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Article

Signal-Injection-Based Topology Identification for Low-Voltage Distribution Networks Considering Missing Data

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Abstract: With the widespread use of new equipment such as distributed photovoltaics, distributed energy storage, electric vehicles, and distributed wind power, the control of low-voltage distribution networks (LVDNs) has become increasingly complex. Acquiring the most recent topological structure is essential for conducting accurate analysis and real-time control of LVDNs. The signal-injection-based topology identification algorithm is favored for its speed and efficiency. This study proposes a new signal-injection-based topology identification algorithm aimed at solving the issues of reduced completeness and correctness of identification caused by missing feature signal records (FSRs). By analyzing the correlations between FSRs of different positions, the algorithm employs vertical and horizontal completion methods to effectively address missing data, combined with inclusion detection algorithms, to identify the topology of LVDNs. Based on the study of actual LVDN data, the results indicate that the algorithm not only significantly improves the completeness and correctness of topology identification for LVDNs but can also increase the number of devices in operation by evaluating the status of topological equipment, further enhancing the topology identification performance.

Keywords: topology identification; low-voltage distribution network; signal injection

1. Introduction

With the rapid development of user-side equipment such as distributed photovoltaics, distributed energy storage, and electric vehicles, the functions performed by LVDNs are becoming more complex. Accurately determining LVDNs' topology structure is becoming increasingly important for power grid managers. First, accurate LVDN topology information is the basis for conducting analyses such as power flow calculation, state estimation, fault location, and early warning; it can be used to detect and handle abnormal situations in a timely manner and improve power supply reliability. Secondly, topology information is instrumental in estimating line parameters and analyzing losses, which enable monitoring of line operating status and loss levels, aid in preventing electricity theft, and contribute to enhanced economic efficiency. Finally, with the large-scale access to distributed energy sources in LVDNs, it is necessary to perform stability analysis and real-time control on the grid, and the network topology structure is among the key data. Therefore, identifying the topology of LVDNs has theoretical and practical significance.

Currently, there are two main types of topology identification methods for LVDNs [1]. The first type is based on measurement data. This method mainly uses physical parameters such as the voltage, current, and power in LVDNs to determine the connection relationships between different devices through relevance analysis, clustering analysis, linear programming, neural networks, and other technologies [2–9]. The advantage of this method is that it can use data provided by existing measurement devices. The disadvantage is that it requires a lot of measurement data support, it has

high requirements for data quality and completeness, and the calculation process may be complex and time-consuming. The other method is based on signal transmission; it mainly injects feature signals into the power cable and determines the connection relationships of devices by tracking and analyzing feature signals in power lines [10–15]. The advantages of this method are that it requires small amounts of data, provides fast results, and has low computational requirements. The disadvantage is that it requires the installation of a large number of devices, which increases costs and implementation difficulties.

In recent years, a new generation of intelligent power equipment, such as intelligent integration terminals (IITs), intelligent low-voltage circuit breakers (ILVCBs), and smart energy meters (SEMs), has been widely used in LVDNs following the development of power-line carrier (PLC) communication and edge computing technology. These devices can fully realize the signal-injection-based topology identification method without the need for additional equipment. As a result, many universities and enterprises are once again paying attention to and beginning to research this technology.

The authors of [10] proposed a record-based low-voltage topology identification method that utilizes broadband PLC technology and current topology pulse technology to quickly and accurately identify the consumer–transformer relationships and hierarchical relationships in LVDNs. This scheme can sense topology changes and adapt to dynamic environments, characterized by low algorithm complexity, high real-time performance, and reliability. In [11], the authors used phase voltage zero-crossing modulation and the alternating direction multiplier method to achieve dynamic identification and model comparison of LVDNs. The proposed scheme, while implementing topology identification using hardware, can also perform topology verification with the main station system, enhancing the model's accuracy and reliability. The authors of [12] introduced a physical topology identification method for LVDNs based on pulse current feature analysis, utilizing pulse current communication technology, Hilbert–Huang transform algorithms, and spatiotemporal charge feature verification algorithms based on edge computing, to safely, quickly, and accurately map the physical topology. In [13], the authors presented a topology identification technology based on intelligent measurement switches, using modulation, demodulation, and encoding methods of feature current signals to accurately identify the physical topology of low-voltage distribution substations and generate self-portrait structural diagrams of the online substations. The authors of [14] introduced a method for identifying the topology of low-voltage substation areas in distribution networks. This method utilizes feature signals from intelligent terminals, reactive power compensation, and edge computing to enhance efficiency and real-time capabilities in topology identification. The authors of [15] employed high-speed PLC communication technology and external electrical frequency signals, automatically completing topology identification through the correlation of characteristic information collected by intelligent monitoring units and voltage zero-crossing offset characteristics.

Different methods have been used in the abovementioned papers to achieve signal-injection-based topology identification, but none of them have considered the impact of the integrity of the injected and received signals on topology identification. There are many connected devices in LVDNs, and their topology is complex and rapidly changing. In such an environment, it is very difficult to ensure that the injected signal is received stably and reliably; hence, the topology structure built on these incomplete data may also have errors. Incorrect topology structure can affect subsequent analysis and control for LVDNs, especially for applications that require real-time control. Therefore, how to achieve topology identification in the absence of data has important engineering value for all LVDN topology identification methods that use signal injection.

