Physical fusion method of power grid information based on power flow calculation

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Abstract. From the perspective of information physical fusion, considering the relationship among power network, communication network and information network, the power information system model considering the coupling relationship between power network and information network is established. Firstly, a three-layer model framework of power information physical system considering communication transmission factors is proposed. The whole modeling process is divided into three parts: power network, information network and communication channel, which are effectively associated with power network and information network; Then, a mathematical model of power information physical system integration considering multi-layer coupling is proposed; Finally, the power information physical model based on ieee9 bus is used to verify the effectiveness of the proposed modeling method based on power flow calculation and topology analysis.

1. Introduction

With the gradual deepening of smart grid construction and the rapid development of information and communication technology, a large number of sensors, computing and control equipment are connected to the power grid, which makes the interaction mechanism between power network and information network increasingly complex. The traditional single power network has developed into a power grid information physical system (power grid CPS) with various typical characteristics of CPS. The information physical system (CPS) integrates computing system, communication network and physical network through 3C technology to form a multidimensional heterogeneous complex system with real-time perception, dynamic control and information service fusion[1-2].

According to the operation characteristics of power CPS, scholars at home and abroad have carried out a lot of research on its modeling methods from different angles. It mainly includes the following three aspects: (1) Modeling method based on complex network theory. For example, in reference[3], based on the theory of interdependent network theory, established the power information physical interdependence network model. In reference[4], power network and information network are regarded as two dependent networks, and the influence of different coupling modes between them on the structural vulnerability of power information physical system is demonstrated; In reference[5], based on complex network theory, the vulnerability of 500kV power information interdependent network in Central China is analyzed, and a border protection strategy is proposed. (2) Modeling method based on power flow model. For example, reference[6] established a power CPS coupling model based on AC power flow; reference[7] established a narrow sense energy Internet model based on information
physical coupling considering the electric gas heat mixed power flow. (3) Research on joint simulation technology based on power grid information physical system. For example, reference[8] introduces common power system and information network simulation software and divides CPS joint simulation method; reference[9] proposes a non real time simulation method based on state cache considering simulation scale and simulation capability.

Based on the idea of Information Physics fusion, this paper first proposes a three-layer model framework of power information physical system considering communication transmission factors. The whole modeling process is divided into three parts: power network, information network and communication channel, which effectively connects power network and information network. Then, the mathematical model of integrated integration of power information physical system considering multi-layer coupling is obtained. Finally, taking ieee9 node system as an example, the correctness of the proposed model is verified based on the power flow calculation analysis.

2. Power information physical system model framework

For the topological structure of information network, the modeling method of most literatures is single. In this paper, considering with the actual situation of power grid and considering the hierarchical structure of information network, it is divided into access layer, convergence layer and core layer. The access layer node monitors and controls the power network nodes, and one-to-one coupling with the power network nodes; the convergence layer node gathers the data collected by the access layer and forwards it to the core layer; finally, the core layer carries out analysis and calculation to generate decision-making information. The interconnection mode of information network and power network is hierarchical mode, that is, the system parameters and operation data are collected by sensors installed on the primary power equipment, and then summarized to the access layer, and then transmitted to the control center from bottom to top (up channel) through the substation. The control center generates control commands according to the control algorithm and control strategy, and is transmitted from top to bottom (down channel) to the execution. The implementation of the power line operator. The flow process of data can be summarized as collection upload processing distribution execution. Therefore, a three-layer architecture of the power information physical system as shown in Figure 1 is proposed. The power information physical system is divided into perception execution layer, data transmission layer and information decision layer. The perception execution layer is the actual power network, including the power generation, transmission, transformation, distribution, use and other links; the data transmission layer is the power communication system, including the up /
down communication channels; the information decision-making layer includes all kinds of substations, master stations, workstations and other equipment, which is fully responsible for the information monitoring, state estimation, automatic control and other services of each link of the power grid.

Drawing on the idea of complex network theory modeling, this paper proposes the idea of power information physical system modeling design, as shown in Figure 2. According to the main equipment and connection relationship of the system, the information network topology diagram and the power network topology diagram are summarized respectively, and then the interconnection relationship between the nodes of the two-layer network is determined according to the corresponding relationship of communication data transmission.

