

Research on distributed energy resources operation and control information model based on IEC 61850

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Abstract

INTRODUCTION: High-ratio distributed energy resources (DERs) impact distribution network operation and require effective scheduling. IEC 61850 7-420 defines a DER model, but massive small/medium DERs in low-voltage networks hinder station-area aggregated management.

OBJECTIVES: Enable aggregated management, dynamic scheduling of small/medium DERs and ensure DER data security.

METHODS: 1. Analyze station-area structure and information needs via cluster control

2. Establish a general information model of DER equipment.

3. Build a new communication security control logical node

4. Realize the source-side dynamic conversion of inverter data

RESULTS: Key results: 1) IEC 61850-based DER scheduling model; 2) DER data security logical node; 3) Inverter data protocol conversion.

CONCLUSION: The proposed model, node and method resolve core DER management issues, providing a feasible distribution network scheduling solution.

Keywords: the station area, distributed energy resource, information model, data transformation, Modbus

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1. Introduction

The proportion of distributed energy resources (DER) connected to distribution networks is gradually increasing, which poses significant challenges to the structure, operation, control and post-fault self-healing control of power supply recovery of distribution networks. Therefore, it is necessary to conduct effective scheduling and monitoring of DER [1-3].

At present, the self-healing control technologies for distribution networks mainly include three types: centralized control mode, decentralized control mode and centralized-decentralized coordinated control mode. The traditional centralized control method is difficult to meet the regulation and control needs of DERs with dispersed locations and huge

numbers [4]. Virtual power plant (VPP) integrates artificial intelligence, advanced communication technology and so on [5], which can adopt cluster control technology to dynamically coordinate and control dispersed DERs according to the state and demand of the distribution network [6], and realize the dynamic division of clusters [7]. Therefore, the aggregation management of DER under the station area can refer to the method of VPP in order to realize the decomposition of DER information aggregation and power scheduling within the station area by the distribution terminal or fusion terminal of the station area. The current research mostly focuses on the algorithm of cluster division [8], but different types of DERs have different models and mapping

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protocols, which makes it difficult to realize interconnection and interoperability of DERs, and a large number of DERs with different statutes are difficult to be integrated quickly, which is easy to form an “information island”, This leads to the integration difficulty of “intra-group autonomy and inter-group coordination”.

In order to solve the problem of monitoring and communication of DER, IEC 61850-7-420 standardizes the DER information model. Existing DERs access the distribution network in a variety of ways, for large-capacity DERs accessed by medium-voltage distribution networks, existing distribution network management systems have monitored and controlled them, and they can be directly modeled using standards such as IEC 61850-7-4 and IEC 61850-7-420, and the models have covered most of the functions, and DER monitoring and other functions can be realized through the references of logical nodes [9]. For medium- or small-capacity DERs accessed by the LV distribution network, the existing distribution network management system is insufficient to monitor and control them due to the large number of DERs accessed by the LV distribution network and the large differences in communication conditions. Although the individual capacity of DER accessed by LV distribution network is small, the number is large, so its impact on the operation and control of distribution network should not be ignored. Especially when the distribution network is faulty, the observable and controllable DER in the process of power supply restoration can give full play to the supportive role of DER in case of fault. For DER monitoring and control of LV distribution network access, the IEC 61850 7-420 information model can solve the data representation of single DER, but it is also necessary to solve the problem of aggregation management of DER under the station area. Meanwhile, the Ukraine blackout in 2015 demonstrated that the risk stacking effect caused by cyber-attacks poses a serious hazard to the power grid [10]. Existing research ensures data security through security measures such as authentication and security encryption [11], but the information model of security control is not yet able to meet the security needs of the station.

Devices in the DER inverter category transmit data to the DER monitoring terminal through the inverter communication interface. There are a large number of inverters that are widely distributed, making it difficult to interact with data because of the varying data specification from different manufacturers [12]. Currently, most inverters use the Modbus protocol for data transmission, which is based on a data point table format. However, due to the differences in manufacturers and inverter models, the table information content and address offset of the data point table varies significantly. This results in a large workload for engineering installation, commissioning, and maintenance applications, making it hard to accomplish distributed power management and control.

In order to realize the aggregation management of DER for distribution network access, this paper establishes a station

area general information model supporting dynamic division of DER based on the IEC 61850-7-420 standard, so as to realize the decomposition of DER information aggregation and power scheduling by terminals in the station area. Through the new communication security control logical node, the security measures of both communication parties are clarified to realize the data security of DER equipment. Meanwhile, the data conversion between IEC 61850 standard and Modbus protocol is studied to realize the dynamic transformation of DER data into IEC 61850 data objects at the source end.

2. Communication requirements for the station area based on cluster control

With the increasing penetration of DER in the distribution network, the control of DER devices, such as power generation device and storage device, needs to be realised by station area using cluster control method to meet the peak demand, frequency, and voltage regulation in the distribution network [13]. However, there are various ways of DERs access, and for large-capacity DERs accessed by medium-voltage distribution networks, the D5000 management system can directly adopt the IEC 61850-7-420 standard to establish an information model and realize the monitoring and control of DERs. For small and medium-sized DERs accessed by low-voltage distribution networks, DER aggregation management cannot be realized due to the large number and differences in communication conditions.

