ARCHIVES OF ELECTRICAL ENGINEERING VOL. 70(2), pp. 297–306 (2021)

DOI 10.24425/aee.2021.136985

Topology identification of low voltage distribution network based on current injection method

HAOTIAN GE, BINGYIN XU, WENGANG CHEN, XINHUI ZHANG, YONGJIAN BI

Shandong University of Technology
China

e-mail: sdutght@163.com

(Received: 12.08.2020, revised: 04.12.2020)

Abstract: The structure of the low-voltage distribution network often changes. The change of topology will affect fault detection, fault location, line loss calculation, etc. It leads to fault detection error, inaccurate positioning and abnormal line loss calculation. This paper presents a new method to automatically identify the topology of a low-voltage power grid by using the injection current signal. When the disturbance current signal is injected into the low-voltage line, the current upstream of the injection point will change, and the current downstream of the injection point will not be affected. It is proved theoretically by using the superposition principle. With this method, the disturbance current signal can be injected into the line in turn, and the topology can be identified by observing the change of the current in line. The correctness of the method is proved by Matlab simulation and laboratory verification.

Key words: current injection, low-voltage distribution network, topology identification

1. Introduction

The low-voltage distribution network delivers electricity to the end users of the power network. Generally, the low-voltage distribution network is a radial topology with the secondary side of the distribution transformer as the source [1]. In operation, the topology of the low-voltage distribution network often changes with the change of the user load. This kind of change often needs manual intervention, and it is easy to make mistakes. The wrong topology has a serious impact on the rapid fault detection, line loss calculation and fault location [2, 3]. Therefore, the automatic topology identification method of the low-voltage distribution system to calculate the connection relationship of electrical equipment in the park, community and building, that is, topology analysis, is in a very important position in the line loss calculation and energy saving analysis of the low-voltage distribution system [4].

There are three kinds of topology identification methods for a distribution area, carrier method, power frequency injection method and correlation analysis method.

1. The carrier method, as in [5, 6], uses the existing low-voltage power line carrier technology to identify the structure of the electrical network by sending and returning the carrier signal through the concentrator and collector of the telecommunication acquisition system. This kind of method is simple and easy to implement, but there is a blind area in recognition, which is easily affected by the load in the distribution area.
2. The power frequency injection method injects power frequency signals into the low-voltage bus, and uses mobile acquisition equipment to detect the injected signals at the electrical equipment, so as to carry out topology identification [7]. This kind of method has high accuracy, but the field test wiring is more complicated.
3. The correlation analysis methods, through analyzing the similarity of user voltage data in a distribution station area, identify the connection relationship between a power source and electrical equipment, such as in [8–10]. This kind of method is simple and novel, but the accuracy needs to be improved.

References [11, 12] adopt the method of voltage and current data association to identify the topological relationship by analyzing the relationship between voltage and current. A graph algorithm and adjacency matrix such as in references [13–15], are also important methods for topology calculation and recognition.

Therefore, a method based on current injection is proposed in this paper. A current square wave signal is injected into the electrical equipment, whose period is different from the power frequency signal and its harmonic. The current on the line generates disturbance. The connection relationship between the power supply and the electrical equipment is detected by using the propagation characteristic of the disturbance in the direction of the power supply.

2. Network structure of low voltage distribution system

2.1. Structure of low-voltage distribution network

The low-voltage distribution network is the power distribution network from the secondary side of the distribution transformer to the household interface. It is composed of different types of power cables, transformer units and other equipment. Equipment specifications and construction comply with the current national standards. The voltage level of the low-voltage distribution network in China is usually 220 V/380 V, and the connection modes are mainly radial, trunk and ring. In most cases, only one distribution transformer supplies power to the power customers, and the loads are at the end of the distribution network. The radius of the power supply is usually less than 1000 meters in the city center.

