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Overview on topology identification technologies for a low-voltage distribution network

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Abstract: The topology identification of low-voltage distribution networks is an important foundation for the intelligence of low-voltage distribution networks. Its accuracy fundamentally determines the effectiveness of functions such as power system state estimation, operational control, optimization planning, and intelligent electricity consumption. The low-voltage distribution network is composed of transformers, lines, and end users. The key task of topology identification is to distinguish the connection relationship between distribution transformers, low-voltage lines, and phase sequence with end users, which can be divided into transformer user relationship, line user relationship, and phase user relationship. At present, the main methods of low-voltage network topology identification can be divided into signal injection method and data analysis method. The signal injection method requires a large number of additional terminal devices and is difficult to promote. The data analysis method combines the characteristics of switch state, voltage, current, electrical energy, and other data to perform topology analysis. The commonly used methods include correlation analysis and feature learning. Finally, typical problems that urgently need to be solved in topology recognition and representation were proposed, providing a reference for the research and development of low-voltage distribution network topology automatic recognition technology.

Key words: data-driven method, low-voltage distribution network, signal injection method, topology identification

1. Introduction

A low-voltage distribution network plays a paramount role in delivering electric energy to the end users of a grid. As a consequence, it's crucial to ensure the quality of power supply [1, 2]. Meanwhile, it is a critical node for the connection of distributed generation supply and power grid [3, 4]. In recent years, the proportion of distributed power supplies that are treated as a kind of clean energy connected to the grid has risen increasingly along with the proposal of the target of "Carbon Peak and Carbon Neutrality". The grid connection with a multitude of distributed power supplies has altered the structure of the low-voltage distribution network and made it become a network with multiple power supplies; the distribution of power flow has changed accordingly. The structure and topological relation of a low-voltage distribution network has become a vital research theme. As a result, if the topological relation is unclear, numerous, which will seriously affect the safe operation of the low-voltage grid as well as the safety of people's lives and properties.

In China, a low-voltage distribution network refers to an electric grid with 10 kV distribution transformers as the power supply point, the voltage of 380 V/220 V, and single-phase loads or three-phase loads as the user load. Generally, the equipment specifications and construction of a low-voltage distribution network should comply with current national technical standards concerned. Nevertheless, the equipment of a low-voltage distribution network is various in diverse places owing to the regional features and dissimilar levels of economic development in these places. On a grand scale, the low-voltage distribution network involves numerous lines and users. As indicated in the statistics of 2018 [5, 6], the number of low-voltage users in China was as high as 534 million, the total number of distribution transformers was about 5.23 million and the total length of low-voltage distribution lines was 6.59 million kilometers. For a long time, due to the lag in technology and management, low-voltage distribution networks have been facing problems such as a large number of terminal devices, complex types, low intelligence levels, inconsistent standards, and non-standard network wiring. As a result, the operation and maintenance of the Taiwan region, equipment regulation, user experience, and asset management are still relatively backward.

The distribution of low-voltage users is comparatively scattered. At present, the power is principally supplied by zoning [7, 8] in line with the unit of distribution area. The low-voltage distribution equipment is classified into low-voltage switch, low-voltage cable branch box, and integrated distribution box on a low-voltage connection pole. The low-voltage distribution network takes the secondary side of a distribution transformer as the source point to form a radial topology structure [9], which may be temporarily changed frequently as a result of load variation, equipment failure, and other reasons during operation. With the connection of numerous low-capacity distributed generation and low-voltage power grids, the complexity of a low-voltage distribution network has been further increased [10, 11], putting forth some new requirements for the construction and topology identification of a low-voltage distribution network.

Topological identification of low-voltage distribution networks is an important foundation for supporting the intelligent construction of low-voltage distribution networks. The key task of topology identification in low-voltage distribution networks is to sort out the connection relationships between distribution transformers, low-voltage lines, phase, and users, which are specifically divided into the transformer-household relationship, the line-household relationship, and the phase-household relationship. Its accuracy fundamentally determines the effectiveness of power system state estimation, operational control, optimization planning, intelligent electricity consumption, and bidirectional interaction.