The rest of this paper is organized as follows: Section 2 describes the method of signal-injection-based topology identification for LVDNs in detail. Section 3 presents in-depth research on a topology identification algorithm that considers data loss. In Section 4, a real topology identification project for LVDNs is introduced, and the engineering data are studied to verify the validity of the algorithm.

2. Signal-Injection-Based Topology Identification

2.1. Topology Identification Principle

LVDNs usually refer to power networks with voltage levels of 1000 V and below in urban and rural areas. The structure of an LVDN from the substation to users is generally a multilayered tree. After power lines emerge from the transformer, the equipment to which they usually connect includes switches, protection devices, and cables, all of which have very little impact on the injected signal due to their small internal resistances. Therefore, a feature signal such as feature current or feature power injected into power lines by an end device can be detected by all of its superior devices. Such features can be used to identify the connectivity of a specified branch. After all devices in the LVDN have completed signal injection, the edge computing device collects FSRs of all devices and performs topological identification analysis to determine the latest topology structure.

Two types of devices are required to complete signal-injection-based topology identification in practical engineering: The first type is topology identification devices (TIDs), which mainly complete the injection and reception of feature signals. This type of device can be independently connected to the LVDN or integrated into intelligent equipment to achieve this function, such as signal processing modules (SPMs), ILVCBs, and SEMs. The second type is signal analysis devices, which are generally installed on the low-voltage output side of the transformer. These control TIDs in LVDNs remotely through a specific communication channel, such as PLC, wireless. Their main function is to send commands, collect FSRs from all TIDs, and execute the topology identification algorithm. Figure 1 shows the installation and data processing of each device in an actual LVDN.

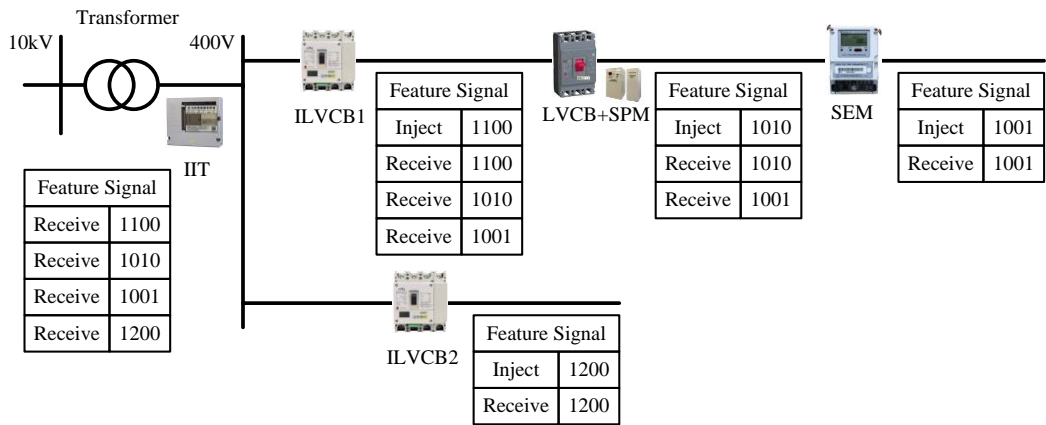


Figure 1. The installation and data processing of each device in an LVDN.

As shown in Figure 1, the ILVCB, SEM, and the combination of LVCB and SPM are used for signal processing, installed in different positions of the LVDN. The IIT near the transformer is used for signal analysis. When the SEM injects signal “1001” into the power line, superior devices such as the SPM, ILVCB1, and IIT will all receive signal “1001”. Similarly, the ILVCB1 and IIT can receive signal “1010” injected by the SPM, while only the IIT can receive signal “1100” injected by the ILVCB1. Since the ILVCB2 is located on another branch, only the IIT can receive signal “1200” when ILVCB2 injects it.

2.2. Topology Identification Process

The topology identification process for LVDNs via signal injection unfolds in three distinct phases: the initialization phase, the signal injection and detection phase, and the data processing phase. A comprehensive illustration of this process is presented in Figure 2.

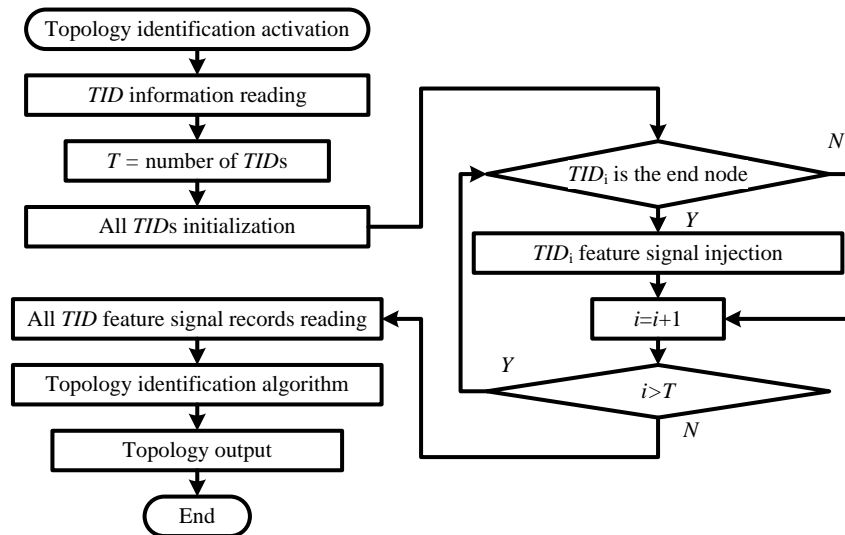


Figure 2. The topology identification process for LVDNs via signal injection.

