The Theoretical Research on Modelling Method for the Grid Information Model of Substation

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Abstract—On the basis of analyzing the logical structure of grid information model (GIM), a modeling method of GIM using the set theory is proposed for the substations. By studying the coupling principle of power flow and information flow, the GIM was defined as the interconnection between the set of physical objects and the set of information objects. Then, the GIM was decomposed into the power subsystem and load subsystem, which were described from the aspects of input, output, state changes and network structure. Under the constraints of the existing power grid network, subsystems were connected in accordance with rules from different perspectives to form the complete GIM system.

1. Introduction

The smart grid is highly integrated with advanced measurement systems, intelligent electronic equipment and flexible control technologies, etc., through the mutual coupling of the primary system and the secondary system to form a typical cyber physical system (CPS). Real-time interaction provides a new solution for the safe operation of the power grid. By improving the ability to perceive, share, and large-scale distributed real-time computing of power grid information, the power system can be equipped with collaborative optimization control and adaptive functions in the future, which will greatly improve grid operation economics, reliability and security. However, in the situation where power systems increasingly rely on information feedback and information decision-making, any abnormal information flow may cause a chain reaction in the physical world [1]. Analyzing the deep relationship between information flow and physical flow and studying the integration mechanism of information system and physical system has become the most urgent task in the field of electric power and even the whole industrial control field. It has important theoretical value for ensuring the safe and stable operation of the power system and realistic meaning.

At present, key technologies in the field of grid information model (GIM) for substation include information-physical coupling characteristics analysis, system control, and formal verification. Among
them, a fusion model of information systems and physical systems is established to characterize power. The complex information-physical interaction in the system is the basic scientific problem of GIM and the basis of other related applied research [2]. Combined the input (output) signals of the generator and the internal (external) part of the load, and established considerations. Dynamic model of generator and load integrated with information and physics, and the CPS model of the distribution network was constructed according to the constraints of the power system. Reference [3] proposed a modeling method for the information network and power network based on the power system and graph theory methods. The impact of network attacks on physical systems is analyzed on the basis of improved IEEE 13-node systems. References [4] established a steady-state and dynamic analysis model based on the discussion of the power CPS fusion architecture, which provided a reliable grid Thinking on security and security analysis [5]. Considering the spatio-temporal heterogeneity of information and physical systems in the network, a new method based on the integration of information physics is proposed. A joint energy internet model [6] from the perspective of information and physical system cascading failures, an information-physical fusion power system cascading failure model that considers physical layer power flow analysis and information layer delay is established. References [7] applied complex network theory to the modeling of power CPS, and analyzed the application of the model using an actual power failure event as an example [8]. Based on a CPS modeling framework of multiple heterogeneous entities, a CPS system is proposed. The collaborative modeling method of structure and dynamic behavior, the complex diversity of power system equipment and the information flow, as well as the complex correlation between energy flows have brought great challenges to GIM system. At present, the research work in the entire field has not yet formed a scale. The research results are largely aimed at solving specific practical problems, and is unable to fully characterize the essential characteristics of the fusion of information and physical systems, lacking a relatively complete framework and research methods.

This paper focuses on the coupling characteristics of information flow and energy flow in power systems, uses set theory to describe the information-physical interaction characteristics of GIM system and their subsystems, and provides a unified mathematical description form for information and physical systems with different structures. Based on the analysis of the logical and functional connection relationship between information objects and physical objects, the networking rules of “vertical pyramid collection and horizontal logical interconnection” are proposed to interconnect subsystems to form a complete GIM architecture, which can be used for further simulation analysis and application research of GIM, and provide theoretical support as well.

2. **Analysis of power network information-physical coupling characteristics**

The typical characteristic of CPS is the deep integration of 3C (computation, communication, control), and it adapts to changes in the physical environment autonomously through sensing and control functions. The CPS characteristics of smart grids are reflected in the close coupling and strong correlation between the primary system and the secondary system: When the power system is running, energy flows through the power plant, substation, transmission line to the load; the secondary system collects the state data of the system through the information equipment, and realizes control, protection and monitoring of the physical world through post-processing and analysis. From the perspective of CPS, the information-physical coupling architecture of GIM is constructed as follows:

1) **Physical side-information side**: The information system obtains various types of numerical information of the primary system of the power grid through sensors, such as topological structure data, remote measurements and remote signals, and transmits it to the control center of the secondary system through the Internet and wireless communication network.