2. Structure of a low-voltage distribution network

2.1. Low-voltage distribution network

A low-voltage distribution network in China (as exhibited in Fig. 1) refers to the 380 V/220 V distribution network [12], which adopts 10 kV medium-voltage distribution transformers as its power supply and is connected with low-voltage distribution transformers and end users as Transformer in Fig. 1. The phase-to-phase voltage is 380 V and phase-to-ground voltage is 220 V. The user loads are mostly single-phase loads or three-phase loads. In Fig. 1, S11, S12, S13, S17, S18, S27, and S28 are single-phase users. T15, T16, T19, and T29 represent three-phase users. With a simple structure, the low-voltage distribution network has the basic wiring modes mostly including radial type, trunk type, and loop type, among which the trunk type with distribution transformers as the center is more common. Interconnection switches may be installed between the low-voltage main lines of adjacent transformers to act as backup powers for each other. As in Fig. 1, there are two radial lines with outgoing switches K1 and K2. K0 is the switch that connects the bus on the low voltage side of the transformer. Both line 1 and line 2 are 3-phase 4-wire. A low-voltage distribution network generally supplies the power by region and the supply range of a low-voltage line shall not exceed the segment switches on a medium-voltage overhead line. In most cases, only one distribution transformer supplies the power to a grid and the user load is at the terminal of the distribution network. The power supply radius is usually less than 150 meters for the downtown of large cities, and not more than 400 meters for counties, prefecture-level cities, and economically developed central towns. The chain distribution is feasible for the electrical devices that are at a low capacity, far away from the power supply point, and relatively close to one another. For a multi-story building, the trunk distribution or zoned trunk distribution may be used from the main distribution box to each floor distribution box. In high-rise buildings, the power is primarily supplied to each distribution point on each floor using zonal trunk distribution. Generally, radial distribution is used from the distribution box in the floor distribution room or shaft to the user distribution box.

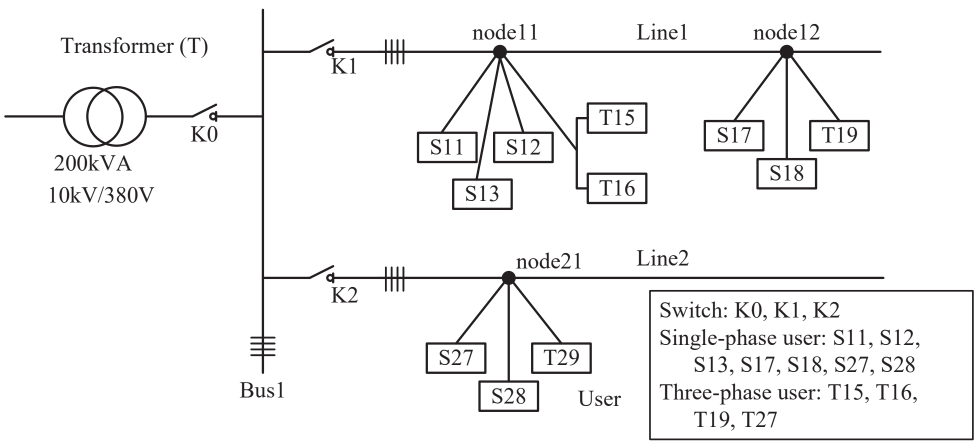

Fig. 1. Structure of a low-voltage distribution network

2.2. Topology model of power distribution network

The topology of a power distribution network describes the connection relation among the devices of a distribution network. IEC 61970 classifies the topological relation into Connectivity Model and Topology Model [13]. The Connectivity Model describes the physical definition of how electrical devices are connected and is correlated with the planning and design of a distribution network. The Topology Model not only describes the logical definition of how devices are connected by closing switches but also describes how changes in switch positions and operating modes will trigger changes in the Topology Model. The Topology Model lays a solid foundation for the state estimation, power flow analysis, and automatic fault section location of a feeder.