2.1. Typical Structure of the Station Area Based on Cluster Control

The emergence of distribution IoT has led to the formation of a cloud-pipe-side-end IoT architecture. GB/T 41236-2022 recommends that DER devices should be grouped into clusters to interact with energy grid in a specific manner. A DER cluster is defined as a group of DERs, loads, and storage resources consisting of electrically close DERs that complement each other in terms of active power timing, and have a balanced in-situ supply and demand of reactive power [14]. This approach offers advantages such as easy management, high efficiency, and low cost, making it suitable for application in distribution networks with a large number of dispersed DER devices.

Within the station area of the distribution network, the distribution transformer terminal or the integrated terminal will cluster the DERs within the monitoring scope to form a station area dispatching control architecture as shown in Fig. 1. The station area can achieve mutual supply of resources within the cluster area. When power is insufficient or there is excess power, it can prioritize to draw or supply power from the nearest distribution area to maximize the utilization of resources.

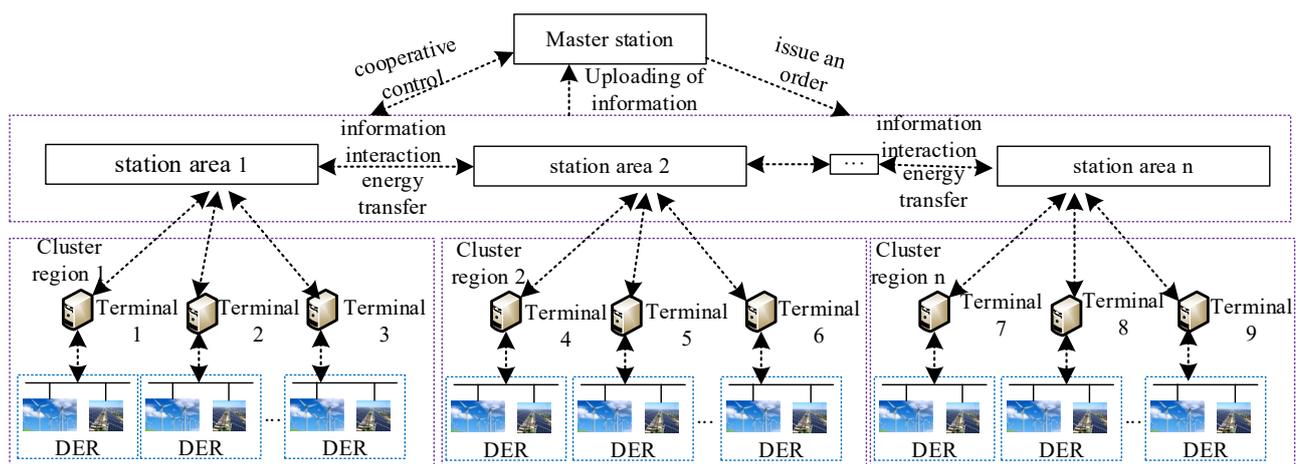


Figure 1. Station area scheduling and control architecture

2.2. Information exchange requirements for Cluster Control

When station area uses cluster control to dynamically divide DERs, it is challenging to accurately manage and regulate different types of DERs due to variations in different models and mapping protocols. There are differences in communication methods among different types of DERs. For example, DERs with inverter interfaces often use the Modbus protocol to communicate with monitoring terminals through inverters. Reliable communication is essential for clustering to acquire information recognition, concurrent processing, and security encryption. However, several manufacturers do not facilitate data fusion due to varying data specifications. While monitoring terminals upload DER data across the firewall in the Internet region using identity authentication, file encryption and other forms of transmission data security [11], the current security control of the logical nodes may not yet meet the requirements. Needless to state that DER output is affected by natural factors, behavioral constraints of the main body of interest, DER status, resulting in dynamic output characteristics. When station area adopts cluster control, DERs need to support coordinated control among various station area. Thus, DERs need to exhibit plug-and-play functionality, for which the information model is the basis for its implementation. Currently, the CIM model is often used in the main stations of dispatching and distribution network. However, limited information is available on the model of secondary protection device, which is not sufficient to model the terminal device. The IEC 61850 standard adopts an object-oriented data model based on the logical nodes to describe the decomposition characteristics for various types of DER. If the distribution network embraces the same IEC 61850 standard as the substation, it can facilitate unified management with substation device, regulate the access of devices from different manufacturers, and realise plug-and-play functionality. The dynamic invocation of DER by station

area relies on accurately expressing the dynamic characteristics of different DER objects. Unfortunately, there is a lack of information models pertaining to cluster control, which hinders the achievement of a normalised description of DER dynamic resources.