As shown in Fig. 1, the line from the distribution transformer to the low-voltage customers can be divided into two parts. One is a common trunk line from the distribution transformer to the customers' buildings. Generally, a three-phase four-wire (three phase lines A, B, C and one neutral line) or five-wire (three phase lines A, B, C, one neutral line and one earth line) overhead line or a cable line are adopted in China. A three-phase four-wire line is also widely used in North

America [1]. The other is the customer line that is from the trunk line to the customer's electric meter. For a single-phase customer load, a two-wire (live and neutral) line is generally adopted, while for a three-phase customer load, a four-wire (three live and one neutral) line is generally adopted.

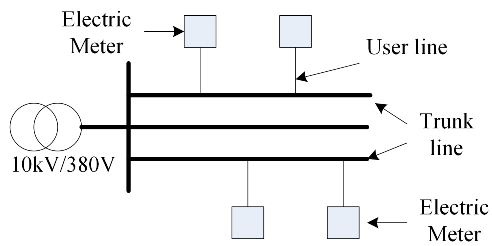


Fig. 1. Structure of low-voltage distribution network

2.2. Trunk line

A trunk line is the backbone of the low-voltage distribution network, connecting a distribution transformer to the vicinity of customer buildings. An overhead line or a buried cable line with a relatively large wire diameter are generally adopted.

Overhead lines are lines installed on outdoor poles to transmit electric energy. Low-voltage overhead lines generally adopt a three-phase four-wire system and are arranged horizontally. Cross-linked polyethylene (XLPE) insulated overhead cables are generally used. According to the number of users, the cross-sectional areas of cables are 120 mm^2, 150 mm^2, 240 mm^2, etc. The distance between two conductors shall not be less than 1000 m.

Underground lines are generally buried in underground cable trenches. Low-voltage cable lines are generally made of three-phase and four-wire lines, and cross-linked polyethylene insulated power cables can be selected. The cross-sectional areas of cables depending on the number of users used are 120 mm^2, 150 mm^2, 240 mm^2, etc., according to the load of users. The cross-sectional area of the cable is 120 mm^2, 150 mm^2, 240 mm^2 and so on.

2.3. Customer line

For low-voltage household lines, the single-phase two-wire system or the three-phase four-wire system is generally adopted from the main line of low-voltage lines to the meter records of users. A low-voltage cross-linked polyethylene copper-core insulated conductor is used for household connection. The conductor cross-section shall be selected according to the continuous current carrying capacity and voltage loss, generally 10 mm^2, 20 mm^2, etc.

3. Principle of current injection method

3.1. Current injection method

The current injection method is to inject a current signal different from the power frequency signal in the vicinity of the power user, causing a disturbance to the current on the entire distribution line. According to the propagation direction of the current disturbance, the connection relation of electrical equipment can be judged.

In the power distribution line shown in Fig. 2(a), a current signal different from the power frequency is injected at the load B, the injected current signal can be detected at A1, in the power supply direction of the load B, while the injected current signal cannot be detected at C1 behind the power supply of the load B. A current signal is injected at the load B, and the influence of the injected current signal on the circuit can be analyzed according to the equivalent circuit diagram shown in Fig. 2(b) using the superposition principle of the circuit. In Fig. 2(b), R_{11}, R_{21} and R_{31} are the resistances of the live wires of lines source S1 to A1, A1 to B1, B1 to C1, respectively. And R_{12}, R_{22}, R_{32} are the resistances of the neutral wires of lines S2 to A2, A2 to B2 and B2 to C2, respectively. In most cases, the conductor size and length of the live and neutral wires are the same. So, R_{11} is equal to R_{12}. Use R_1 to represent the sum of R_{11} and R_{12}, that is, $R_1 = 2R_{11}$. Similarly, $R2$ represents the resistance from A to B, $R_2 = R_{12}$, and R_3 represents the resistance from B to C, $R_3 = 2R_{23}$.