IEC 61970 defines the information models used by the Topology Model, involving Equipment, Terminal, Connectivity Node, Topology Node, Topology Island, etc. And the definition is expanded to Feeder [14–16] based on the distribution feature and normalized in IEC 61968 necessarily [17, 18]. In IEC 61850, System Configuration Description Language (SCL) is used for the configuration of the topology information of electrical devices and connection information of intelligent electronic devices (IEDs) [19].

The Feeder is a crucial concept in the description of the topology of a distribution network. As in [14, 16], the CIM model was expanded in line with the characteristics of a distribution network, and the models including the Feeder were proposed, which then were incorporated into the information model provided in IEC 61970 and used as the informative model. Nonetheless, considering the characteristics of a feeder and the change of the feeder during operation, some experts and scholars maintain a cautious attitude toward the establishment of the Feeder model; as a result, the Feeder model has not been included in the formal models of IEC 61970 yet. The FA (Feeder Automation) function was achieved through the adjacency relation between adjacent switches on a feeder that was configured based on a custom format in [20, 21]. A feeder-oriented approach was put up for describing and analyzing the topology information of a medium-voltage distribution network. SCL and Logical Node (LN) were adopted to describe topology in IEC 61850 [15]. And in another reference [22], the elements including Process and Line of the new SCL in the systems stipulated in IEC 61850 were utilized to describe the topology of a distribution network. The Line model was adopted for the main lines and branch lines in a distribution network in the model description of SCL and Substation was utilized to describe the medium/low voltage distribution stations and switching stations in a distribution network [23]. The logical nodes including the unit topology logical node (RTCN) and topology slice node (RTPM) were adopted to represent and store the topology in the feeder domain [24].

2.3. Topology identification method

According to the relevant research results, the existing low-voltage distribution topology recognition methods can be divided into three categories: signal injection method, data analysis method, and other methods, as shown in Fig. 2. Among them, the data analysis method mainly uses the switch status, voltage data, and power data.

Common topology analysis methods and characteristics are listed in Table 1. The detailed analysis is in the following chapters.

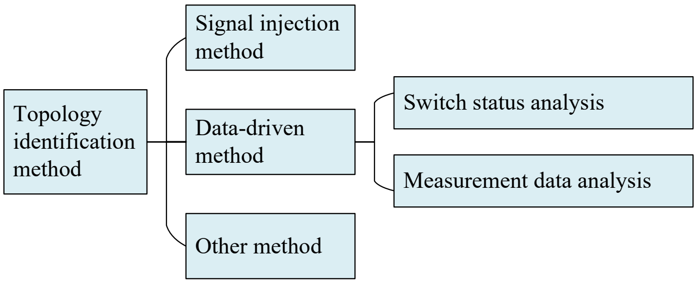

Fig. 2. Low-voltage distribution network topology identification technology

Table 1. Topology identification method

Type	Characteristics	Deficiency	Representative literature
Signal injection method	Inject a voltage or current signal into the distribution network	– Select the appropriate injection signal. – Signal injection and receiving devices are indispensable.	[25–35]
Switch status analysis	Switch status, graph theory	– New switch status acquisition and communication devices may need to be installed. – The absence of the switch state may lead to extensive errors in the analysis results.	[36–49]
Measurement data analysis	Using voltage, current and energy data for data analysis and data mining	– New data acquisition and communication devices may need to be installed. – The calculation method is complicated and depends on a large number of measurement data.	[50–93]

3. Topology identification based on signal injection method

The signal injection method means to inject a signal different from the power frequency voltage or current into the distribution network at first, then track and detect the path and characteristics of the injected signal, to discover the direction of the distribution line and connection relation among the power distribution devices [25].