Standards such as GB/T 41236-2022 and Q/GDW 10667-2016 specify that DER should provide basic information including electrical analogue quantity, electrical energy, status quantity, and relevant basic information to the grid dispatching agency. However, for medium and small-sized DERs connected to the low-voltage distribution network, due to their scattered geographical locations, large quantities, and significant differences in communication conditions, the existing management systems are insufficient in monitoring them, and thus cannot achieve reliable and effective power restoration during the power restoration process. The dynamic information exchange of the cluster primarily involves bi-directional data flow: the first is the data information that DER needs to transmit upwards. It is the prerequisite for station area to perceive resources and it forms the basis for real-time monitoring and control of DER and its dynamic cluster division. The second involves the control commands issued to DER. For instance, setting the power generation target of DER according to the operation demand of the distribution network, sending request for current operation settings to DER, issuing start/stop operation commands to DER, and changing or setting new operation parameter for DER. However, due to different private protocols of the manufacturers, the large number and diversity of DERs are challenging to interconnect, resulting in inconsistencies in the data model standards for transmission. Since DER resources belong to various interest groups and their behaviour is subject to individual constraints, station area needs to dynamically adjust resource allocation when calling DERs using cluster control method.

3. Station area information model

Based on GB/T 41236-2022 standard, it is essential for DERs participating to function in a coordinated and compatible manner within the energy internet. They should have the capability for monitoring and controlling DER clustering. To address the challenge of information interoperability between DER devices and distribution networks, the IEC TC57 introduced the IEC 61850-7-420 Ed2.0 standard. This standard facilitates information modelling of DER devices by defining various logical nodes. Although the current information model, based on the IEC 61850 standard, encompasses most functions that allow reference to logical nodes for monitoring and control of DERs [9]. For large-capacity DER connected to medium-voltage distribution networks, the IEC 61850-7-420 Ed2.0 standard can be directly adopted to establish an information model. However, for small and medium-capacity DER connected to low-voltage distribution networks, due to their large quantity and significant differences in communication conditions, it is difficult to manage them collectively. It still lacks the necessary information model for security control-related logical nodes and dynamic cluster division.

3.1. Logical Nodes Required for DER Device Monitoring and Management

To effectively control of DER devices, the WG 17 working group of IEC TC57 developed IEC 61850-7-420 Ed2.0. This standard defines distributed power logical nodes for photovoltaics, fuels, combined heat and power and other DERs. It is used for information modelling of DER device objects. The development of the IEC 61400-25 standard was based on the IEC 61850 information modelling methodology for implementing monitoring and control of wind farms. Fig. 2 illustrates the logical nodes necessary for DER device access to the distribution grid.

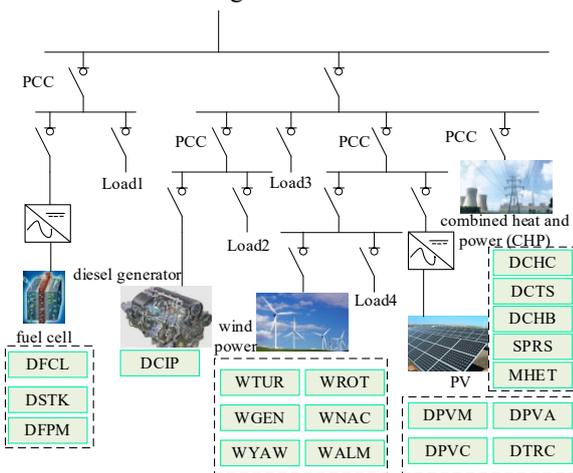


Figure 2. Logical nodes required for DER devices to connect to the distribution network

When creating the information model for the DER device, it is important to analyse it in a hierarchical classification to

meet the needs of different application functions. When a station area adopts cluster control for DER devices, it is necessary to specify the types of DER devices. Meanwhile, the uploaded DER data must be accurate in order to facilitate the dynamic division of DER clusters. To address the characteristics of different types of DER devices, specific logical nodes are established for photovoltaic, storage, wind power, and other DER devices in IEC standards such as IEC 61850-7-420, IEC 61850-90-9, and IEC 61400-25 standards, respectively. Similarly, logical nodes related to DER monitoring devices, such as electrical and non-electrical quantity monitoring and control of DER-related devices (inverters, collection devices), are established to analyse their functions. The establishment of the corresponding functional logical nodes is shown in Figure 2 and specified logical nodes can be found in IEC 61850-7-420 and other standards.

The DER device information model is created by considering the asset status, operation status, dispatchability, health status, and other factors. For large-capacity DER connected to medium-voltage distribution networks, the distribution network management system can directly adopt the information model based on IEC 61850-7-420. However, for medium and small-capacity DER in low-voltage distribution networks, due to their scattered locations, large quantities, and poor communication conditions, it is difficult to achieve the aggregation management of DER. IEC 61850-7-420 can solve the data representation of individual DER, but it has not yet addressed the aggregation management problem of DER under the distribution transformer area. Therefore, cluster control can be adopted to dynamically divide DER equipment, but currently, no relevant information model for cluster control has been established. To ensure the security of data transmission for DER devices, it is necessary to establish a security control logical node. However, the current logical node for communication security control does not meet the data transmission security requirements.

