer on the i-th feeder when \( dm_{ij} = 0 \):

- \( t_{ej} = 1 \) when \( dm_{ij} = 1 \)
- \( t_{ej} = -1 \) when \( dm_{ij} = -1 \)
Wherein, the $te1_k$ is the information of the k-th distribution transformer that should not be connected but wrongly connected on the feeder. The $te2_k$ is the information of the k-th distribution transformer that should be connected but missed on the feeder. The $k=1, 2, 3, \ldots, w$. The $w$ is the maximum number of elements with 1 and -1 in the standard real-time difference information matrix SRDM. If $te1_k$ and $te2_k$ do not exist, the value is -1.

So far, the identification of feeder-transformer relationship in distribution network has been completed, and the elements in the feeder-transformer relationship error information matrix SRDM are the name information of distribution transformers with missing and misconnected feeders.

4. Case analysis
In the distribution network shown in Figure 1, if the upstream incoming feeder of the distribution transformer $T12$ of the feeder $Feeder1$ is short-circuited. First, the outgoing switch $S1$ of the substation is tripped, the anti-islanding protection of the distributed power supply is activated, the distributed power grid connection switch $P1$ is opened, the distributed generator $G1$ is disconnected from the grid, and the entire feeder loses power. Then, according to the fault alarm information, Feeder Automation (FA) of the DMS master station determines that the fault occurs in the area enclosed by the section switch $B3$, the branch switch $F2$ and the tie switches $L1$ and $L2$. Then the remote control switches $B3$ and $F2$ of the DMS are opened to isolate the fault. Finally, the remote control switch $S1$ of the DMS system is closed to restore the upstream power supply of the fault area, and the remote control grid-connected switch $P1$ of the distributed power source is closed to realize the power supply of the distributed power source $G1$ to the downstream area of the branch switch $F2$.

When the remote control switches $S1$ and $P1$ are closed, the distribution and transformation recovery information received by the DMS master station is shown in Table 1.

| Closing switch | Distribution transformer for restoring power supply |
|---------------|---------------------------------------------------|
| $S1$          | $T1, T2, T4, T6, T18, T26, T45$                    |
| $P1$          | $T8, T10, T11, T21, T30, T39$                      |

The RRIM and SRIM are:

$$
RRIM = \begin{bmatrix}
1 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & -1 & -1 & -1 \\
0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & -1 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0
\end{bmatrix}
$$

$$
SRIM = \begin{bmatrix}
1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & -1 & -1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
$$

The SRDM and FTEM are:

$$
SRDM = \begin{bmatrix}
0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & -1 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & -1 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0
\end{bmatrix}
$$

$$
FTEM = \begin{bmatrix}
T3 & T5 & T9 & -1 & -1 & -1 \\
T18 & T21 & T26 & T30 & T39 & T45
\end{bmatrix}
$$

It can be seen that distribution transformers $T3$, $T5$ and $T9$ should not be connected, but they are wrongly connected to feeder $Feeder1$. The distribution transformers $T18$, $T21$, $T26$, $T30$, $T39$ and $T45$ should be connected, but they are not connected to feeder $Feeder1$. 
5. Conclusion
In this paper, a new identification method based on power restoration information matrix is adopted to study the problem of identification and verification of topological relationship between feeder and distribution transformer in distribution network. The main conclusions can be summarized as follows: (1) The identification model of feeder-transformer relationship is established through the distribution network feeder-transformer information matrix (FTIM). (2) Through the identification model of feeder-transformer relationship, the real-time power restoration information matrix (RRIM) and the standard power restoration information matrix (SRIM) are established. (3) The standard real-time difference information matrix (SRDM) is established to describe the difference between the SRIM and the RRIM. (4) The feeder-transformer relationship error information matrix (FTEM) is established to describe the name information of distribution transformer with misconnection and leakage on a feeder. In future work, fault outage information and maintenance restoration power supply information can be combined to enhance the identification accuracy of feeder-transformer relationship.

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