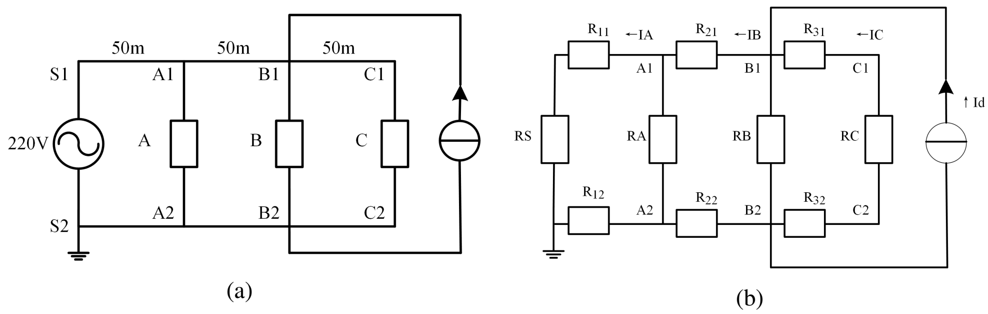


Fig. 2. Current injection: schematic (a); equivalent circuit (b)

As shown in Fig. 2b, the interference current is injected at point B1, and the current at point C1 (I_C) is:

$$I_C = \frac{\frac{1}{R_C + R_3}(-I_d)}{\frac{1}{R_C + R_3} + \frac{1}{R_B} + \frac{1}{(R_A//(R_1 + R_S)) + R_2}}, \tag{1}$$

where: R_A, R_B and R_C represent the resistances of the load A, load B and load C, respectively, R_S is the equivalent internal resistance of the AC power supply, R_1, R_2 and R_3 represent the resistances of S to A, A to B and B to C lines, which are the sum of the resistances of the live wire and the neutral wire in the lines.

In (1), the resistance of the line is much smaller than the resistance of the load and the internal resistance of the power supply. So (1) can be simplified as:

$$I_C \approx -\frac{R_S + R_1 + R_2}{R_C} I_d. \tag{2}$$

Since $R_S + R_1 + R_2$ is much smaller than R_C, it can be seen that the injection current has little influence on the load behind the injection point.

The current at point B1 (I_B) is

$$I_B = \frac{R_C I_d}{(R_1 + R_2 + R_S) + \dfrac{R_C}{R_B}(R_1 + R_2 + R_S) + R_C} \approx I_d. \tag{3}$$

It can be seen that most of the current at the injection point flows to the power supply direction. The current at point A1 (I_A) is

$$I_A = \frac{R_B I_B}{R_B + (R_1 + R_2 + R_S)} \approx I_B. \tag{4}$$

It can be seen that the change of the injection current can be obviously detected by the monitoring point of the injection point power supply direction.

Through the above analysis, we can draw a conclusion: when the load point current changes, the upstream of the line (power supply direction) can obviously detect the current change, and the downstream of the line cannot detect the current change.

3.2. Topology identification method

By injecting a current disturbance signal into the load node, it can be detected upstream of the power supply direction, and the topology connection relationship of the electrical equipment can be identified if it cannot be detected downstream.

A current detection device is sequentially installed on the low-voltage distribution line to detect the current on the line. Inject a current disturbance signal at the load:

1. If the disturbance current can be detected, the position is upstream of the load;
2. If no disturbance current is detected, this position is downstream of the load.

By injecting disturbance current signals into load nodes one by one, the topological relations of power loads on distribution lines can be marked and identified one by one.

3.3. Steps for topology identification

In the process of topology identification of electrical equipment (load) on low-voltage distribution lines, the following steps can be followed:

1. Determining n nodes needing topology identification to form a node queue $\boldsymbol{v} = [v1,\ v2,\ \ldots,\ vn]$;
2. Forming an injection receiving matrix:

$$\boldsymbol{A} = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix},$$

   wherein: a_{ij} indicates the condition that the node j is injected with disturbance current at the node i, 1 indicates that the disturbance current can be detected, 0 indicates that the disturbance current cannot be detected, and initializing all $a_{ij} = 0$;
3. From the first node to the n-th node, the disturbance current signal is injected, and the node with disturbance current signal is marked $a_{ij} = 1$;
4. Simplify the matrix $\boldsymbol{A}$ to generate the adjacency matrix.