3.2. Logical Nodes Required for Communications Security Control

As the number of DER devices connecting to the distribution network increases, their impact on the power system also grows. If the communication network is tampered with and data is falsified, it can lead to the loss of device function or even trigger large-scale power outages, posing a threat to the safety of people and property. Therefore, it is critical to secure access to DER data (reading, writing, and controlling) to ensure the security of the network.

In order to ensure the security of device communication, a new communication security control logical node can be created. This will allow both parties involved in the communication to specify certain security measures to protect DER data. Consequently, the functions of the pull model and push model of IEC 62351-8 role-based access control (RBAC) can be decomposed to form logical nodes corresponding to DER communication security. Taking insight from the GSAL logical node of general security application, the extended security protection logical node has been constructed in Table

1. The extended General Transport Layer Security (GTLS) logical node provides TLS functions such as signature verification, encryption, and decryption. The extended General Authentication and Authorisation Security (GAAS) provides authentication for accessing roles. The extended General Permission Identification Security (GPIS) identifies the operations of roles and authenticates them. Finally, General Actor Control Ssecurity (GACS) roles are authenticated based on authentication and can be based on the

results of the authentication to execute read, write and other operations along with related functions.

Regarding the GACS security protection logical node in the role of read and write permissions for IdAlwd data objects, refer to Fig. 2 where the Standard Commands for Programmable Instruments (SCPI) does not contain TVTR read access. Therefore, it is not possible to read the information of TVTR directly, but PTOC can read the information of TVTR directly.

Table 1. Communication security control logical node

logical node	full name	attribute name	clarification
GTLS	General Transport Layer Security	OpcntRs	Resettable operation counter
		TlsStr	Enabling the TLS service
		PkiStr	Enable Signature Verification Service
		SenStr	Enable encryption and decryption services
		SigSuc	Verify Success
		SigFail	validation failure
GAAS	General Authentication and authorization security	OpcntRs	Resettable operation counter
		FailNum	Number of validation failures
		AuthNum	Number of authentications
		AuthFail	Authentication failure
		AuthSuc	Authentication successful
		AuthStr	current status
		AuthLoc	Number of failed validation lockouts
		AuthTime	Latch reset time
GSID	General Permission identification security	OpcntRs	Resettable operation counter
		AucSt	Are permissions and identities mapped
		AucAlwd	authority identification
GACS	General actor control security	OpcntRs	Resettable operation counter
		ErrNum	Number of ultra vires operations
		IdAlwd	Read and write permissions for roles
		SvcVoli	ultra vires operation
		AcsFail	Access Control Failure Alarm
		IdStr	current status
		NumLoc	Number of lockouts

3.3. Information Modelling for DER Cluster Control

The station area uses cluster control to perform dynamic division of DER clusters. However, DER devices with different owners have difficulty sharing information due to

the use of private communication technology. Consequently, the station area cannot accurately control DER devices and needs to establish an information model to invoke DER devices effectively.

The generic model of DER device established based on the IEC 61850-7-420 Ed2.0 standard primarily comprised four parts: DER resource, electrical connection points, operations,

and management functions. The DER device can either be an aggregated resource of the station area or represent a single resource within the station area. It is used to describe the data, settings, and status related to electrical resources. The electrical connection points include related status, measurement, and configuration information which defines the Point of Connection (POC) of the DER as well as related measurements. The operations unit can handle the operational requirements of the DER device. The management functions involve using multiple DER resources within the station area as inputs and determining the outputs based on the priority, capabilities, algorithms, and other factors.

As exhibited in Fig. 3, the DER cluster region 1 includes three main components - distributed generation, storage, and controllable load. The entire DER cluster region 1 is considered a single logical device, and the three logical nodes represent it: DLOD (load), DSTO (storage), and DGEN (distributed generation). To specify a particular DER device, one can choose a specific logical node in Fig. 2. The DGEN, DSTO, and DLOD logical nodes account for cases where the cluster area consists of only one DER unit or combination of DER resources. They also referenced the attributes of the DER units or resources using specific ORG types (e.g., InclDer, EqDer, FctRef, OutEcpRef) to reflect the entire attributes of the cluster region in the model.