3. Derivation of power CPS model

3.1. Power network modeling

Define the topology abstracted from power network \( G_p = (N_p, B_p) \), \( N_p \) and \( B_p \) are the node and branch set of the system respectively, the number of nodes is represented by \( |N_p| \), and the number of branches is represented by \( |B_p| \). According to the complex power expression of AC power network and the assumption of DC power flow model, for the system with \( |N_p| \) nodes, the DC power flow matrix expression of node injected power is as follows:

\[
P = B \theta
\]  \hspace{1cm} (1)

Where: \( P \) is the active power vector injected into the node; \( B' \) is the node admittance matrix; \( \theta \) is the node voltage phase angle vector. Let matrix \( A = [1, 1, 1, \ldots, 1] \in M_{1\times |N|} \), then the expression of branch power flow matrix \( F \in M_{|N|\times |N|} \) is as follows:

\[
F = (\theta A - A^T \theta^T) \odot B
\]  \hspace{1cm} (2)

The grid power matrix \( P^{\text{ori}} \in M_{|N|\times |N|} \) is defined as node injection power and branch switching power, which can be obtained by combining formula (1) and equation (2):

\[
P^{\text{ori}} = \text{diag}(P) + F
\]  \hspace{1cm} (3)

Equation (3) represents the power network model obtained from the DC power flow equation, where \( \text{diag}(P) \) is the diagonal element matrix of the node injected power vector \( P \). The diagonal element of \( P^{\text{ori}} \) represents the active power injected by the node, and the non diagonal element represents the active power of the branch, and satisfies the directionality of power flow.

In addition to the power flow model, the power grid topology matrix \( T \in M_{|N|\times |N|} \) is defined as shown in formula (4). The diagonal element of the matrix \( T \) is 0, and the non diagonal element \( T_{ij} \in \{0, 1\} \). If \( T_{ij} = T_{ji} = 1 \), it means that branch \( I-J \) is connected, if \( T_{ij} = T_{ji} = 0 \), it means branch \( I-J \) is disconnected.

\[
T = \begin{bmatrix}
T_{11} & 0 & \cdots & T_{1|N|} \\
T_{21} & T_{22} & \cdots & T_{2|N|} \\
\vdots & \vdots & \ddots & \vdots \\
T_{|N|1} & T_{|N|2} & \cdots & 0
\end{bmatrix}
\]  \hspace{1cm} (4)

3.2. Information network modeling

The modeling of power information network should be studied from three aspects: linkage interface, communication channel and dispatching center.
3.2.1. Communication interface modeling. Based on the power information physical modeling framework proposed above, for sensor nodes, the sensor matrix $R \in M_{|V_s| \times |V_s|}$ is defined

$$
R = \begin{bmatrix}
R_{11} & R_{12} & \cdots & R_{1|V_s|} \\
R_{21} & R_{22} & \cdots & R_{2|V_s|} \\
\vdots & \vdots & \ddots & \vdots \\
R_{|V_s|1} & R_{|V_s|2} & \cdots & R_{|V_s||V_s|}
\end{bmatrix}
$$

(5)

$$
S = \begin{bmatrix}
S_{11} & S_{12} & \cdots & S_{1|V_s|} \\
S_{21} & S_{22} & \cdots & S_{2|V_s|} \\
\vdots & \vdots & \ddots & \vdots \\
S_{|V_s|1} & S_{|V_s|2} & \cdots & S_{|V_s||V_s|}
\end{bmatrix}
$$

(6)

Where: $R_{ij} \in \{0,1\}$, the diagonal element $R_{ii} = 1$ indicates that node $i$ is equipped with sensor equipment, and $R_{ii} = 0$ indicates that node $i$ is not installed; non diagonal element $R_{ij} = 1$ indicates that branch $i$-$j$ is equipped with sensor equipment, and $R_{ij} = 0$ indicates that branch $i$-$j$ is not installed.

Similarly, for actuator class nodes, the actuator matrix $S \in M_{|V_s| \times |V_s|}$ is defined

3.2.2. Communication channel modeling. Based on the proposed model framework, $C_{up} \in M_{|V_s| \times |V_s|}$ is defined as the uplink communication channel matrix, and the matrix element $C_{up,ij} \in \{0,1\}$. The diagonal element $C_{up,ii} = 1$ indicates that there is an uplink data communication channel between the sensor installed in the power network node $i$ and the information network control center, and the transmission content is the injected power information of node $i$, and $C_{up,ii} = 0$ indicates that there is no such uplink communication channel; The off diagonal element $C_{up,ij} = 1$ indicates that there is an uplink data communication channel between the sensor installed on the branch $i$-$j$ of the power network and the information network control center, and the transmission contents include the power flow information of branch $i$-$j$ and the opening and closing state of the circuit breaker, and $C_{up,ij} = 0$ indicates that there is no such uplink communication channel.

$$
C_{up} = \begin{bmatrix}
C_{up,11} & C_{up,12} & \cdots & C_{up,|V_s|} \\
C_{up,21} & C_{up,22} & \cdots & C_{up,|V_s|} \\
\vdots & \vdots & \ddots & \vdots \\
C_{up,|V_s|1} & C_{up,|V_s|2} & \cdots & C_{up,|V_s||V_s|}
\end{bmatrix}
$$