3.4. Case analysis

In the distribution line as shown in Fig. 3, the loads A, B and C are separated by 50 m in sequence, and the loads C, D and E are installed at the same position. Set up 5 observation points A1, B1, C1, D1 and E1 as shown in Fig. 3, respectively. Current disturbance signals are injected from the loads A, B, C, D and E, respectively.

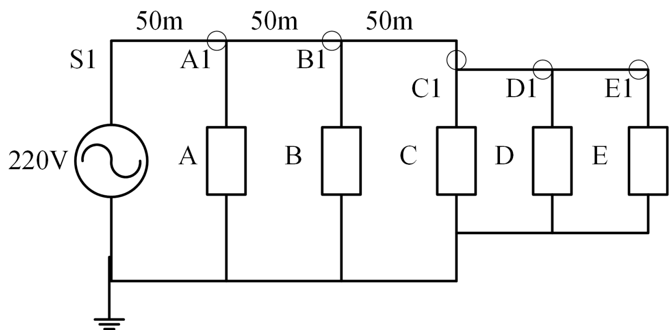


Fig. 3. Model of low-voltage distribution network

Taking the injected current interference signal at the load B as an example, interference signals can be detected at A1 and B1, and no interference signals can be detected at C1, D1 and E1.

After the interference signals are sequentially injected, a matrix is formed.

$$\boldsymbol{A} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 & 1 \end{bmatrix}.$$

Simplifying the matrix $\boldsymbol{A}$ we obtain a connection matrix.

$$\boldsymbol{A} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \end{bmatrix}.$$

4. Simulation and experimental verification

4.1. Matlab simulation

As in Fig. 3, a simulation current is built in Matlab (Fig. 4), and an interference current signal is injected from the load B, the parameter voltage source of each component is 220 V, the internal resistance is 0.5 Ω, the line impedance of each line segment is $0.1 + 0.07j$ Ω, the load