After the topology identification process starts, the IIT reads the information of all TIDs installed in the LVDN. TID information includes the total number of TIDs (T), the identification number, the device type (e.g., ILVCB, SPM, SEM), and the communication channel.

By obtaining this information, the IIT sends an initialization command to each TID to command them to clear their FSR queue. After entering the feature signal injection and detection stage, the IIT will sequentially send a signal injection command to each TID, controlling them to inject feature signals representing themselves into the power line. At the same time, TIDs located upstream on the same line will receive this feature signal and record it in their local queue.

Following the completion of signal injection by each TID, the IIT will initiate a command to gather the FSRs from all TIDs. Subsequently, it will analyze the accumulated data and execute a topological identification algorithm to ultimately generate the most recent topology structure of the LVDN.

2.3. Impacts of FSR Completeness on Topology Identification

The most important data in the entire topology identification process are the FSRs of each TID. However, obtaining complete FSRs is not easy in practical engineering, as it is affected by the following factors:

1. **Communication quality:** Reliable communication between the IIT and TID is fundamental for the operation of topology identification. If this communication fails, the IIT cannot send commands to the TID to initiate the signal injection and detection process, rendering the entire topology identification system inoperative.
2. **Feature signal injection equipment:** In the event that a TID's feature signal injection circuit malfunctions, the other TIDs within the same line are unable to receive the feature signal. This scenario renders the affected TID "invisible" to the topological identification algorithm, which consequently cannot ascertain its position.
3. **Feature signal reception equipment:** When the feature signal sampling sensor works abnormally, the corresponding TID will not recognize any feature signals. As in the case of communication failure, the FSRs of that TID will become empty.
4. **Environmental interference:** The LVDN is connected to a multitude of electrical devices, making the characteristics of its current or power extremely complex. Although the feature signals emitted by TIDs are specially designed, it cannot be guaranteed that they will be effective at all times and in all places. When a TID misses one or more feature signals, the FSRs will correspondingly decrease. Since this type of data loss is random and unpredictable, it has the most significant impact on topological identification.

For actual LVDNs, the probability of the above four factors occurring is not small. Especially for the fourth factor, it cannot be avoided every time topology identification is performed. Therefore, how to correctly supplement these missing data through algorithms to ensure the completeness and correctness of topology identification is one of the key points for signal-injection-based topology identification for LVDNs.

3. Topology Identification Algorithm Considering Data Loss

3.1. Feature Signal Record Matrix

The feature model of TID t , which is used to record the information of the TID and the FSRs that it receives, can be represented as follows:

$$C_t = \{ID_t, N_t, S_t, X_t\} \quad (1)$$

where ID_t is the device identifier of TID t , used to describe the unique identification of the TID; N_t represents the total number of feature signals recorded by TID t ; S_t acts as the position marker for the TID, with varying values assigned to it, each denoting the node's topology type; X_t is the FSR vector for TID t , recording all feature signal values. Following the collection of feature models from all TIDs by the IIT, these data must be transformed into an FSR matrix. This matrix is defined as follows:

$$M = \{C_1, \dots, C_T\} \quad (2)$$

where the element C_t in M is the feature model of TID t , and T is the total number of TIDs in the LVDN.

3.2. Characteristics of FSRs

The FSRs of LVDNs have the following characteristics:

1. Existence: If the communication is normal, the TID's FSR will definitely have a record describing itself, regardless of whether it has been detected or not. This is because as long as there are no issues with the communication, the device physically exists, and even without an FSR, its impact on the topology must be considered.
2. Inclusiveness: If a TID is capable of receiving the FSR from another TID, this indicates that the former is situated upstream of latter. Since an LVDN is a tree-shaped topological structure, its current and power converge towards the root of the tree. According to Kirchhoff's current law (KCL), the feature signal emitted by a TID on a branch will definitely produce a feature current of the same magnitude but in the opposite direction on its upstream branch. Based on this principle, all TIDs corresponding to the FSRs are downstream devices of the TID that possesses these FSRs.
3. Transitivity: If a TID can receive the FSRs of its downstream devices, then all devices upstream of that TID must also have those FSRs. By identifying a primary trunk within the tree-shaped topology of an LVDN, it can be found that any TID's FSR comprises both its individual record and the collective FSRs of all subordinate devices. Therefore, the FSR of the TID has an inclusive relationship with the FSRs of all downstream devices. Conversely, if an FSR appears in the queue of a downstream device, due to the transitivity of that trunk, the FSR must be present in the queues of all of its upstream devices.