In the early stage, the injected signal is chiefly used for line selection and location of single-phase ground faults in a medium-voltage distribution network. Holding to this research orientation, Shandong University has formed a relatively complete technical system and developed relevant products [26, 27] applied to on-site fault judgment through a series of attempts and explorations. Professor Sang Zaizhong *et al*. from Shandong University employed the injected signal at a fixed frequency of 220 Hz. And Professor Zeng Xiangjun *et al*. of Huazhong University of Science and Technology proposed the frequency conversion signal injection method by use of the resonant frequency [28] in line with the research result of Professor Sang, which further ameliorated the accuracy of fault detection. Professor Pan Zhencun *et al*. of Shandong University further put forward the improvement suggestions, such as lessening the frequency of the injected signal, applying phase information of the injected signal, and applying the dual-frequency signal [29].

The signal injection method can be adopted to identify the direction of distribution lines effectively, especially to search and comb the buried cable lines effectively. Some literature [30] mentioned, the voltage near the zero-crossing point of the phase line was modulated to produce distortion and the signal of distortion could be detected by the low-voltage monitoring unit on the same phase line; thus, the identification of low-voltage distribution line could be conducted. And another literature [31] put forth a low-voltage distribution network identification technology for power frequency load transmission and synchronous sampling technology to meet the needs of site surveys in some areas. In another literature [32], the identification of topology and Phase A, B and C of a low-voltage area was realized based on the power frequency distortion communication technology, which further enabled the application of plug-and-play in the intelligent terminals of the area. As demonstrated in the literature [33], the topology identification could be carried out with a harmonic current signal at a specific frequency formed by regular load on-off control, which was achieved by installation of an on-off module for load resistor between the phase line and the zero line of an electricity meter. In another literature [34], the bottom-up identification of the user's topological relation was accomplished with injection of a low-frequency signal, that is, the approach of the signal injection at the user side and signal detection at the supply side. In reference [35], a high-frequency signal of 5 MHz is injected into the supply side and detected at the user side to realize top-down topology recognition. The one-way flow of high-frequency injection signal is realized by using the impedance characteristic of a high-frequency signal inductor. The length of the line segment can be roughly calculated by the delay of different observation points on the feeder. The effectiveness of this method has been verified using MATLAB. At present, there is no further Physical verification.

Although the topology identification with the signal injection method provides comparatively high accuracy, how to select the frequency of the injected signal should avoid the influence on the user equipment. Because generally, the injected signal is weak and easily disturbed by the noise; the identification performance is not tremendously satisfactory in an area with a large variation of the load. In addition, additional terminal equipment needs to be installed, which can lead to some problems such as high investment and difficult operation and maintenance.

4. Topology identification based on data-driven techniques

The previous topology analysis method mainly regarded the two ends of a closed switch as one topology node. From the perspective of graph theory, there is mainly depth-first (DFS) algorithms and breadth-first (BFS) algorithms. This type of method is the mainstream method for topology analysis of high-voltage power grids. However, due to the inability to monitor the opening and closing status of some low-voltage switchgear (as K0, K1, K2 in Fig. 1) in practice, the effectiveness of this method is limited. In recent years, the extensive application of Advanced Metering Infrastructure (AMI) has accumulated a large amount of user-side (as S11, S12 etc. in Fig. 1) measurement data, laying the foundation for topology analysis based on measurement data.

4.1. Topology analysis method based on switch status data

From the viewpoint of graph theory, the topology analysis of a power grid provides a scientific basis for determining the connectivity of relevant graphs [36]. If the nodes and loads in a power grid are equivalent to vertices and the branches are equivalent to edges; then the grid can be abstracted into a bivariate system $\boldsymbol{G}$, $\boldsymbol{G} = (\boldsymbol{V},\ \boldsymbol{E})$ composed of the set of vertices $\boldsymbol{V} = \{v_i\}$ and the set of edges $\boldsymbol{E} = \{e_k,\ e_k = (v_i,\ v_j)\}$. The correlation between vertices and edges can be represented by the incidence matrix. The incidence matrix formed by v vertices and e edges is $A_a = (a_{ij})v \times e$. From this standpoint, the topology analysis of a power grid is the same as that of other networks (such as a communication network, water supply network, and natural gas network), all of which are the graph connectivity analysis. The search method and matrix analysis method predominantly provide feasible approaches for dealing with the problem of graph connectivity.

