Distributed Topology Identification Information Model of Distribution Network Based on IEC61850

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Distributed Topology Identification Information Model of Distribution Network Based on IEC61850

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Abstract. This paper proposes a distributed topology information model based on IEC61850 to support the distributed topology processing function of the distribution network automation system. The information model expands the new logical nodes and common data classes for storing local topology information of local subgraphs and communication information of adjacent intelligent electronic devices. By using the distributed adaptation of graph connectivity algorithm and the extended IEC61850 information model, the dynamic topology identification function of the distribution network structure is realized. The extended information model and topology recognition algorithm are verified by the cyber-physical simulation system.

1. Introduction
The distributed intelligent FA has the advantages of short service restoration time, high reliability and easy maintenance. It does not depend on the global information of the master station or the substation, and has better adaptability to the dynamic topology changes in distribution grids [1-3]. IEC61850 has a complete data object modeling method and a consistent service interface. Applying IEC61850 to distributed intelligent FA enables data communication and interoperability of devices from different manufacturers, and improves system integration efficiency [4-6].

Obtaining accurate real-time topology information of distribution network is a prerequisite for implementing distributed intelligent FA. Compared with the centralized topology analysis system, the distributed topology analysis system does not need the main station to monitor all the field devices in the distribution grid, and has the advantages of light data transmission burden, small communication delay and matching the function of the distributed intelligent FA. W. Ling et al. [7] proposed a distributed FA system based on local topology information. The system transfers messages between adjacent switches and processes topology information in a decentralized manner. N. Honeth et al. [8] presented a fully distributed topology processing algorithm. The core algorithm is based on processing measurement time series, and uses statistical correlation to judge the connectivity between feeder nodes. In [9], a distributed adaptation of graph connectivity (DAGC) algorithm was proposed to divide the global topology of the distribution network into several subgraphs. The local topology information of each subgraph is calculated by the local distributed agent, and the calculation result is exchanged between adjacent agents to obtain complete global topology information.

The work discussed above supports IEC61850 in principle. However, they don't carefully analyzed how to implement the topology processing algorithm with IEC61850. The logical nodes and common data classes, which are included in the existing IEC61850 standard, do not yet support the description of the distribution network topology information. In order to solve these problems, this work...
investigates the requirement of distributed topology processing algorithm and propose the information model which supports the DAGC algorithm. This work based on the approach of Z. Zhu et al. [9], which implement the distributed topology processing with DAGC algorithm.

2. Distributed topology algorithm based on DAGC

2.1. DAGC algorithm

According to the graph theory, the distribution network topology can be simplified to a global undirected graph. The circuit breaker or load switch is mapped to the edge of the graph, and the cable or overhead line between the switch and the circuit breaker is mapped to the node of the graph. According to the DAGC algorithm [9], the nodes of the global undirected graph are evenly distributed to several subgraphs, and the device state of each subgraph is monitored by an intelligent electronic device (IED). The topology information of the subgraph is analyzed by distributed topology processing (DTP) agents.

The nodes in the subgraph can be divided into several types: the nodes representing the main power source are called root nodes (RNDs). The nodes representing the load are called leaf nodes (LNDs). Some nodes located at the boundary of the subgraph are monitored by multiple IEDs, called overlapping nodes (ONDs). The OND on the power side of the subgraph is called a parent node (PND).

The following two rules should be followed in the topology processing process of the power distribution network:

1. Each node has four different topological states, de-energised (DE), energised but undefined to an electrical island (EU), energised and identified to an electrical island (EI), alarm to violation of topology constraints (ALR). For DE nodes, the feeder ID is always "NULL". For the EU node, its feeder ID is "Unknown". For the ALR node, the feeder ID is "Alarm".

2. To facilitate the description of graph theory, the concept of electrical distance is introduced. The RND is set to the origin, and the electrical distance of each edge of the graph is set to 1 unit. The electrical distance from any node to the RND is defined as the number of edges between the node and the RND. The electrical distance of any edge is equal to the average of the electrical distances of the nodes at both ends.

