Research on Modeling and Simulation of Smart Substation Cyber-Physical System Considering Coupling Analysis

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Abstract. With the rapid development of Internet of Things and communication technologies, substations are becoming more intelligent, which brings opportunities for cyber attacks, threatens the safety of substations, and the high coupling of equipment in substations increases the threat. This paper analyzes and studies the information-physical characteristics and equipment coupling problems of smart substations, constructs a smart substation CPS model based on the balance equation of state quantity, and designs a line fault simulation example to verify the stability of the model.

1. Introduction
Cyber-Physical System (CPS) is a system construction concept that organically integrates information networks and physical networks, and can realize real-time control of large-scale systems. The concept of CPS was first proposed by scholars studying embedded systems, and has received extensive attention in various fields in recent years. In China, the National Natural Science Foundation of China and the "973" and "863" programs of the Ministry of Science and Technology have all listed CPS as a key funding area. In recent years, CPS has been deeply applied in the power industry. In smart substations, the access of various embedded devices, the communication between devices, and the security of the system all require the key technologies of CPS.

There have been many studies on CPS in smart substations at home and abroad. According to the definition of cyber attacks in the field of power CPS, literature[1] summarizes and analyzes typical scenarios of cyber attacks from the four links of power generation, transmission, distribution, and power consumption;[2,3] analyzed the driving force of CPS modeling and evaluation in the power system, and then deeply studied the key technologies of CPS modeling; literature[4] simulated the network attack suffered by the substation and simulated the automatic voltage of the substation Control; Literature[5] models the power CPS based on the Petri net, uses a variety of attack methods to simulate attacks, and tests the stability of the power CPS model.

To sum up, the existing technical methods basically perform CPS modeling of smart...
substations from the perspective of safety protection, and do not fully consider the information-physical fusion characteristics of substations and the coupling of equipment, so the constructed model has defects. Based on actual requirements, this paper analyzes the coupling characteristics of energy flow and information flow in smart substations, and proposes a CPS modeling method for smart substations based on the state balance equation, which provides a model reference for building smart substation CPS modeling.

2. CPS Modeling of Smart Substation

A major feature of smart substation CPS is the strong coupling of power energy flow and information flow. The close coupling makes the risk of smart substation operation and management process increase sharply, and the failure of physical system and information system will cause sequential or cascading failures[7] These faults spread between the information network and the physical network, eventually leading to the collapse of the entire substation, and even threatening the safe operation of all power industries.

2.1. Coupling characteristics of energy flow and information flow

The energy flow form during the operation of the substation is shown in Figure 1. The energy flow of the physical system drives the work of the primary equipment, the measurement data during work is transmitted to the information system, and the information flow of the information system drives the work of the secondary equipment to realize the secondary equipment. Control of the physical system. In this way, the exchange and transmission of energy flow is manifested as a multi-form information flow [8], and the exchange and transmission of information flow reacts to the energy flow to make it continue to be transmitted, thus forming a closed loop.

2.2. CPS Modeling and Analysis of Smart Substation

As shown in Figure 2, the intelligent substation CPS can be abstracted into three layers: information system, physical system, and communication network. The logical nodes on each layer are mapped. This reflects the high coupling of the intelligent substation CPS and the data of the physical system. It interacts with the information system through the communication network, and the information system responds based on these data and sends instructions to the physical system to detect and control the physical state of the device.
2.3. Balance equation construction

The system topology determines the complexity of CPS modeling in smart substations. The substation information system contains a large number of information components and complex communication protocols. Direct modeling is not only cumbersome to construct, but also has low computational efficiency of the model [10]. Therefore, consider the use of a directed weighted graph $G = (V, E)$ for modeling. The nodes, edges, and weights in the graph can store a large amount of information. In the model, the node $V$ is used to represent the state quantities in the physical system and the information system. Edge $E$ represents information processing, transmission, and other interactive links, where the first and last nodes are input and output data respectively. For any state quantity $v \in V$, $M_v$ can be used to represent its information interaction capability, $D_v$ represents the delay in information interaction. For any communication line $(p, q) \in E$, use $B_{p,q}$ to represent the bandwidth of the line, and $D_{p,q}$ indicates the delay in the line.