4.1.1. Search algorithm

The search method of network topology analysis is principally represented by Depth First Search (DFS) algorithm and Breadth First Search (BFS) algorithm. DFS are adopted in some literatures [37, 38], starting from a power node, searching forward along a path, defining the nodes connected by a closed switch as a topology node till the last node on the path and then backtracking to the nodes on the search path in order. The same method was adopted to search for a new path until all nodes are searched out. BFS are used in some literatures [39–41] alternatively. Similarly, BFS starts from some power point and searches outwardly in a radial mode until all nodes are searched out. BFS algorithm can avoid the repeated node search occurred in DFS to some extent. In view of the features of a distribution network, BFS and DFS were analyzed and compared to the literature [42]. It was concluded that BFS was more suitable for the generation of a feeder tree as BFS only accessed each node once. In addition, the selection of initial vertices will not affect the number of searches, while DFS is more suitable for the generation of feeder segments, in that a multitude of nodes searched are inessential during the generation process, and it does not require a myriad of backtracking searches.

The change of switch position may pose an influence on the topology of a distribution network during its operation. Nonetheless, such influence always is localized; especially for a distribution network, the change of switch position on a feeder line may affect nothing but several relevant feeders. For the analysis of the topology resulting from such a change of switch position, the local topology modification is often adopted to accelerate the response of topology analysis. The heuristic search algorithm was adopted for update local topology to enhance the timeliness of topology analysis in the literature [43]. The concepts of static topology and dynamic topology were proposed in other literature [44]. The part that was not affected by the change of switch state was treated as the static topology Apart from that, nothing but the dynamic topology was subject to the influence of the change of switch position. The calculation of the dynamic topology could be considerably speedy since plenty of the preparation work was done by the static topology, facilitating the overall topology analysis. The topology identification method for a weakly meshed distribution network was adopted in the literature [45] to obtain the most possible radial topology in accordance with the number of possible radial distribution networks among all distribution networks determined. Nonetheless, this method is an off-line distribution identification method, which does not use any current electrical and state quantity in any network. As a consequence, the topology structure of the distribution network obtained is not real-time.

4.1.2. Adjacent matrix method

With respect to the adjacency matrix method for topology analysis of a power grid, its nature is how to obtain the adequately connected matrix $\boldsymbol{A}_{\text{adj}}$ indicating the global connectivity with certain algorithms starting from the initial adjacency matrix $\boldsymbol{A}_{\text{org}}$.

Adjacency matrix $\boldsymbol{A}_{\text{org}} = [a_{ij}]_{n\times n}$, $(i, j = 1, 2, \ldots, n)$, where

$$a_{ij} = \begin{cases} 1 & \text{Node } i \text{ is directly connected to node } j \\ 0 & \text{Node } i \text{ and node } j \text{ are not directly connected or disconnected} \end{cases}. \tag{1}$$

Connection matrix $\boldsymbol{A}_{\text{adj}} = [a_{ij}]_{n\times n}$, $(i, j = 1, 2, \ldots, n)$, where

$$a_{ij} = \begin{cases} 1 & \text{Node } i \text{ is directly or indirectly connected to node } j \\ 0 & \text{Node } i \text{ is disconnected from node } j \end{cases}. \tag{2}$$

The adequately connected matrix can be obtained by Boolean multiplication with a power of $(n-2)$ of the initial adjacency matrix $\boldsymbol{A}_{\text{org}}$, that is, $A_{\text{adj}} = \boldsymbol{A}_{\text{org}}^{n-2}$. This method is called Full Matrix Involution and its calculated quantity is huge [46]. The calculation of a sufficiently connected matrix with a square can effectively lessen the computation time of matrix analysis. The matrix obtained through a further square operation for the adjacency matrix is sufficient to express the connection relation. Aside from that, the network analysis result can be obtained only by scanning the matrix in reverse order, accelerating the speed of network topology further [47]. If the initial adjacency matrix is treated as a coefficient matrix and the sufficiently connected matrix as a solution vector matrix, the Gaussian elimination [48, 49] can be adopted to deal with the equation to obtain the result of network topology distribution, which is another deformation algorithm of adjacency matrix method in topology analysis.