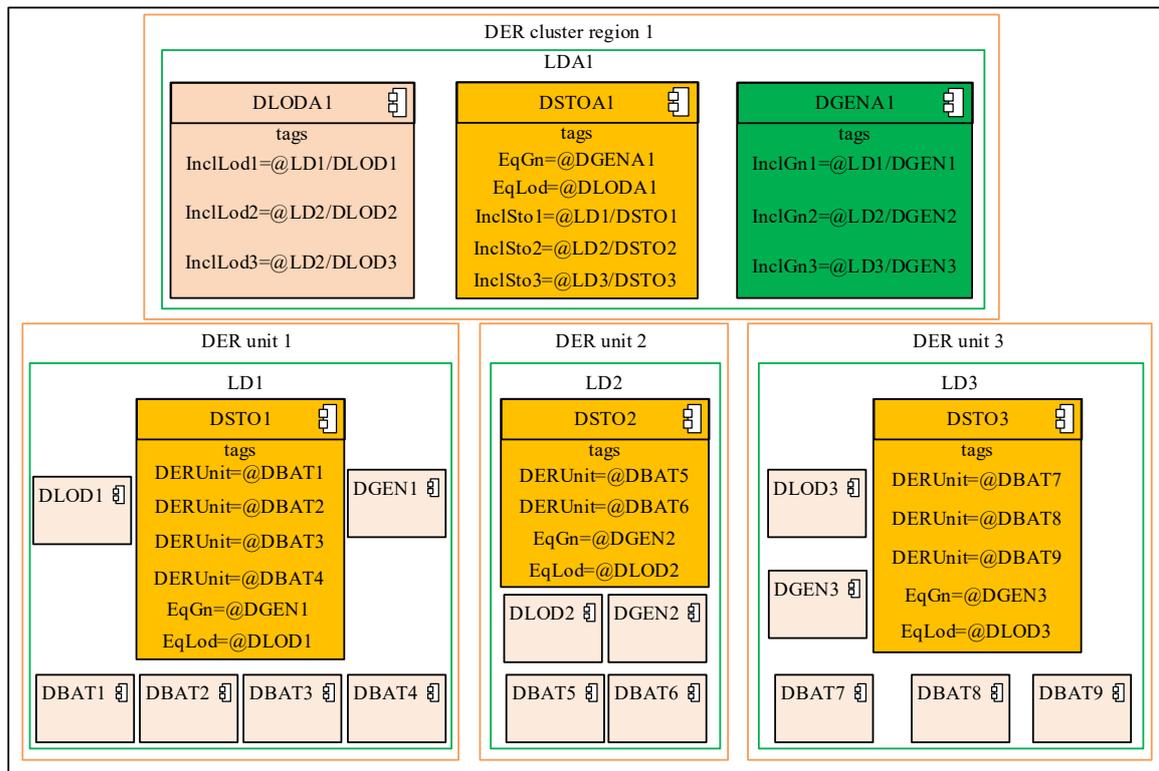


Figure 3. Information model for DER cluster region 1

As shown in Fig. 3, DER cluster area 1 is modelled as logical device LDA1, which serves as the upper-level unit of the combined resource and is generated by the aggregation of three DER units modelled as logical devices LD1, LD2 and LD3. To realise the effective management of DER by the station area, it distinguishes whether the DER device can participate in scheduling by adding the data objects of active and reactive power. By establishing an information model for the DER cluster control, it is possible to demonstrate unified management of the DER device with small capacity, multiple types, and large numbers, leading to wider distribution. Overall, the DER cluster area provides freedom to the coordinated capability of each DER to meet the load demand through scheduling and management of each DER device.

3.4. Information Modelling of Virtual Power Plant Cluster Areas

When the station area control area is a combined resource, the information carried by the common interfaces must be calculated by aggregating the functional and common interfaces of each resource in the combined resource. This can be executed by using the Data Mining-based Data Replication (DMDR) strategy to describe the aggregated resource, as illustrated in Fig. 4. The DPMCA1, as the management system of the station area1, evaluates the underlying DER data as inputs, and controls the DER resources by modifying the settings, requests, or commands to satisfy the human-set or higher-level management module's specified objectives.

Similarly, DPMCA1 sends the values of active and reactive power for the scheduling requests to the underlying DPMC1 through the operation function of DWGC. The combined resources of generation and storage of DER unit 1 are

described as DMDR1, and the underlying DPMC3 and DPMC4 receive requests from the upper layer DPMC1, or other requests, through priority settings to control the respective resource outputs.