Figure 3 illustrates how to use these characteristics to complete the FSR data. The topology diagram contains four TIDs, where TID_1 is the upstream device of TID_2 , and TID_2 is the upstream device of TID_3 and TID_4 . After completing a round of feature signal reception, the FSR vectors of TID_1 and TID_2 are as follows:

$$X_1 = \{TID_2\}, X_2 = \{TID_2, TID_3, TID_4\} \quad (3)$$

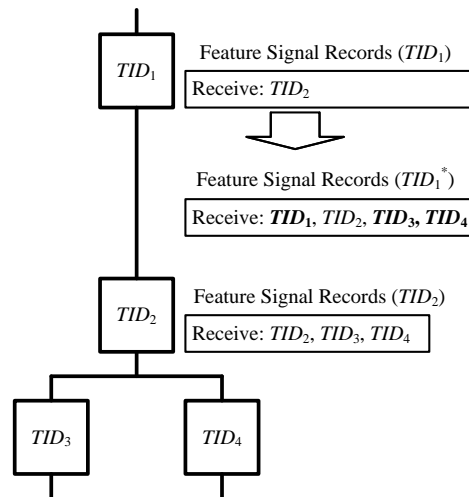


Figure 3. Completing the FSR data within a branch consisting of four TIDs.

Firstly, it can be observed that TID_1 's FSR lacks its own record, which can be supplemented according to Characteristic 1. Secondly, since TID_1 's FSR includes the record of TID_2 , it can be determined that TID_1 is the upstream device of TID_2 according to Characteristic 2. Since TID_2 's FSR includes the records of TID_3 and TID_4 , these two records can be added to TID_1 's FSR according to Characteristic 3. Finally, by integrating all of the data, the completed FSR vector for TID_1 can be obtained as follows:

$$X_1^* = \{TID_1, TID_2, TID_3, TID_4\} \quad (4)$$

Based on these three FSR characteristics, it is possible to perform vertical and horizontal completion of the existing FSR vectors, minimizing the impact of missing data on topology identification.

3.3. Vertical Completion of the FSR Vector

The vertical completion algorithm for the FSR vector is based on a recursive process, and its formula is expressed as follows:

$$X_t' = \{f_v(x_t, i) | i \in [0, N_t]\} \quad (5)$$

where X_t' is the FSR vector after vertical completion, x_t is an element in the original FSR vector X_t , and N_t is the total number of elements in X_t . The function f_v is a reconstruction function that uses recursion to achieve the vertical completion of X_t , which can be expressed as follows:

$$f_v(x_t, i) = \begin{cases} \text{null} & \text{if } x_t \text{ already exists in } X_t \\ \{x_t, i\} & \text{if } x_t \text{ does not exist in } X_t \end{cases} \quad (6)$$

where the function returns null when the feature signal x_t already exists in the dataset X_t , indicating that the recursive search for x_t can end at this branch. When the number of feature signals in X_t is not greater than 1, and the given x_t does not exist in the dataset X_t , the function returns $\{x_t, i\}$, which is the feature signal itself, indicating that the current dataset of the recursive search only has the feature signal itself as valid data, and there is no need to enter an iterative search. When the number of feature signals in X_t is greater than 1, the recursive function f_v is called, indicating that there are multiple valid data in the current dataset, and the recursive search is needed for each feature signal and their corresponding TID's FSR vector.

3.4. Horizontal Completion of the FSR Vector

For some FSR vectors after vertical completion, there is also a transitive relationship between each pair, which is reflected in the inclusion property between the two vectors. As shown in Figure 4(a), when two FSR vectors have no intersection, their data are independent of one another, without transitivity, and cannot be completed. When one FSR vector completely belongs to another FSR vector, as shown in Figure 4(b), the relevant data of one vector already exist in the upstream vector, and there is no need for data completion. When two FSR vectors have an intersection but no inclusion relationship, as shown in Figure 4(c), according to the inclusiveness of the FSR, it can be determined that the actual situation must be that one vector includes the other; therefore, the non-communicative part can be directly copied to another vector, forming an inclusive form and achieving horizontal completion of the data.

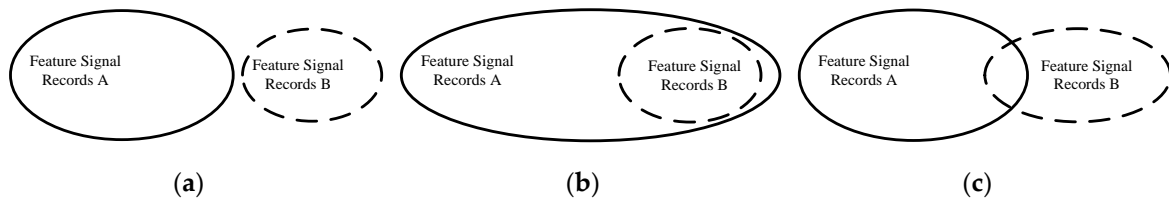


Figure 4. The inclusion relationship between two FSR vectors: (a) Characteristic signal vector A and characteristic signal vector B have no intersection. (b) Characteristic signal vector A includes characteristic signal vector B. (c) Characteristic signal vector A and characteristic signal vector B have an intersection.

There is an issue here: when it comes to data completion, the vector to which the data are copied is uncertain. According to the inclusiveness characteristic of the FSR, the vector that receives new data also moves upstream in its physical position, which can impact the correctness of topological recognition. Therefore, the data copy cannot be designated arbitrarily. Analyzing the FSR characteristics reveals that the intersection between two vectors exists because neither vector contains the TID information of the other. To determine which vector represents the upstream device, one must analyze the historical topological structure. For algorithms running on signal analysis devices, this method is overly complex and resource-intensive. Therefore, the algorithm in this study does not determine which vector corresponds to the upstream device; instead, it marks all relevant vectors for further analysis by the main station system.