4.2. Topology identification based on measurement data

4.2.1. Measurement data

Along with the construction of Automatic Meter Reading (AMR) and Advanced Metering Infrastructure (AMI), the automatic meter data reading has been realized for an increasing number of end users [50, 51]. As exhibited in relevant reports, in 2020, State Grid Corporation of China (SGCC) realized the automatic reading of electricity meter data for 510 million end users. Moreover, China Southern Power Grid Company Limited realized the automatic reading of electricity meter data for 120 million end users, accounting for 100% of the total number of end users [52]. Plenty of user data lays a foundation for topology identification based on electricity consumption data [53]. The data read through smart electric meters of the users includes electrical energy data, voltage data, current data and so forth. The corresponding topological relation can be determined, and then the line and phase [54, 55] of a user can be judged by the relation among the data on the same line.

A distribution circuit presents a radial structure and the data including voltage and current etc. on the circuit has a strong correlation. Bolognani *et al.* put forward an automatic identification method for the topology of a distribution circuit with the voltage data detected on the distribution circuit and verified the method by use of the node models provided in IEEE 37 [56] in the 52nd

IEEE Decision and Control Conference in 2013. As phasor measurement has been extensively applied, the topology identification on a distribution network with the data obtained through phasor measurement also is a considerably effective method. Marco Pignati *et al.* proved that the state estimation process of an active distribution network of a Phasor Measurement Unit (PMU) has a unique time determinability and update rate, allowing it to meet the time requirement on protection and accuracy requirement on faulty line identification [57]. Literature [58] put forth a topology identification method for a distribution network based on Bayesian recursion, which employed the structures and state estimations of a distribution network stored in the database previously for comparison obtaining the maximum possible value, that is, the topology. Nonetheless, this method takes up plenty of memory for a distribution network with a complicated structure. For instance, for a test system with 77 nodes, as many as 376 477 structures are required to be stored.

4.2.2. Data correlation analysis

There is a substantial similarity among the voltage waveforms of the same line and same phase in a low-voltage distribution network. So, the similarity analyses on voltage waveform data were carried out directly to identify the relation between a line and a user in some literature [59–61]. In other literature [62], the Nodal Voltage Coefficient Method was put forth, indicating the stronger the nodal correlation was, the higher the coefficient would be. As hypothesized in the above-mentioned method, the voltage amplitude from a parent node to the child node would decrease gradually during topology construction and voltage amplitude was the criterion of connection relation in this study. The Mutual Information Method was suggested in the literature [63] to judge the connection relation as per the value of mutual information entropy of a nodal voltage, and then to construct the topology structure based on a simple principle, such a method only fixes its attention on the correlation of nodal voltage waveforms. Nonetheless, its identification capability and adaptability are relatively poor.