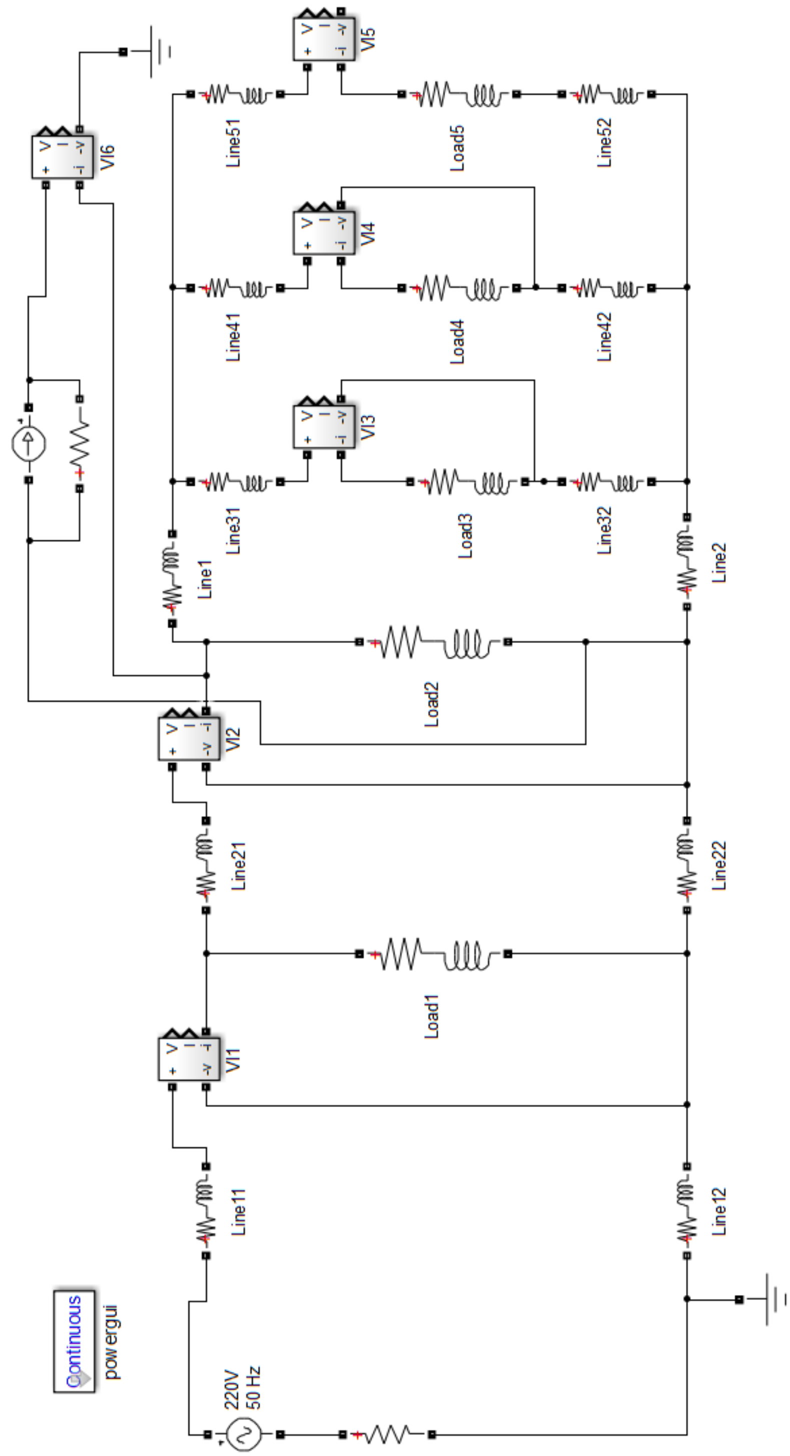
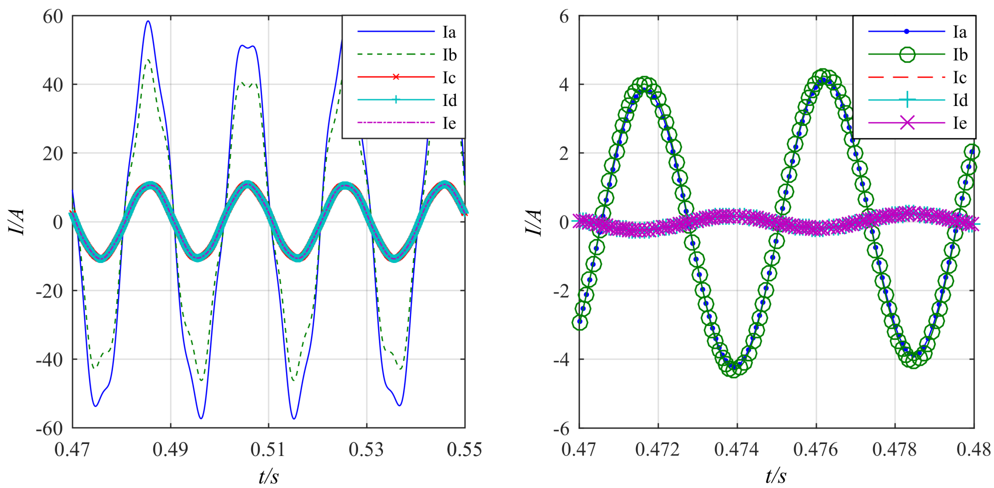


Fig. 4. Model of low-voltage distribution network

is 2000 + 400j VA, the AC current source 5 A, 220 Hz and the internal resistance is 10 kΩ are selected for injection. The current disturbance components detected at observation points A1, B1, C1, D1 and E1 are respectively recorded as *Ia*, *Ib* and *Ic*, *Id*, *Ie*, as shown in Fig. 5(a). The current signal passes through the filter to remove 50 Hz, and the current is shown in Fig. 5(b).