Assuming that there are $N$ groups of state variables in the substation system, use $Z_{p,q}(i)$ to represent the information flow of the $i$-th group of state variables into the system. The node information flow balance equation for a certain group of state variables is:

$$Z_{p,c} + \sum_{k=1}^{n_c} Z_{c,k}(k) = Z_{c,q} + \sum_{k=1}^{n_q} Z_{c,k}(k)$$

In formula 1, node $c$ is the intermediate node between node $p$ and node $q$; $n_c$ and $n_q$ represent the number of states at node $c$ and the number of states at node $q$; $Z_{c,k}(k)$ and $Z'_{c,k}(k)$ represent the number of states at node $c$ K groups of state quantities are injected into the information flow of the system and the $k$-th group of state quantities terminated at node $c$.

Among them, the maximum information flow of nodes and the maximum information flow of lines must meet the following constraints:
As shown in Equation 2, the information flow of any node cannot exceed the upper limit of its information interaction capability, and the information flow of any line should not exceed its bandwidth.

The state quantity of the information flow in the information system is discrete and can be solved by accumulation according to Equation 1. However, the state quantity of the energy flow in the physical system is continuous. Although Equation 1 is also applicable, the calculation is more cumbersome. According to the nature of calculus, continuous functions are integrable, so the energy flow state quantity equation is integrated and solved in a certain time interval to calculate the energy flow rate in this time period.

Let \( t_j \) be the moment when the energy flow reaches the node \( j \), \( F_{p,q}(i) \) represents the state quantity equation of the energy flow between the \( j \)-group of nodes \( p \) and node \( q \), then the node energy flow balance equation of a certain group of state quantities As shown in Equation 3.

\[
Z_{p,c} + \int_{t_p}^{t_c} F_{p,c}(i)dt = Z_{c,q} + \int_{t_c}^{t_q} F_{c,q}(i)dt
\]

Among them, the maximum information flow of the node needs to satisfy formula 4, and the maximum information flow of the line cannot exceed the bandwidth of the line.

\[
0 \leq Z_{p,c} + \int_{t_p}^{t_c} F_{p,c}(i)dt \leq M_c
\]

Through analysis, it can be seen that the value of the maximum information flow of the node obtained by the integral is an approximate value. The shorter the line between the nodes, the closer the value is to the true value.

3. Simulation example of intelligent substation

The calculation example in this paper is based on the process-level communication network of a 220 kV smart substation. In order to reflect the most serious competition for resources between the SV status and the GOOSE status, the shared network transmission method is adopted. An information interaction model under the shared network transmission scenario is constructed, and the transmission delay is analyzed through the action response of the relay protection under the line fault. The network topology is shown in Figure 3.
Taking 220kV smart substation as the simulation object, statistical analysis is carried out on the transmission delay of SV state quantity and GOOSE state quantity of different data flows. After several tests, the average value is taken to retain two decimal places. The results are shown in Figure 4(a), Figure 4(b) as shown.

![Communication topology of 220 kV smart substation](image)

**Figure 3.** Communication topology of 220 kV smart substation

**Figure 4(a).** Comparison of packet traffic

**Figure 4(b).** Comparison of packet delay

**Table 1.** Simulation results of 220 kV intelligent substation line fault.

| Data flow                                    | Delay(SV) | Delay(GOOSE) |
|----------------------------------------------|-----------|--------------|
| Line Merging Unit -> Line Protection Device  | 56.38     | 77.35        |
| Line merging unit->Bus protection device     | 202.66    | 33.13        |
| M-T Merging Unit -> M-T Protection Device   | 51.27     | 61.51        |
| M-T Merging Unit -> Bus Protection Device   | 253.21    | 72.53        |
| Bus merging unit->Bus protection device      | 84.42     | 78.64        |
| Bus Protection Device->Line Intelligent Components | /         | 22.39        |
| Bus protection device -> M-T Intelligent components | /         | 84.72        |

It can be seen from Table 1 that when the line fails, the transmission delay increase of the SV state quantity is unstable, and the transmission delay of the GOOSE state quantity is
basically stable within 90 μs, which verifies that the jump priority of the GOOSE state quantity is higher than the SV state quantity. In the case of a shared network, if the same transmission bandwidth is occupied, the queuing delay of the SV state quantity in the switch is longer.

4. Conclusion

Nowadays, smart substations are becoming more intelligent and larger in scale. Therefore, the CPS model of smart substations is becoming more and more complex, and the coupling of equipment is becoming tighter. The description of the cyber-physical integration characteristics of smart substations becomes difficult. Through the coupling analysis of information flow and energy flow, the real-time control and safety protection of smart substations can be improved, which is essential to the safe and stable operation of smart substations.

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