Nevertheless, the success rate of guessing the upstream device can still be improved through simple analysis of some data features. An important feature is the number of records in the FSR vector. Theoretically, the data received by the upstream topological devices in a tree-shaped LVDN are likely to be more than received by the downstream devices, so supplementing the data to the vector with more records has a good chance of matching reality. According to the description above, the formula for the horizontal completion algorithm is as follows:

$$X_t'' = \left\{ \bigcup f_H(X_t', X_i') \mid i \in [0, T], i \neq t \right\} \quad (7)$$

where X_t'' is the FSR vector after horizontal completion, X_t' is the characteristic signal vector of X_t after vertical completion, and X_i' is the FSR vector of other devices after vertical completion of X_i . The function f_H is a merging function, which is expressed as follows:

$$f_H(X_1, X_2) = \begin{cases} X_1 \cup X_2 & (X_1 \cap X_2 \neq \emptyset, X_1 \neq X_2, N_1 \geq N_2) \\ X_1 & \end{cases} \quad (8)$$

where the merging function compares the FSR vectors of all other devices with its own vector. The two vectors are merged only if they intersect but are not identical, and the record count of the function's own vector is greater than that of the other vector, forming a new vector for the device itself. In this formula, the merging function evaluates the FSR vector against those of other devices.

A new vector is formed for the device only when there is an intersection—yet no identity—between vectors, and when the record count of the device's vector surpasses that of the others.

3.5. Topology Identification Algorithm

After completing both vertical and horizontal data completion, the next step is to analyze the topological hierarchy. According to inclusiveness of FSRs, there is a direct relationship between the topology among TIDs and the inclusion of FSR vectors. By analyzing the inclusion relationships among the vectors, the topological structure of the LVDN can be organized systematically.

During the process of topology identification, TIDs are divided into two categories: edge nodes and channel nodes. Edge nodes are those at the end of the topology; during signal injection and reception, they can only detect their own feature signal; hence, the length of their FSR vector is always 1. Channel nodes are all nodes other than edge nodes; since they receive feature signals from more than one other node, the length of their FSR vector is greater than 1. To implement the topology identification algorithm, it is necessary to perform inclusion detection—that is, to ascertain which channel nodes contain the edge nodes within their vectors and, subsequently, to arrange these vectors in descending order so as to obtain topological branches. After the inclusion detection, by further integrating the topological branches, the final topological structure of the LVDN can be determined. The process of the topology identification algorithm is shown in Figure 5.

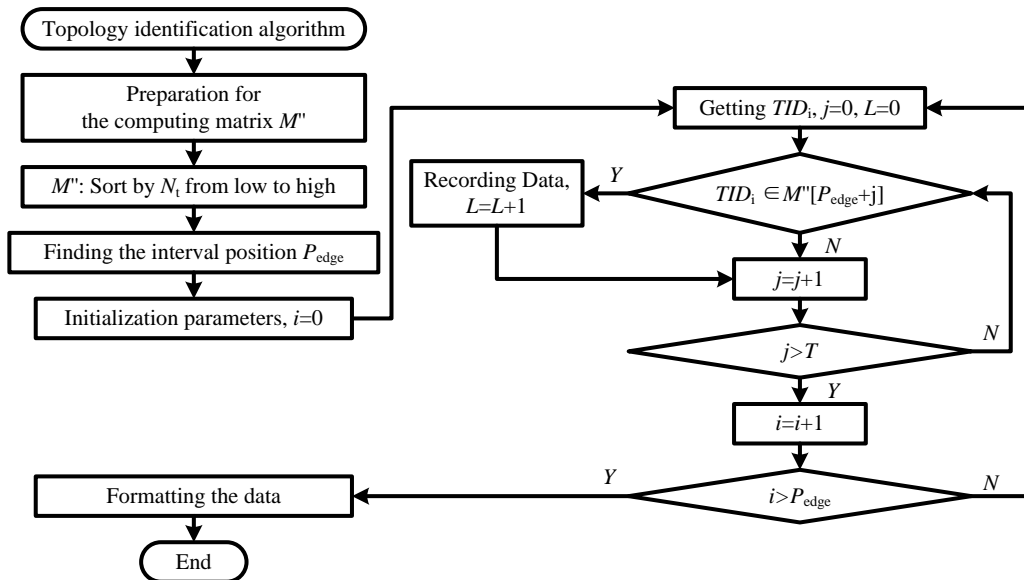


Figure 5. Topology identification algorithm flowchart.

Firstly, the algorithm distinguishes between edge nodes and channel nodes to create matrix M'' using all of the completed FSR vectors $\{X_1'', \dots, X_T''\}$ and then sort them by the element number of each FSR vector in ascending order. Since edge nodes have only one FSR, the boundary between edge nodes and channel nodes can be found by searching for the last vector with an FSR count of one and marking that position as P_{edge} .

Next, the algorithm advances to the primary process of inclusion detection for edge nodes. The steps are as follows:

1. Initialize parameters related to inclusion detection, setting both the loop count i and the hierarchical parameter L to 0.
2. Extract the device identifier (TID_i) of the i -th edge node matrix from M'' .
3. Check whether this device identifier is included in the vector of the channel nodes.
4. If the channel node vector contains TID_i , this indicates that the node is an upstream node of TID_i . Record the position of this channel node vector and the hierarchical parameter in the topology matrix M_{TOPO} , and then increase the hierarchical parameter L by 1.