The classification of voltage data at various measurement points based on clustering analysis also is available to judge either the correlation between nodes and related lines, or the relationship between lines and users. In the literature [64, 65], Principal Component Analysis (PCA) was first applied to extract the feature vectors from the original time series. And then the constrained K-means clustering was performed to divide the customer/smart electric meter into dissimilar stage connection groups. based on outlier detection and ameliorated K-means algorithm, the user phase identification method for an area established was put forward in the literature [66, 67]. Another literature [68] provided the topology identification method by Gaussian Mixture Model (GMM) clustering by use of the smart meter data from the end users at a low-voltage feeder. The Constrained Multi-Tree Clustering was adopted for the identification of the measurement topology of a low-voltage distribution network in line with the underlying structure of the low-voltage distribution network defined with voltage measurement in the literature [69]. Aiming at a distribution network with a static tree structure, the connection relations among the nodes were first judged with the polynomial relation of the combinations of standard deviation and the mean value of the voltage drops. Then, according to the features stated in another literature, that is, the standard deviation of different voltage drops on the same branch may increase from the parent node to the child node, the topology is constructed in line with the order of nodes traversed by the relevant standard [70]. In another literature [71], the Pearson correlation coefficient was applied to measure the fluctuation similarity among the voltage curves of diverse users, while the K-medoids algorithm was simultaneously applied to cluster the users with similar voltage curves into relevant user groups, to compare and analyze the total current of diverse user groups and the three-phase current value of the transformer, and thereby to identify the phase sequence of the transformer connected to the low-voltage users. As stated in the literature [72], the t-distributed stochastic neighbor embedding (t-SNE) technique was first applied to lessen the dimension of the original load data. Then, BIRCH was applied to cluster the load data after dimensionality reduction to achieve the identification of the phase position and accessed meter box of the single-phase users in an area. Some literature [73–75] mentioned a new phase position identification method for the users with spectrum clustering and mitigation for three-phase unbalance, which adopted the voltage-time sequence generated by the AMI device to verify and correct a label of user phase. With a satisfactory identification capacity and adaptability, the clustering approaches can take the tree structure of a low-voltage distribution network into consideration. Nevertheless, the voltage waveform defined only with the nodes may limit the identification capability of these methods.

The phases of all users are further taken as a variable to develop an optimization model for a solution by utilizing user power data in line with the principle that the power sum of the users in the same phase is balanced with the power at the head end generally [76, 77]. With the augment of the nodes of a low-voltage distribution network, both the calculation efficiency and the identification capability will be far from satisfactory. In the literature [78], another topology identification method based on the knowledge graph was put forward and to some extent, it avoided the disadvantage of low operation efficiency as a result of occupation of the communication channel when there is too much running data. As a result, this method may produce a desirable result for a specific scenario. And another literature [79] provided a multi-objective optimization model considering both power balance and waveform classification of voltage-time sequence, further improving the effectiveness of the algorithm. Moreover, the identification of a user-meter box was also achieved by the integration of the address information [80].

4.2.3. Artificial intelligence method

At present, it's a crucial way to streamline operations and elevate efficiency by data dimensionality reduction with an artificial intelligence approach. And the data-driven method established based on PCA and the interpretation of its graph theory was applied to infer the steady-state network topology from the electrical energy measurements of smart meters in some literature [81, 82]. The matrix composed of voltage sequences was classified into the product of the load matrix and component matrix through PCA. And the connection relation among the nodes was obtained as per the composition of the component matrix and the relations among various node components were analyzed. In another literature [83], the topology network was identified with the query-able data of real-time electricity prices. Part of the electric energy matrix was first decomposed into an inverse matrix of the node admittance matrix, then the regularization term was added into the objective function to keep the sparsity of the admittance matrix and incidence matrix after decomposition. Moreover, the node admittance matrix was adopted to judge the network topology. A particular system topology was searched with the maximum likelihood classification in some literature [84, 85]. In another literature [86], the regression method of Least Absolute Shrinkage and Selection-Operator (LASSO) with regularization of penalty term was proposed to achieve the identification of user phase connection in a low-voltage distribution network. As introduced in the literature [87], the multivariate linear regression equation was first established by using the data of the gate table and the single-phase table, and then the determination coefficients of the three regression equations composed of the single-phase table as well as the three-phase gate table were calculated respectively, to judge the phase in line with these coefficients. This literature [88] proposes a novel spectral and saliency analysis (SSA) identification method to overcome incomplete datasets. As introduced in the literature [89], a novel data-driven phase identification method based on Bayesian inference, uses load consumption profiles as inputs. A method that uses a high-pass filter to remove the redundant and irrelevant parts of the power consumption time series in literature [90, 91] was proposed. Literature [92] uses the Evolutionary algorithm based on deterministic crowding and load measurement correlation analysis through a heuristic optimization algorithm to improve data availability and reduce the impact of data loss on topology analysis results.