2) **Information side-physical side**: The control center generates remote adjustment commands based on the multi-stage processed state data. The controller acts on the physical system in the form of changing the operating status or operating parameters of the equipment, and adjusts the energy flow distribution of the power grid. GIM is a huge non-linear system made up of many subsystems connected and interacting with each other. In order to analyze the relationship between the signal and
energy in the system, the basic unit with the information-physical coupling characteristics in GIM is defined as the GIM subsystem. In addition to the physical objects used to implement specific functions in the GIM subsystem, at least a set of corresponding sensors and controller are applied to realize data upload, command release and interactive tasks with other subsystems.

3. Grid information model description

Based on the idea of system decomposition, this paper adopts the method of "model + rule" to build a GIM system. From a macro perspective, the entire GIM system can be described using the mathematical language of set theory; from a micro perspective, the basic characteristics of the GIM subsystem can be described from three aspects: network structure, behavior level, and state structure level. At the micro and macro levels, the interconnection rules of subsystems can be proposed to realize the logical and functional connection of GIM subsystems, thereby building a complete GIM system architecture.

3.1. Mathematical models for BIM subsystems

A system is a unity formed by the interconnection and interaction of several parts. The general system form based on set theory can be described as:

\[ S \subseteq \{V_i : i \in I\} \]  (1)

Set theory provides an effective solution for the simultaneous description of discrete structures and continuous systems [9]. In this paper, GIM is described in the manner shown in (1). By merging many objects in the system into several sets according to their nature and status during interaction, GIM is defined as the relationship between finite sets:

\[ S \subseteq V_1 \times V_2 \times V_3 \times V_4 \]  (2)

where \( V_1, V_2, V_3, \) and \( V_4 \) are control center, sensor collection, controller collection, and physical object collection, respectively. In the GIM described in (2), \( V_1, V_2, V_3, \) and \( V_4 \) reflects the interrelationships between the control center, sensors, controllers and physical objects, and the subsystem of GIM can be given by:

\[ (x, y, z, r) \in S \]  (3)

where \( x \in V_1, y \in V_2, z \in V_3, \) and \( r \in V_4 \).

In all components of GIM, power and load have obvious real-time changes and interaction characteristics. According to the logic structure of GIM subsystem, the power source subsystem and load subsystem can be described as:

\[ P = (x_1, y_1, z_1, r_1) \]  (4)
\[ L = (x_2, y_2, z_2, r_2) \]  (5)

Fig. 1 and Fig. 2 show the subsystem network structure. The solid lines with arrows indicate the physical connection and energy flow relationship between the objects, and the dashed lines indicate the signal flow between the elements. The network structure diagram clearly expresses the connection between information objects and physical objects in the GIM subsystem on the edge of the diagram, providing a unified and clear expression form for the complex interrelationships in the system.

![Figure 1. Structure of power source subsystem.](image-url)
Behavior level describes the relationship between input and output of the system based on the signal transmission between the information and physical objects in the power system and the way energy flows. The quaternion $H$ can be used to describe the behavior level of the subsystem:

$$H = \{(x_i, y_i); (x_i, z_i), (r_i, r_j), (z_i, z_j)\} \quad (6)$$

where $(x_i, y_i)$ is the sensor $y_i$ to output the physical information of the device to the control center $x_i$; $(x_i, z_i)$ is the controller $z_i$ accepts the control command issued by the control center $x_i$; $(r_i, r_j)$ is the current physical object $r_i$ and other physical objects $r_j$, the power is output to other parts of the system and the load receives power; $(z_i, z_j)$ is the information interaction between the controller $z_i$ in the subsystem and other local controllers $z_j$ and realizes the intelligent control of the power grid through cooperative work.