5. If the channel node vector does not contain TID_i , continue searching in the next vector until all channel node vectors have been checked.

In this way, the various topological branches are identified. The topological structure data of the LVDN can be obtained through subsequent data processing of the topology matrix M_{TOPO} .

4. Experimental Analysis

4.1. Application of the Topology Identification Algorithm in Practice

The signal-injection-based topology identification algorithm proposed in this paper for LVDNs, which accounts for data loss, has been applied in an actual LVDN in Northern China. An IIT was installed on the transformer's low-voltage side, and the topology identification algorithm runs on this terminal, as shown in Figure 6(a). In the branch boxes connected to the supply line, LVCBs and SPMs are installed, which can communicate with the IIT via PLCs to complete operations related to topology identification, as shown in Figure 6(b).

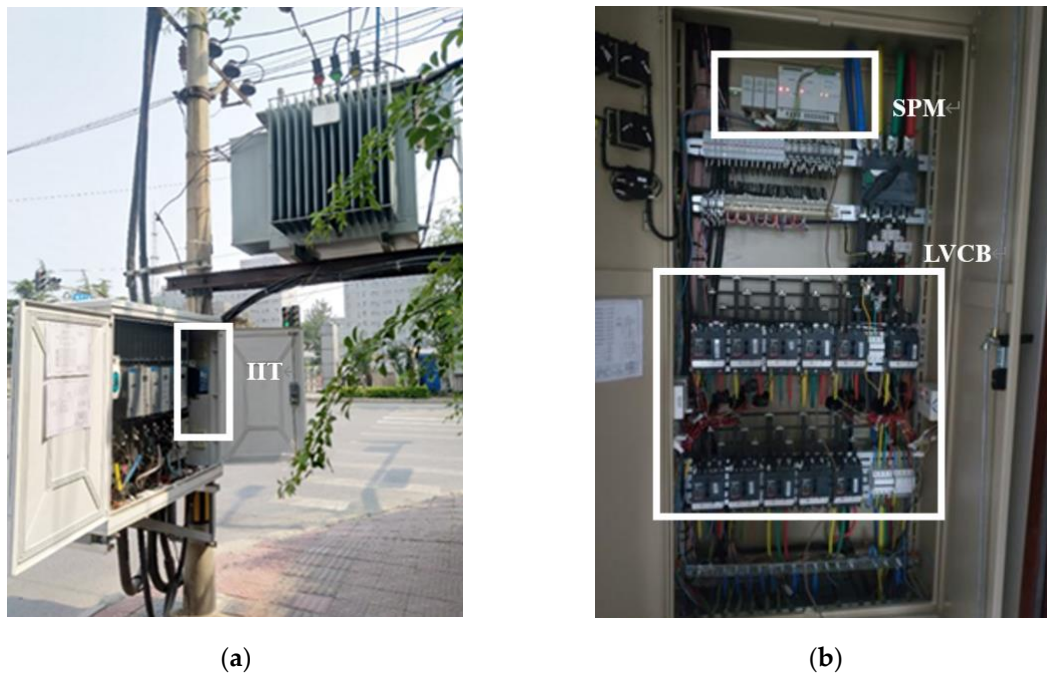


Figure 6. Application of signal-injection-based low-voltage power distribution network topology identification in power distribution networks: (a) IIT onsite installation situation. (b) LVCB and SPM onsite installation situation.

The algorithm's application scenario consists of one low-voltage incoming cabinet, three outgoing cabinets, three branch boxes, and four meter boxes. The low-voltage incoming cabinet (IC) is connected to the low-voltage side of the transformer and has an SPM installed to monitor the transformer's operation data (1005). The three feeder cabinets (FCs) connected to the incoming cabinet are equipped with smart circuit breakers (2003, 1011, and 1001) to monitor and control each feeder line. Downstream, each of the three feeder lines is connected to a branch box (BB) equipped with smart circuit breakers, which are BB1 (2110, 2061, 2121, 2150), BB2 (2009, 2006), and BB3 (1010, 2015, 2053, 2054). As the second-layer link, the branch boxes are connected to meter boxes (MBs), with BB2 connected to MB1 (2095, 2029, 2158, 2159), and BB3 connected to MB2 (2099, 2071), MB3 (2001, 2063, 2148), and MB4 (2118, 2102, 2104, 2126). The topology structure of the LVDN is shown in Figure 7.

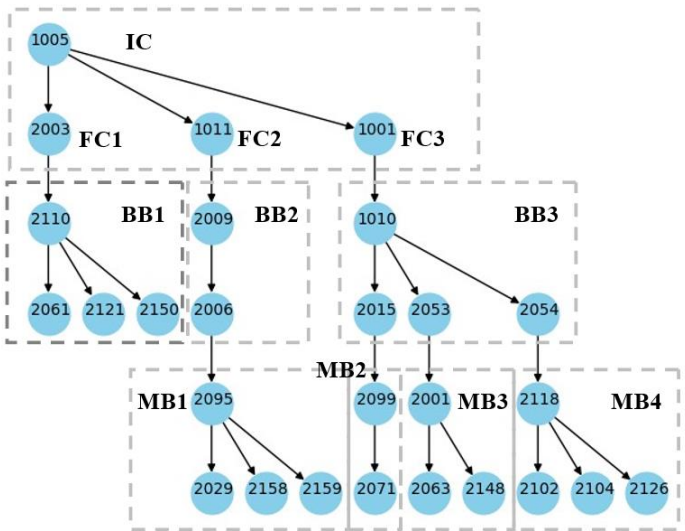


Figure 7. Topology structure of the LVDN.