(a) (b)

Fig. 5. Current injection: schematic (a); equivalent circuit (b)

As we can see from Fig. 5, the disturbance components of the current can be obviously detected at A1, B1, and hardly detected at C1, D1, E1.

4.2. Laboratory simulation

In the laboratory, we build the experimental circuit as shown in Fig. 6(a). The normal load is connected to point A and the current is about 3 A. Theoretically, the larger the amplitude of the injected signal, the easier it is to detect. When the injection current signal is large, the larger amplitude will bring adverse effects on all aspects of the system operation; when the injection current signal is small, considering the influence of signal interference, signal flow process loss, transition resistance shunt and other factors, the amplitude will be smaller. The small signal may not be detected. Therefore, the amplitude of injection current should be increased as much as possible within the allowable range of bus capacity. Simulation experiments and field operation experience show that the amplitude of the injected signal is generally 3–6 A. To make the experimental effect more obvious, points B and C are in an open circuit and no load is connected. The injection waveform is a 240 Hz square wave signal. The selection of the injection signal frequency mainly depends on:

1) the frequency of the injected signal must be distinguished from the frequency of the power system, that is, the fundamental and harmonic frequencies cannot be used;

2) the frequency of the injected signal should not be too low, otherwise it is easily affected by the power frequency and DC components, and the detection error will increase;
3) the frequency of the injected signal should not be too high, otherwise the system capacitive reactance will increase and the detection sensitivity will be decrease.

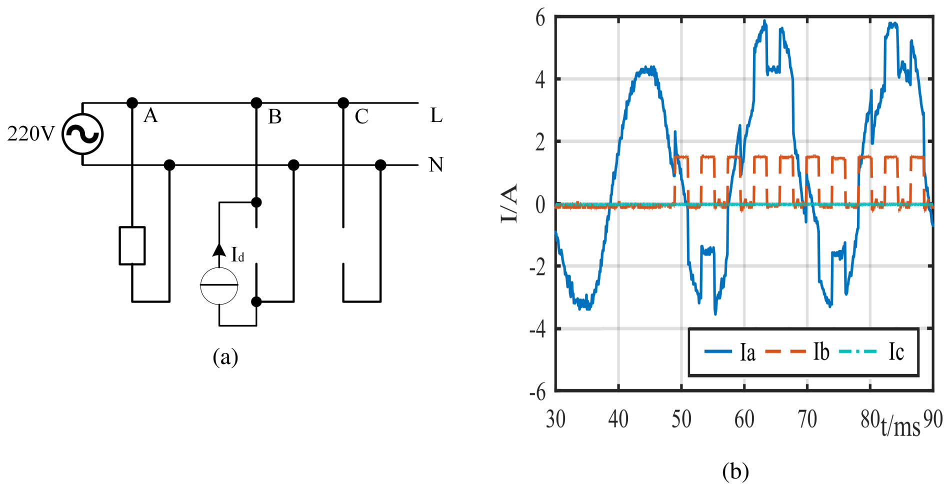


Fig. 6. Laboratory simulation: experimental circuit (a); current waveform (b)

So, the disturbance current signal adopts a 240 Hz square wave signal.

It can be seen from the current waveform in Fig. 6(b) that after the current signal is injected, point B changes with the fluctuation of the injected current, maintaining the characteristics of the square wave signal. This is because there is no load at point B and the original current is 0. There is load current at point A. After injecting the signal, it presents the superposition of the injected signal and the original current signal. At point C, it is not affected by the injected signal. It can be seen from the experiment that the injection signal can be detected at the injection point and the observation point in the direction of power supply (upstream). The observation point downstream of the injection point cannot detect the injection signal.