For an undirected subgraph, \( G = \langle V, E \rangle \), \( E \) represents the set of edges, and \( V \) represents the set of nodes, and \( V = \{v_1, v_2, v_3, \ldots, v_n\} \). \( n \) denotes the number of nodes in the subgraph. Subgraphs can be represented as adjacency matrices \( A=(a_{ij})_{n \times n} \):

\[
a_{ij} = \begin{cases} 
0, & \text{if } (i,j) \in E \land i \neq j \\
1, & \text{if } (i,j) \in E \land i \neq j
\end{cases}
\]

(1)

When \( i \neq j \), and \( a_{ij} = 1 \), the nodes \( v_i, v_j \) have closed edges. \( v_i, v_j \) have a first-level connection. If \( a_{ij} \neq 1 \), but another node \( v_k \) satisfies \( a_{ik} = a_{jk} = 1 \), \( v_i, v_j \) are connected by \( v_k \) to form a second-level connection relationship. The \( l \)-th level connectivity can be obtained by calculating Boolean matrix multiplication of \( A \) for \( l \) times, that is, \( A^{(l)} \). The maximum connection relationship of the \( n \)-order matrix is \( n - 1 \), so the connection matrix can be defined as:

\[
C = A^{(n-1)}
\]

(2)

If \( v_i, v_j \) are connected, then \( c_{ij} \) is equal to 1. If \( v_i, v_j \) are not connected, then \( c_{ij} \) is equal to 0.

On the basis of the adjacency matrix and the connection matrix, the distance matrix is defined as shown in equation (3). It should be noted that the adjacency matrix \( A \) and the connection matrix \( C \) are both Boolean matrices, and their elements have a value of 0 or 1. The distance matrix is a common numerical matrix.
\[ D = E + A + A^2 + \ldots + A^{n-1} \]  

(3)

\( E \) is an \( n \)-order identity matrix. If any two nodes \( v_i, v_j \) are connected, that is, \( c_{ij} = 1 \), the electrical distance between \( v_i \) and \( v_j \) is:

\[ d_{ij}^E = n - d_{ij} \]  

(4)

The above calculation process is implemented by DTP to obtain local topology information of each subgraph.

2.2. Mutual communication between DTP

In order to obtain the global topology information of the distribution network and identify the dynamic feeders and determine the tie switches, the DTPs of adjacent subgraphs need to cooperate with each other. This process uses the DAGC algorithm to calculate the connection status of each node with the RND or PND. The most important information is the connection status between PND/RND and OND. This information is transmitted through communication between DTPs.

DTP is in standby when the topology status in the distribution network has not changed. DTP will act in two cases. In one case, the local subgraph topology has a change. DTP uses the DAGC algorithm to recalculate the topology state, and then broadcasts the calculation results to the adjacent DTP. The other case is that the topology information from the adjacent DTP is received. After receiving the message, the DTP processes the local topology information and sends it to the DTP on the load side.

The interaction process between DTPs is as follows:

1. DTP initializes the parent node or the root node to \( V_{0i} \), and the ID of feeder to which \( V_{0i} \) belongs is set to "feeder_m".
2. Calculating the connection matrix \( C \) with the DAGC algorithm, and determine whether \( V_{0i} \) and other nodes in the subgraph are connected.
3. Define \( S_{vi} \) as the set of nodes which is connected to \( V_{0i} \) in the subgraph, mark the feeder ID of \( S_{vi} \) nodes as "feeder_m", and calculate the electrical distance of each node.
4. Check if the set \( S_{vi} \) contains an OND node, and if so, send a message to the neighboring DTP.
5. After receiving the message, DTP repeats steps (1)-(4) until the state of all nodes in the feeder is known.
6. For any edge \( e_{ij} \), DTP checks the feeder ID of \( v_i \) and \( v_j \). If the two nodes have the identical feeder ID, \( E_{ij} \) also obtain the same ID. If any side is powered, the nodes at both ends belong to different feeders and remain for a period of time, DTP will alarm, indicating a topology error.
7. For the open edge \( s_{ij} \), it is not represented as an edge in the adjacency matrix, but can be recognized by the DTP. The open edge still has two endpoints \( v_i' \) and \( v_j' \). The DTP checks the feeder ID of \( v_i' \) and \( v_j' \). If the ID of the two nodes are different and their states are EI, the switch is marked as a tie switch.

3. IEC61850 topology processing logical node expansion

According to the above analysis, there are two types of information that need to be stored and exchanged for distributed topology processing:

1. Topological state information for analyzing a single subgraph, such as an adjacency matrix, a connection matrix, a distance matrix.
2. Information used to interact with neighboring subgraphs to obtain status information of the complete topology, such as node type information (can be set to RND, PND, OND), topology status information of nodes (can be set to EI, EU, DE, ALR), the ID of the feeder, etc.

The logical nodes and common data classes defined by IEC61850 can not meet the functional requirements of topology identification. Taking the adjacency matrix as an example, for a 5-node subgraph, the adjacency matrix is a 5th-order matrix and cannot be modeled by a defined logical node. Therefore, we expand the information model as needed, defining new logical nodes \( SGTO, NECP \) and
common data classes SGN, SGE and NCP. These logical nodes and common data classes are described below.