4.2. Data Analysis

After all devices were installed, the process of signal-injection-based topology identification was initiated. Following the steps of feature signal emission, reception, and data collection, the FSR vector was received by the IIT. The data are shown in Table 1.

Table 1. Feature signal records vector.

No.	Device ID	Number of Records	Records
1	1001	1	1010
2	2001	0	
3	2003	5	2150, 2121, 2110, 2061, 2003
4	2006	0	
5	1010	10	2126, 2118, 2104, 2102, 2099, 2071, 2054, 2053, 2015, 1010
6	2015	2	2099, 2071
7	2029	0	
8	2053	1	2053
9	2054	5	2126, 2118, 2104, 2102, 2054
10	2061	0	
11	2063	0	
12	2071	1	2071
13	2095	4	2159, 2158, 2095, 2029
14	2099	1	2071
15	2102	1	2102
16	2104	1	2104
17	2110	4	2150, 2121, 2110, 2061
18	2118	4	2126, 2118, 2104, 2102
19	2121	1	2121
20	2126	0	
21	2148	0	
22	2150	0	
23	2158	0	
24	2159	1	2159
25	1011	1	2009
26	2009	5	2009, 2159, 2158, 2095, 2029

27	1005	12	2126, 2118, 2104, 2102, 2099, 2071, 2054, 2053, 2015, 1010, 1011, 2003
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By analyzing the data, it can be seen that nine devices did not receive any feature signals, and the number of feature signals received by other devices was also relatively lower compared to theoretical expectations. Such situations are quite common in the process of topology identification field testing. In this scenario, using traditional topology identification algorithms yields poor results in terms of completeness and correctness. However, employing the algorithm proposed in this paper for topology identification leads to better outcomes. The results are shown in Figure 8.

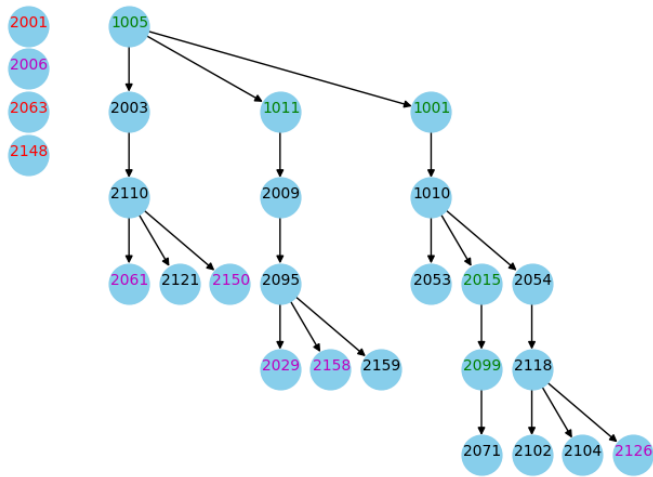


Figure 8. Topology identification results.

In Figure 8, TIDs are divided into four categories by color: red TIDs indicate no response in communication; purple TIDs are those without any FSRs; black TIDs have original FSRs that have not been completed; green TIDs are those whose FSRs have been completed. Analyzing the topology identification results, it can be seen that the new algorithm has brought about two changes to the identification results: Firstly, channel nodes whose positions could previously not be determined can now find their correct positions through data completion. For example, by completing the data for nodes 1005, 1011, and 1001, the topological positions of all nodes in the outgoing and feeder cabinets can be correctly identified; in the topology identification of BB3 and MB2, by completing the data for nodes 2015 and 2099, their positions can also be correctly identified. Secondly, edge nodes can be correctly discovered through data completion. For instance, in BB1, MB1, and MB4, although some nodes did not receive feature signals, they could be determined to be edge nodes through completion; thus, their positions could also be correctly identified.

There are two particularly notable points in these topology identification results. The first is in BB2, where TID 2006 did not receive any feature signals, and other devices also did not receive any feature signals emitted by it, so it was ultimately treated as an unidentified node. Although the topology identification for this node was unsuccessful due to insufficient data, the phenomenon itself indicates a high probability of signal injection and detection hardware faults in the device. Upon actual onsite inspection, it was found that the SPM device of this place was not connected to the line, so neither injection nor reception could be achieved, consistent with the results of topology identification. The second point is that the IIT was unable to establish communication with TIDs 2001, 2063, and 2148, resulting in the inability to determine the topological positions of these three devices. After actual line inspection, it was discovered that the line where these three TIDs were located had a power outage. Consequently, communication between the devices was not possible. This observation is consistent with the identification findings.

In summary, even with a significant amount of missing data in the FSR vector, the topology identification algorithm proposed in this paper can accurately determine the actual topology structure of LVDNs through data completion, demonstrating its effectiveness. At the same time, further analysis of the identification results can also evaluate whether current equipment has faults, identify the causes of those faults, arrange for timely maintenance by personnel, and further improve the completeness and correctness of topology identification.