The state structure level describes the physical state of the nodes in the system. The state information of each physical node in the power system is jointly determined by the power system model or the function of the network elements that reflect the physical system interaction. In continuous time, the state of the nodes continuously evolves according to deterministic rules, and it can be given by:

$$\dot{s} = f(s, p) \quad (7)$$

where $\dot{s}$ is the time derivative of $s$, describing the change of system status over time; $p = \{p_1, p_2, \ldots, p_m\}$ is the set of factors that affect the state change, which varies with the type of physical node, and normally includes control signals and switch status. In addition, meteorological factors and electricity prices are often used as input factors that affect the status of physical nodes.

Taking the commonly used synchronous generator as an example, under the assumptions of [10], the physical state of the GIM power subsystem at a certain moment is described by the rotor voltage equation and the stator voltage equation, as shown in the following formula.

$$\begin{align*}
T_{d0} \frac{d^2 e_d}{dt^2} &= e_q'' - e_q' - (x_d - x_d^*) e_d \\
T_{d0} \frac{de_d}{dt} &= E_f - e_q' - (x_d - x_d^*) (e_q'' - e_q') \\
T_{q0} \frac{de_q}{dt} &= e_d'' - e_d' - (x_q - x_q^*) e_q \\
T_{q0} \frac{d^2 e_q}{dt^2} &= -e_d' - (x_q - x_q^*) (e_d'' - e_d') \\
\end{align*} \quad (8)$$

$$\begin{align*}
u_d &= e_d' + x_d q - r_d i_d \\
u_q &= e_q' + x_q q - r_q i_q \\
u_0 &= r_d i_d \\
\end{align*} \quad (9)$$

As an energy consumer, load changes in real time due to various factors such as season and weather. Compared with considering load as a constant [11], a dynamic model that captures the time-varying
characteristics of load to characterize the state of the load subsystem is applied. According to historical
data, an auto regressive (AR) model is used to predict the statistical law of the load change process and
predict the load value. Let the current value of the load sequence \( L_i(t) \) be weighted by the finite term of
its own past value and an interference \( a(t) \) (assume white noise), then the load state can be given by:

\[
L_i(t) = \sum_{j=1}^{q} \phi_j L_i(t-j) + a(t) \quad (10)
\]

The order of the model \( q \) and the coefficients \( \phi_i (i = 1, 2, ..., q) \) are determined by past values through
model identification and parameter estimation.

3.2. GIM subsystem interconnection
In order to couple many subsystems with auxiliary equipment to form a complete GIM architecture, this
paper proposes a "vertical pyramid collection, horizontal logical interconnection" subsystem
interconnection rule based on the electrical constraints of the physical system and the logical
connection relationship of the information system. The overall network structure of GIM is set up in a
way that is coupled with logic step by step, as shown in Fig. 3.

The specific description of the interconnection rules is as follows:

1) Horizontal angle: Logical nodes \( x, y, z \) and functional nodes \( r \) implement data collection and
monitoring control through signal transmission; the logical nodes are associated and combined
according to the characteristics and functions completed according to the needs; the functional nodes
are electrically connected.

2) Longitudinal angle: According to the role and position of different GIM subsystems in the entire
power system, regional interconnection is further realized; other auxiliary equipment is integrated into
the regional GIM interconnection structure to build a complete GIM network architecture.

Traditional power systems use electrical wiring diagrams or geographic wiring diagrams to describe
the electrical constraints of physical systems. This article does not change the physical system wiring,
integrates the control center, sensors, and controllers, and realizes the interconnection of all devices
according to the rules of subsystem interconnection, forming a structure diagram of GIM network that
can simultaneously reflect information flow, energy flow, and information-physical coupling.

4. Conclusions
This paper analyzes the interaction between power grid information flow and energy flow, proposes a
GIM system modeling method based on set theory, uses set theory to describe the entire GIM system,
and proposes a "vertical pyramid collection, horizontal logical interconnection" networking rules to
build a complete GIM system network structure. The proposed model provides a unified mathematical
expression for heterogeneous information and physical systems. It not only describes the characteristics of information physical correlation within CPS, but also facilitates the analysis of the nature relationship between the subsystem and the entire system. The interconnection rules provide strong technical support for the research on joint simulation, calculation and application analysis of GIM system. The model proposed in this paper can be used to analyze the impact of security problems (attacks and potential disturbances) in the information network on the operation of the physical system, thereby facilitating the security evaluation and joint analysis of CPS.

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