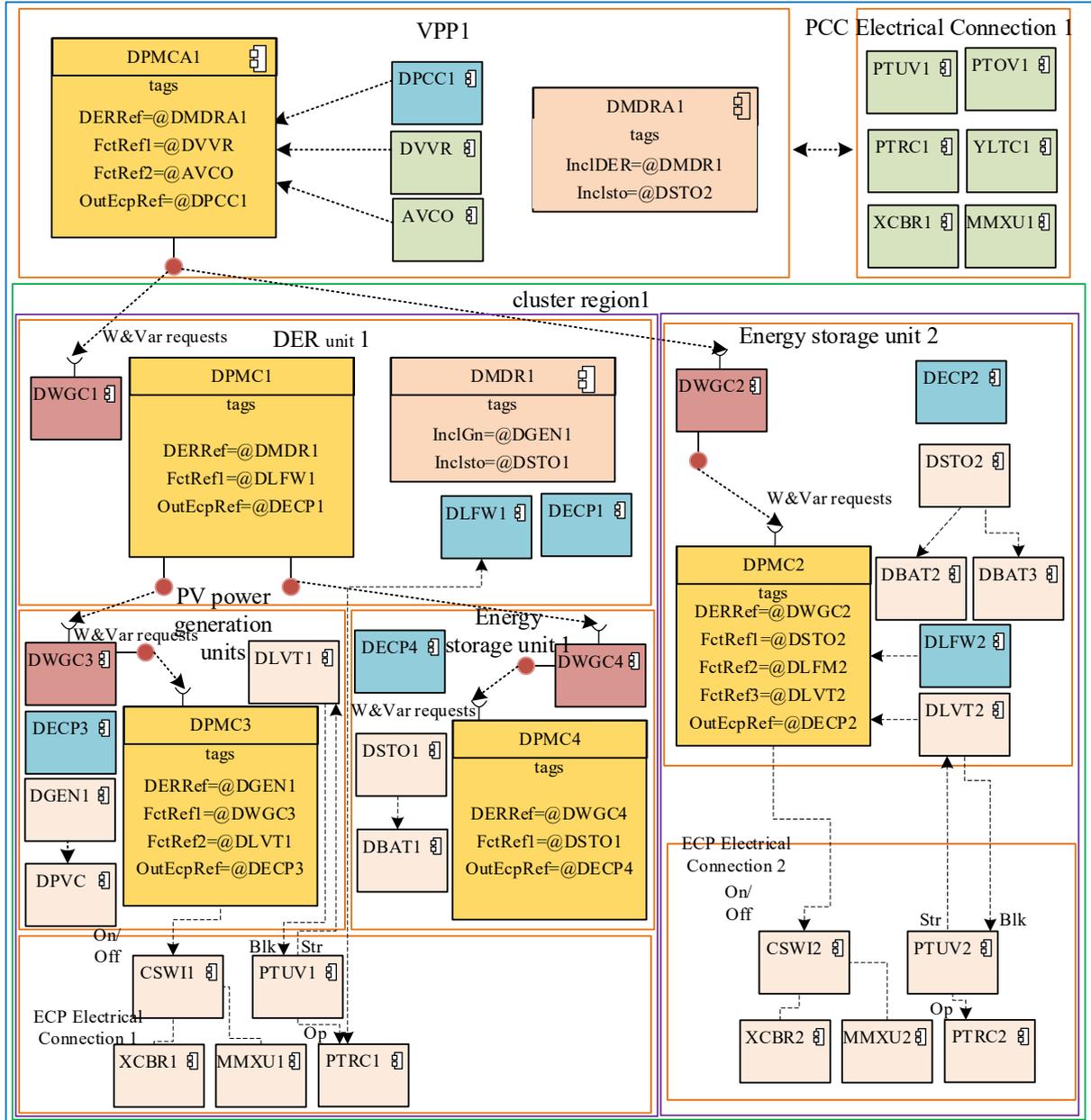


Figure 4. Information model for the station area

The station area is responsible for managing the lower cluster area 1 containing a DER unit and a storage unit. The DER unit is connected into the distribution network through a POC using DECP to describe the electrical connection point. The DPMC management function invokes the DER resource

by setting a set value between it and the DER resource to satisfy the active power request of the load power. Due to the different priorities of the loads, the representation of the ModPrio attribute assigning priority values is used for weighting to satisfy the setting of the priority of the energy request.

4. Model Transformation Process

The station area encompasses two main aspects of information interaction. The first involves the information exchange between the station area and the master station, based on common information model (CIM). The second aspect is the information flow between the station area and the underlying device. The third aspect is the information exchange between station areas. For the station area with cluster control, coordinating control and management is necessary based on the underlying DER data. The monitoring terminal converts the data transmitted by DER of inverter interface using Modbus protocol into IEC 61850 data objects, which standardises DER data at the source end. Other industrial field protocols can also refer to this method for data transformation. Using cluster control, the station area dynamically divides DER clusters based on the uploaded data, and the model established based on the IEC 61850 standard is adopted among the station areas to facilitate data sharing and management. The station area adopts the model based on the IEC 61850 standard to facilitate data sharing and information interaction, and to realise the management of DER device.

To achieve the information interaction between the station area and the master station, the station area needs to convert the IEC 61850 model to the CIM model. The specific transformation method can refer to the standard IEC TS 62361-102, and the prior study has already proposed and analysed the transformation scheme from the perspective of the transmitted data object for the CIM and IEC 61850 models [15]. The specific transformation process between the bottom device data uploaded to the master station is portrayed in Fig. 5.