3.1. Logical node SGTO
The logical node SGTO is used to describe the topology information of the subgraph, and includes two types of data objects \( V_i \) \((i = 1, 2, 3, \ldots)\), \( E_i \) \((i = 1, 2, 3, \ldots)\). Its definition is shown in Table 1. \( V_i \) represents the node of the subgraph, and \( E_i \) represents the edge of the subgraph. The number of \( V_i \) and \( E_i \) in the SGTO can be expanded according to the actual number of nodes.

The data object \( V_i \) belongs to the common data class SGN, and its definition is shown in Table 2. The data attributes \( \text{adjVj}, \text{connVj}, \text{disVj} \) are used to map the elements of the adjacency matrix, the connection matrix and the distance matrix. The \( \text{topoSta} \) is used to describe the topology state to which a node belongs, and is an enumerated type. The topology state can be selected in DE, EU, EI and ALR. The \( \text{type} \) is used to describe the node type. It is also an enumerated type. It can be selected in RND, PND, OND or normal node (NULL). The \( \text{feederId} \) is used to record the ID number of the feeder to which the node belongs. The \( \text{disRND} \) describes the electrical distance between the node and RND.

The data object \( E_i \) belongs to the common data class SGE, and its definition is shown in Table 3. The data attribute \( \text{breName} \) describes the logical node name of the load switch or circuit breaker. The \( \text{brePos} \) is used to describe the position information of the load switch or circuit breaker. If the value is "False", the undirected edge will not be recognized. The \( \text{adjVj}(j = 1, 2, 3, \ldots) \) is used to describe the incidence matrix elements of edges and nodes. The \( \text{disRND} \) is the electrical distance between the edge and the RND. If the switch is a tie switch, the value is -1. The \( \text{feederId} \) is the ID number of the feeder. If the switch is a tie switch, the value is "NULL".

3.2. Logical node NECP
The NECP logical node describes the communication parameters of the adjacent IED, it contains the data object \( \text{CommPari} \), as shown in Table 4. The \( \text{CommPari} \) represents the communication information of the \( i \)-th neighboring IED and belongs to the common data class NCP. As shown in Table 5, the NCP includes the following data attributes: the \( \text{adjIEDName} \) is the name of the adjacent IED; The \( \text{IP} \) is the IP address of the adjacent IED; The \( \text{port} \) is the port number of the adjacent IED; The \( \text{ONDName} \) is the name of OND belong to the IED and the adjacent IED.

| Attribute Name | Attr. Type | Explanation | M/O |
|----------------|------------|-------------|-----|
| V1             | SGN        | Node 1 of the subgraph represents the cable or overhead line between the switch and the circuit breaker | O   |
| ...            | ...        | ...         |     |
| E1             | SGE        | The undirected edge 1 of the subgraph represents a switch or circuit breaker | O   |
| ...            | ...        | ...         |     |
Table 2. Common data class SGN

| Attribute Name | Attr. Type | FC | TrgOp | Value/Value range | M/O/C |
|----------------|------------|----|-------|--------------------|-------|
| Status         |            |    |       |                    |       |
| adjV1          | BOOLEAN    | ST | dchg  | Whether adjacent to V1, true or false | O     |
| ...            |            |    |       |                    |       |
| connV1         | BOOLEAN    | ST | dchg  | Whether it is connected to V1, true or false | O     |
| ...            |            |    |       |                    |       |
| disV1          | INT32      | ST | dchg  | Electrical distance from V1 | O     |
| ...            |            |    |       |                    |       |
| Type           | CODED ENUM  | SV | dchg  | Node Type: RND | PND | OND | NONE | M     |
| TopoSta        | CODED ENUM  | SV | dchg  | Topology status of the node: DE | EU | EI | ALR | M     |
| disRND         | INT32      | SV | dchg  | Electrical distance from the root node | M     |
| FeederID       | INT32      | SV | dchg  | ID of the feeder | M     |

Table 3. Common data class SGE

| Attribute Name | Attr. Type | FC | TrgOp | Value/Value range | M/O/C |
|----------------|------------|----|-------|--------------------|-------|
| Status         |            |    |       |                    |       |
| BrePos         | BOOLEAN    | ST | dchg  | Switch status TRUE | FALSE | M     |
| disRND         | INT32      | ST | dchg  | Electrical distance from the root node | M     |
| FeederID       | INT32      | ST | dchg  | ID of the feeder | M     |

configuration, description and extension
Whether it is adjacent to V1, true or false

The name of the circuit breaker logical node corresponding to the edge

| Attribute      | Attr. Type | FC   | TrgOp | Value/Value range | M/O/C |
|----------------|------------|------|-------|-------------------|-------|
| cp1            | NCP        |      |       |                   | O     |
| ...            |            |      |       |                   |       |

Table 4. Logical node class NECP

Table 5. Common data class NCP

4. Topology identification communication model example

Figure 1 shows a typical open-loop distribution network, where $E_0$ is a tie switch. The feeder topology contains 20 undirected edges and 21 nodes, due to the topology mapping rule. According to the average segmentation principle of the DAGC algorithm and spatial distance principle, the global graph
is divided into seven subgraphs. The operating state of each subgraph is monitored by the IED, and the topology information is handled by the DTP [9].