The correlation analysis is predominantly adopted to judge the connection relationship among the nodes and realize the topology identification in the data-driven analyses and research on power systems. For instance, the values of correlation coefficient [62], mutual information [63], or standard deviation [71] of voltage-time sequence are taken as the basis for identification of the connection relation among the nodes. Among these methods, both data-driven principles and calculation are extremely complex, especially when their physical principles are not clear enough, which is detrimental to extending them to the identification of electrical topology. But references [93] presented an explicit physical meaning in the identification of the line-user relation of a low-voltage distribution network by way of the establishment of an optimization model based on Kirchhoff's current law and conversion of the model into a quadratic programming problem for solution.

5. Main issues to be further explored at present

Based on the previous analysis, the main issues currently existing in the topology analysis of low-voltage distribution networks are:

1. Phase-line identification

Currently, a Distribution Transformer Supervisory Terminal (TTU) (collection unit) may be installed at the head end of a distribution transformer to receive the low-power pulse signals transmitted by the meter box and Collect Transfer Unit (CTU) (distribution unit) at the branch point of a line through dissemination over the wired or wireless network. Furthermore, the fast and high-precision sampling technology of TTU and CTU should be utilized to detect characteristics of the bus at the same time to judge the precedence or parallel correlation, realizing the physical topology of "distribution transformer-branch" and "meter box-user". Nevertheless, the TTU installed at the side of the distribution transformer only is located at the low-voltage side of the distribution transformer and cannot be adopted to measure the electric quantity at each outlet side of the low-voltage bus of the distribution transformer; thus, only the phase identification, not phase line identification, is possible [79]. Apart from that, the impedance of a line is uncertain owing to the instant change of the operation state of a low-voltage distribution network; thus, it's difficult to determine the actual length of the line.

2. Improvement of universality and reuse of topology

At present, the description of topology information is mostly concentrated in the configuration process and cannot adequately mirror the change of topology information timely [94]. Most of the topology analysis is embedded in the relevant application systems and conducted independently, which may give rise to serious resource waste and data redundancy. In a distribution network, any change of operation state, opening and closing of a switch, re-connection of a line and so on will result in the change of topology information. So, the calculations of line loss and state estimation will be affected if the change of topology information cannot be represented timely. That's why it is tremendously important to explore a method for the representation and exchange of real-time topology information under IEC 61970 and IEC 61850 for the operation and maintenance of a low-voltage distribution network.

3. Low-voltage customers have diverse electricity consumption characteristics, distributed power sources such as photovoltaics share the load locally, and household electricity consumption is small, making it more difficult to identify existing data methods. Few studies have been carried out to identify the topology of empty or new energy users, taking into account their characteristics. Constrained by physical laws as well as investment costs, there is a discrepancy between measured and real data. And the study of data incompleteness in the identification of low-voltage distribution network topologies is still under-researched.

Hence some work outlooks are given as follows:

1. A complete framework of topology identification and dynamic zoning for a low-voltage distribution network should be established;
2. The topology information models of distribution networks and IEC61850 models conforming to semantics should be elevated;
3. A desirable local topology update algorithm and the rules regarding zoning result update should be established.

6. Conclusion

A low-voltage power grid is the key to ensure the power quality of users, and also the key to connect with a multitude of distributed power supplies in the future. The topology analysis on a low-voltage grids plays a paramount role in ensuring their safe and stable operation.

The signal injection method can automatically identify the topological relationship of low-voltage power grid. However, a large number of additional equipment needs to be installed, which is not suitable for large-scale low-voltage network topology analysis.

The electricity information collection system has collected a large amount of user data, which can also be used to identify topological relationships. The voltage in the same phase on the same line has significant similarity, and based on this characteristic, the identification of line-user and phase-user relationships can be carried out. The electrical energy of the total meter on the line is equal to the total load of the individual users on the line. This feature can also be used to identify the relationship between line-user and phase-user. The development of artificial intelligence also provides a way to use measurement data for topology analysis, solving the problem of incomplete data collection. However, the physical significance of artificial intelligence methods is not very clear.

In the future, further exploration of the relationship between measurement data can be carried out to identify line parameters and user meter boxes.

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