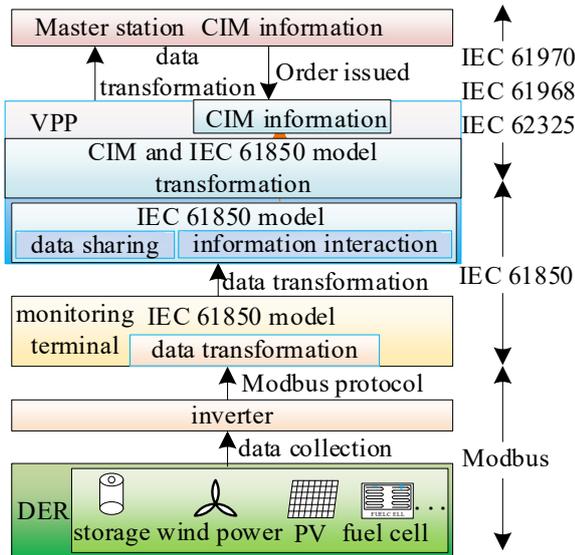


Figure 5. Transformation process of model

5. Transformation of Inverter Data to IEC 61850

A unified communication information model is crucial for ensuring control of DER clusters. The communication information model for DER devices can be established based on the IEC 61850 standard. Currently, DERs mainly use inverters to access the distribution network, and the DER often utilises the Modbus protocol to transmit data to the DER monitoring terminal [16]. Data from inverters made by different manufacturers and models is organised in a point table format, with varying information content and address offsets. This diversity creates a significant workload for engineering installation, debugging, and maintenance, thereby making it unsuitable for the data fusion application.

The Modbus protocol defines a communication data unit (PDU) that includes an address field, a function code, data, and an error check [17,18]. To ensure unique referencing of data, the IEC 61850 standard uses a unique identifier to reference data in a hierarchical information model, using logical device, logical node, data object, and data attribute as the data reference path. The Modbus device data is stored in registers with unique parameter addresses, so the Modbus parameter addresses can be utilised to map the address at the data level to correspond with the data reference paths in IEC 61850.

The inverter device employs the Modbus protocol to transmit data from DER devices made by different manufacturers. This data transmission can be categorised into two main types. The first type involves sending collected data, which mainly contains distributed power generation or storage data of DER device such as voltage and current, and external environmental data such as temperature and humidity from the location of the DER. The second type involves transmitting control commands from the monitoring terminal to the DER. A detailed explanation of the data transformation method can be found in Fig. 6. The first stage comprises establishing the correlation table between the Modbus protocol data and IEC 61850 data objects through differentiation analysis. Based on the GB/T 33593-2017 standard, through the 380V voltage level grid-connected DER, DER can only send current, voltage, and power generation information to the station area during a normal operation. When the conditions allow, it becomes pertinent to reserve the ability to upload the switching state of the grid-connected point. Therefore, the data (data name, offset address, data type, scale factor, and unit) related to the power system can be used for DER devices of different manufacturers and the logical nodes of IEC 61850. Data objects and relevant data attributes to establish a data association table have also been displayed in Figure 6. Based on the established data association table, the XML language is used to configure the association relationship, which then generates the corresponding XSLT data mapping transformation file. Thereafter, the inverter transmits the DER device data to the monitoring terminal using the Modbus protocol. The dynamic transformation of the data source can be demonstrated by configuring the rule file in the monitoring terminal.

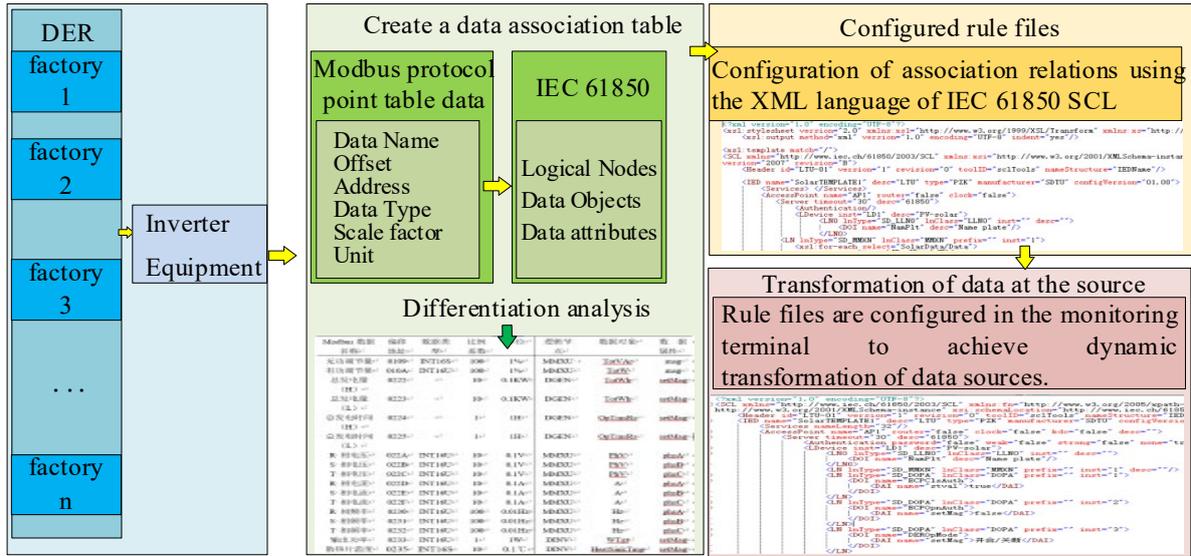


Figure 6. Modbus data dynamic mapping process

The monitoring terminal can directly map the data transmitted by the Modbus protocol to the IEC 61850 data, as evident from Fig. 7(a). When the Modbus communication client process and the IEC 61850 data processing process are independent of each other, as shown in Fig. 7(b), the coupling

can be reduced by writing the Modbus data into an XML file. The XSLT transformation file converts the XML file data generated by the Modbus process into the logical node objects of IEC 61850. Standardising the data at the source side reduces the maintenance effort and facilitates effective control of DER by the station area.