Figure 1. Distribution network example

4.1. Topology identification communication model establishment

Take the IED2 in Figure 1 as an example to illustrate the establishment process of the topology identification communication model. In order to monitor the status of the distribution network, the IED should include the following logical node: PIOC is overcurrent protection; XCBR is a circuit breaker; XSWI is a load switch; TCIR is a current transformer; CWI is an external control switch of the circuit breaker; XXMU is a measurement [2]. In addition, IED2 also includes SGTO logical nodes and NECP logical nodes.

The SGTO should include five SGN data objects, \(V_2, V_3, V_4, V_5, V_6\), and four SGE data objects, \(E_2, E_3, E_4, E_5\), representing nodes and undirected edges. The tree expansion diagram of the SGTO logical node is shown in Figure 2.

Taking the \(V_2\) node as an example, \(SGTO.V_2.adjV_6\) represents the elements of adjacency matrix \(a_{26}\), \(SGTO.V_2.connV_6\) represents the elements of connection matrix \(c_{26}\), and \(SGTO.V_2.disV_6\) represents the elements of distance matrix \(d_{26}\). \(SGTO.V_2.type\) represents the type of \(V_2\) node. In this example, its initial value is "OND". Since \(V_2\) is connected to the root node \(V_{01}\), its value is changed to "PND". At the same time, its electrical distance to the RND is \(SGTO.V_2.disRND\) and its value is 1. \(V_2\) belongs to feeder_1, and the value of \(SGTO.V_2.feederId\) is "feeder_1". Since it belongs only to feeder_1, the topology state value \(SGTO.V_2.topoSta\) is "EI".

For data object \(E_2\), the logical node name of the corresponding breaker, ie the value of \(SGTO.E_2.breName\), is "XCBR2". \(V_2\) and \(V_3\) are adjacent to \(E_2\). Therefore, the values of \(SGTO.E_2.adjV_2\) and \(SGTO.E_2.adjV_3\) are "TRUE". The value of \(SGTO.E_2.adjV_j\) \(j = 4, 5, 6\) is "FALSE". Since all switches in the subgraph are closed, the value of \(SGTO.E_2.brePos\) is "TRUE". \(E_2\) belongs to feeder "feeder_1", so the value of \(SGTO.E_2.feederId\) is "feeder_1". The electrical distance between \(E_2\) and the root node \(V_{01}\) is 1.5, that is, the value of \(SGTO.E_2.disRND\) is 1.5.

The logical node NECP in IED2 contains two data objects \(ComPar_1\) and \(ComPar_3\), namely the communication parameters of IED1 and IED3. Taking the data object \(ComPar_1\) as an example, the corresponding intelligent electronic device name, that is, the value of \(NECP.ComPar_1.adjIEDName\) is "IED1", the communication port information \(NECP.ComPar_1.ip\), \(NECP.ComPar_1.port\) are the IP address and port number of IED1, respectively. \(NECP.ComPar_1.ONDName\), that is, the name of the public node is "V2". The tree expansion diagram of the NECP logical node is shown in Figure 2.
Figure 2. Two logical node structures

4.2. Information flow between information models
The flow of information in the information model is shown in Figure 3.

1) The configured IED description (CID) file presets the three types of data attributes, which are
   the switch name corresponding to each edge \( SGTO.E_i.breName \), the incidence matrix elements of
   the edge and the node \( SGTO.E_i.adjV_j \), and the type of each node \( SGTO.V_i.type \).

2) The circuit breaker switch position \( SGTO.E_i.brePos \) obtains the corresponding value from
   \( XCBR_i.pos.stVal \).

3) The adjacency matrix elements \( SGTO.V_i.adjV_j \) are obtained from the incidence matrix elements
   \( SGTO.E_i.adjV_j \) and the switch position \( SGTO.E_i.brePos \), then the connection matrix elements
   \( SGTO.V_i.connV_j \) and the distance matrix elements \( SGTO.V_i.dis.V_j \) are calculated.