5. Conclusions

This study introduced a novel signal-injection-based topology identification algorithm tailored for LVDNs. The proposed algorithm can effectively complete missing feature signal data, which is crucial for maintaining the completeness and correctness of topology identification. Through the innovative use of vertical and horizontal completion techniques, coupled with inclusion detection, the algorithm ensures precise mapping of the LVDN's topological structure.

The application of this algorithm to real-world distribution network data demonstrated its capability, not only to enhance the completeness and correctness of topology identification but also to provide timely evaluations and alerts regarding the operational status of topological equipment.

The introduction of this algorithm enhances existing signal-injection-based topology identification techniques, enabling accurate results when feature signal data are insufficient. Additionally, its algorithm is simple, computationally fast, and well suited for operation on edge devices, providing a solid data foundation for real-time control and effective analysis of distributed power sources in LVDNs.

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References

1. Qi, C.; Liu, Y.; Xu, D.; Yang, X.; Bi, C.; Hu, B. Overview of Topology Identification for Low-Voltage Distribution Network. In Proceedings of the 2023 8th Asia Conference on Power and Electrical Engineering (ACPEE); IEEE: Tianjin, China, April 2023; pp. 2486–2490.
2. Sun, L.; Chen, Y.; Du, Q.; Ding, R.; Liu, Z.; Cheng, Q. Topology Identification of Low-Voltage Power Lines Based on IEC 61850 and the Clustering Method. *Energies* 2023, 16, 1126, doi:10.3390/en16031126.
3. Ni, Q.; Jiang, H. Topology Identification of Low-Voltage Distribution Network Based on Deep Convolutional Time-Series Clustering. *Energies* 2023, 16, 4274, doi:10.3390/en16114274.
4. Wang, C.; An, J.; Mu, G. Power System Network Topology Identification Based on Knowledge Graph and Graph Neural Network. *Front. Energy Res.* 2021, 8, 613331, doi:10.3389/fenrg.2020.613331.
5. Pappu, S.J.; Bhatt, N.; Pasumarthy, R.; Rajeswaran, A. Identifying Topology of Low Voltage Distribution Networks Based on Smart Meter Data. *IEEE Trans. Smart Grid* 2018, 9, 5113–5122, doi:10.1109/TSG.2017.2680542.
6. Cunha, V.C.; Freitas, W.; Trindade, F.C.L.; Santoso, S. Automated Determination of Topology and Line Parameters in Low Voltage Systems Using Smart Meters Measurements. *IEEE Trans. Smart Grid* 2020, 11, 5028–5038, doi:10.1109/TSG.2020.3004096.
7. Hu, Y.; Cao, Q.; Wang, L.; Huang, T.; Hu, Z.; Fan, Z. Low Voltage Transformer Topology Identification Method Based on De-Noised Differential Evolution. In Proceedings of the 2020 10th International Conference on Power and Energy Systems (ICPES); IEEE: Chengdu, China, December 25 2020; pp. 356–360.
8. Tong, L.; Chai, W.; Wu, D. Topology and Impedance Identification Method of Low-Voltage Distribution Network Based on Smart Meter Measurements. *Front. Energy Res.* 2022, 10, 895397, doi:10.3389/fenrg.2022.895397.
9. Zhou, L.; Ma, J.; Huang, H.; Xia, T.; Ma, X. Automatic Identification Method of Topology Structure of Low-Voltage Distribution Station Area Based on Multi-Point Measurement Data. *J. Phys.: Conf. Ser.* 2022, 2355, 012015, doi:10.1088/1742-6596/2355/1/012015.

10. Xu, C.; Lei, Y.; Zou, Y. A Method of Low Voltage Topology Identification. In Proceedings of the 2020 IEEE Conference on Telecommunications, Optics and Computer Science (TOCS); IEEE: Shenyang, China, December 11 2020; pp. 318–323.
11. Lu, H.; Cai, Y.; Liu, M.; Ying, J.; Feng, S. Topology Identification and Check Method for Low-voltage Distribution Areas. *Electrical Automation* 2020, 42, 95–98, doi:10.3969/j.issn.1000-3886.2020.08.028.
12. Xian, H.; Li, J.; Song, W.; Zhao, C.; Liu, H.; Mao, H.; Wang, Q. A Topology Identification Monitoring Terminal Based on the Pulse Current Characteristic Analysis. *J. Phys.: Conf. Ser.* 2021, 1972, 012013, doi:10.1088/1742-6596/1972/1/012013.
13. Xiong, D.; Du, J. Research on Topology Recognition Technology Based on Intelligent Measurement Switches. *Electronics* 2022, 11, 3903, doi:10.3390/electronics11233903.
14. Wang, R.; Wu, Y.; Wei, H. Wang, C. Topology Identification Method for a Distribution Network Area based on the Characteristic Signal of a Smart Terminal Unit. *Power System Protection and Control* 2021, 49, 83–89, DOI:10.19783/j.cnki.pspc.200984.
15. Zhang, X.; Yang, X.; Liu, Z.; Zhang, Z. Research on Low Voltage Topology Recognition Based on Relevance of Feature Information. In Proceedings of the 2021 6th International Conference on Power and Renewable Energy (ICPRE); IEEE: Shanghai, China, September 17 2021; pp. 749–754.

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