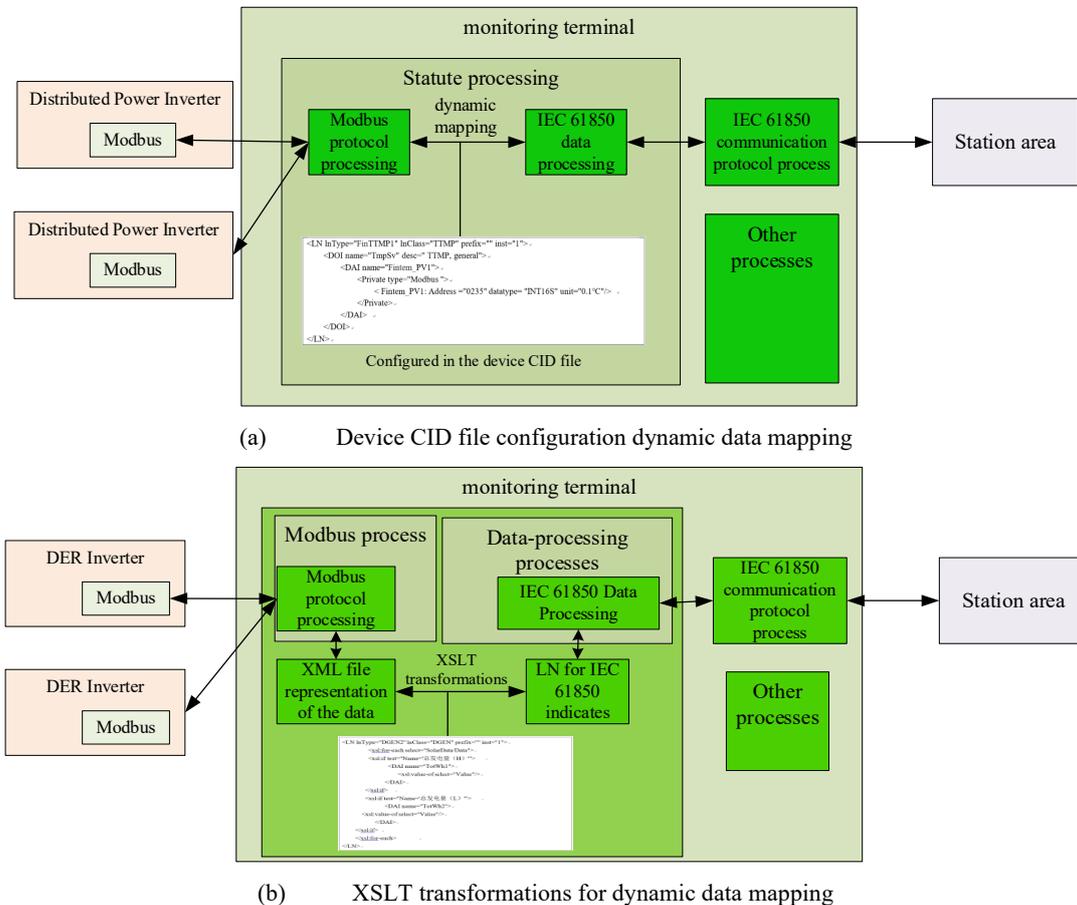


Figure 7. Modbus data mapping method

6. Conclusion

To address the monitoring communication issues of DER, it is necessary to standardize the models of DER devices from different manufacturers and types. Due to the large number of DER devices connected and the significant differences in communication conditions in low-voltage distribution networks, it is difficult to achieve aggregated management. This paper establishes a general information model for distribution areas that supports dynamic division of DER devices based on the IEC 61850 standard, and realizes the aggregated management of DER devices within distribution areas. The contributions of this paper are as follows:

- 1) Implement dynamic clustering division of DER devices through cluster control. This paper establishes a general information model for cluster control based on the IEC 61850 standard. The distribution transformer terminal or integrated terminal of the distribution area realizes the collection of distributed power information and the decomposition of power scheduling within the distribution area.
- 2) Establish a new communication security control logical node to make both communication parties clearly understand specific security measures, so as to achieve secure management of DER devices in the distribution area
- 3) Utilize differentiated analysis to achieve data conversion between IEC 61850 and Modbus, and implement the conversion of DER data at the data source end of the inverter, thereby reducing the workload of manual maintenance.

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