4) From the above three matrix elements and node type information \( SGTO.V_i.type \), and according
   to the electrical distance from the parent node to the root node and the feeder information, obtain
   the electrical distance from each node to the root node \( SGTO.V_i.disRND \) and the feeder ID of each node
   \( SGTO.V_i.feederId \).
(5) Determine the topology state of each node $SGTO.V_i.topoSta$.

(6) Determine the electrical distance of each edge $SGTO.E_i.disRND$ and the feeder ID of each edge $SGTO.E_i.feederId$ to identify the tie switch.

5. Examples and implementation

In order to verify the topology processing information model based on IEC61850, the cyber-physical simulation system was built using the open source protocol library libiec61850 and Simulink [10]. The structure is shown in Figure 4.

![Figure 4. Three-level model](image)

The physical model is a medium voltage distribution network model simulated by Simulink, as shown in Figure 4. The physical model can be abstracted into the process level of the system. The physical model is shown in Figure 1. The simulation parameters are: bus voltage 10kV, frequency 50HZ, ground fault resistance 100Ω, load working power 10kW.

The information model is built by libiec61850, in which the IED is simulated by the MMS server as the bay level of the system. DTP is the client of MMS as the station level of the simulation system. The distributed topology information model runs in the bay level (IED). The Goose service is used to communicate between adjacent DTPs at the station level. Data communication between physical model and information model is conducted with user datagram protocol (UDP).

The correctness of the distributed topology information processing system based on IEC61850 is verified by a distributed (or centralized) feeder automation system. Switch $E_9$ are set as the tie switch. The test is as follows:

Step 1: A three-phase short circuit fault occurs at point 'f1'. If the result of the topology processing is correct, the switching sequences shall be:

1. $E_0$ is tripped, feeder $1$ loses power;
2. $E_5, E_6$ are opened to isolate the fault point;
(3) \( E_01 \) and tie switch \( E_9 \) are closed to restore power.

Step 2: A three-phase short circuit fault occurs at point 'f2'. If the result of the topology processing is correct, the switching sequences shall be:

(1) \( E_{02} \) is tripped, feeder_2 loses power;
(2) \( E_{13}, E_{14}, E_{15} \) are opened to isolate the fault point;
(3) \( E_{02} \) and tie switch \( E_9 \) are closed to restore power.

The phase A current of the circuit breaker/switch in step 1 is as shown in Figure 5.

The specific experimental results of multiple tests are shown in Table 6. For different fault points, the FA system implements the correct switching action based on the topology identification results, and the results of the topology identification are correct.

| Tie - switch | Fault point | Switching actions ( 0—open 1—closed) | Processing results |
|-------------|------------|--------------------------------------|-------------------|
| E9          | V7         | \( E_{01}: 1\rightarrow0, E_6, E_7, E_8: 1\rightarrow0 \) \( E_{01}, E_9: 0\rightarrow1 \) | correct           |
| E9          | V3         | \( E_{01}: 1\rightarrow0, E_2,E_3,E_4,E_5: 1\rightarrow0 \) \( E_{01}, E_9: 0\rightarrow1 \) | correct           |
| E9          | V14        | \( E_{02}: 1\rightarrow0, E_{13},E_{14},E_{15}: 1\rightarrow0 \) \( E_{02}, E_9: 0\rightarrow1 \) | correct           |
| E9          | V6         | \( E_{01}: 1\rightarrow0, E_5, E_6: 1\rightarrow0 \) \( E_{01}, E_9: 0\rightarrow1 \) | correct           |
| E9          | V13        | \( E_{02}: 1\rightarrow0, E_{12}, E_{13}: 1\rightarrow0 \) \( E_{02}, E_9: 0\rightarrow1 \) | correct           |
| E9          | V16        | \( E_{02}: 1\rightarrow0, E_{15}, E_{16}: 1\rightarrow0 \) \( E_{02}, E_9: 0\rightarrow1 \) | correct           |

6. Conclusion
This paper proposes a distributed topology information model based on IEC61850. The information model is applicable to the distributed topology identification scheme based on DAGC algorithm. The model contains two customized logical nodes \( SGTO \) and \( NECP \) and three customized common data classes \( SGN, SGE \) and \( NCP \). The \( SGTO \) is used to describe the subgraph topology information involved in the algorithm. \( SGN \) and \( SGE \) are used to describe the edges and nodes of the subgraph.
NECP and NCP are used to describe communication information of adjacent IEDs. In order to verify the feasibility of the information model, a cyber-physical simulation system was established using libiec61850 and Simulink. The simulation results show that the extended topology information model can operate normally, and the functions of the DAGC algorithm can be realized.

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