5. Conclusions

Current interference signals are injected into low-voltage distribution lines, and the signal propagation direction has obvious unidirectionality and propagates towards the power supply direction. According to this characteristic, a series of acquisition devices are installed on the distribution line, current interference signals are injected at the load nodes, and whether interference signals are detected or not can be judged, so that the identification of the electrical topology connection relation can be carried out.

References

[1] Short T.A., *Electric Power Distribution Handbook, Second Edition*, Crc Press (2014).

[2] Bingyin X., Tianyou L. *et al.*, *Smart Distribution Grid and Distribution Automation*, Automation of Electric Power Systems, vol. 33, no. 17, pp. 38–41 (2009).

[3] Jiang J., Liu L., *Resonance mechanisms of a single line-to-ground fault on ungrounded systems*, Archives of Electrical Engineering, vol. 69, no. 2, pp. 455–466 (2020).

[4] Grotas S., Yakoby Y., Gera I. *et al.*, *Power Systems Topology and State Estimation by Graph Blind Source Separation*, IEEE Transactions on Signal Processing, vol. 67, no. (8), pp. 2036–2051 (2019).

[5] Tianyu L., *Research on Fault Analysis and Topology Identification Based on Power Line Communication*, Master Thesis, Control Engineering, China University of Geosciences (Beijing) (2019).

[6] Xiangyu K., Yuting W., Xiaoxiao Y. *et al.*, *Optimal configuration of PMU based on customized genetic algorithm and considering observability of multiple topologies of distribution network*, Electric Power Automation Equipment, vol. 40, no. 1, pp. 66–72 (2020).

[7] Chao Y., *The Development and Manufacture of a Multi-Function Equipment for Low Voltage Area Identifed*, Master Thesis, Electrical Engineering, China Dalian University of Technology (2014).

[8] Ya L., Rusen F., Wei J. *et al.*, *Research on the intelligent transformer area recognition method based on BP neural network*, Electrical Measurement & Instrumentation, vol. 54, no. 3, pp. 25–30 (2017).

[9] Dong-Feng Y., Su-Quan Z. *et al.*, *A Novel Method for Power Grid Topology Identification Based on Incidence Matrix Simplification*, East China Electric Power, vol. 42, no. 11, pp. 2254–2259 (2014).

[10] Jing M., Yuyu Z. *et al.*, *Power Network Topological Analysis Based on Incidence Matrix Notation Method and Loop Matrix*, Automation of Electric Power Systems, vol. 38, no. 12, pp. 74–80 (2014).

[11] Zeyang T., Kunpeng Z., Kan C. *et al.*, *Substation Area Topology Verification Method Based on Distribution Network Operation Data*, High Voltage Engineering, vol. 44, no. 4, pp. 1059–1068 (2018).

[12] Zongzong L., Xuezhong F., Qing W. *et al.*, *Station area recognition of distribution network based on electricity information acquisition system*, Electrical Measurement and Instrumentation, vol. 56, no. 24, pp. 109–114 (2019).

[13] Jing M., Yuyu Z., Wei M. *et al.*, *Power Network Topological Analysis Based on Incidence Matrix Notation Method and Loop Matrix*, Automation of Electric Power Systems, vol. 38, no. 12, pp. 74–80 (2014).

[14] Zonghui W., Yu C., Bingyin X. *et al.*, *Logical Node Based Topology Identification of Distributed Feeder Automation*, Automation of Electric Power Systems, vol. 44, no. 12, pp. 124–130.

[15] Zengping W., Jinfang Z., Yagang Z., *A novel substation configuration identification algorithm based on the set of breaker-path functions*, Proceedings of the CSEE, vol. 33, no. 1, pp. 137–145 (2013).