(7)

$$
C_{down} = \begin{bmatrix}
C_{down,11} & C_{down,12} & \cdots & C_{down,|V_s|} \\
C_{down,21} & C_{down,22} & \cdots & C_{down,|V_s|} \\
\vdots & \vdots & \ddots & \vdots \\
C_{down,|V_s|1} & C_{down,|V_s|2} & \cdots & C_{down,|V_s||V_s|}
\end{bmatrix}
$$

(8)

In the same way, $C_{down} \in M_{|V_s| \times |V_s|}$ is defined as the downlink communication channel matrix, and the matrix element $C_{down,ij} \in \{0, 1\}$. The diagonal element $C_{down,ii} = 1$ indicates that there is a downlink data communication channel between the actuator installed in node $i$ of the power grid and the information network control center, and the transmission content is the power adjustment signal of node $i$. If $C_{down,ii} = 0$, the downlink communication channel does not exist. $C_{down,ij} = 1$ indicates that there is a downlink data communication channel between the actuator installed on the branch $i$-$j$ of the power network and the information network control center, and the transmission content is the circuit
breaker opening and closing command of branch i-j, if \( C_{\text{down},ij} = 0 \), the downlink communication channel does not exist.

### 3.2.3. Modeling of dispatching center

\( D_{\text{flow}}^{\text{rece}} \in M_{|V_i| \times |V_r|} \) is defined as the received power flow information receiving matrix, and \( D_{\text{topo}}^{\text{rece}} \in M_{|V_i| \times |V_r|} \) is defined as the power network topology information receiving matrix. Their expressions are as follows:

\[
D_{\text{flow}}^{\text{rece}} = R \odot C_{\text{up}} \odot P_{\text{ori}}
\]

\[
D_{\text{topo}}^{\text{rece}} = R \odot C_{\text{up}} \odot T
\]

\( D_{\text{bus}}^{\text{send}} \in M_{|V_i| \times |V_r|} \) is defined as the active power adjustment instruction sending matrix of dispatching center, indicates the active power adjustment instruction after the decision issued by the control center.

\[
D_{\text{bus}}^{\text{send}} = \begin{bmatrix}
D_{11} & 0 & \ldots & 0 \\
0 & D_{22} & \ldots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & 0 & \ldots & D_{|V_r|,|V_r|}
\end{bmatrix}
\]

\( D_{\text{bran}}^{\text{send}} \in M_{|V_i| \times |V_r|} \) is defined as the sending matrix of circuit breaker opening and closing instructions of dispatching center, which means that the control center sends opening and closing instructions to branch I-J circuit breakers.

Where: \( D_{ii} > 0 \) indicates that the injection power of the node increases, and \( D_{ii} < 0 \) indicates that the injection power of the node decreases.

### 3.2.4. Integrated model of power information physical system

As mentioned above, the hierarchical modeling of power network, communication network and information network is carried out. In this section, the integrated model of power information physical system is established by comprehensively considering the correlation characteristics and coupling relationship among the three.

The generalized optimal decision function \( G(M_{|V_i| \times |V_r|}) \) of information network control center is defined; \( P_{\text{bus}}^{\text{disp}} \), \( T_{\text{bran}}^{\text{disp}} \), \( P_{\text{bus}}^{\text{topo}} \) are defined as the injection power matrix, power grid topology change matrix and power flow distribution matrix of power grid dispatching after the decision of control center is completed. The integrated model of power information physical system is deduced as follows.

\[
\begin{align*}
D_{\text{bus}}^{\text{send}} &= G(D_{\text{flow}}^{\text{rece}}) \\
D_{\text{bran}}^{\text{send}} &= G(D_{\text{flow}}^{\text{rece}}) \\
P_{\text{bus}}^{\text{disp}} &= \text{diag}(P) + S \odot C_{\text{down}} \odot D_{\text{bus}}^{\text{send}} \\
T_{\text{bran}}^{\text{disp}} &= S \odot C_{\text{down}} \odot D_{\text{bran}}^{\text{send}} \\
p_{\text{bus}}^{\text{disp}} &= B' \theta \\
F &= (\theta \Lambda - \Lambda \theta^T \odot B')
\end{align*}
\]
\[ P_{\text{fin}} = P_{\text{disp}} + F \]  

(19)

4. Example analysis

In order to verify the effectiveness of the model, based on the standard IEEE9 bus system and based on the analysis method of power flow calculation, the influence process of information network perception decision and generation of control instructions on system state after power grid fault is quantitatively deduced to verify the effectiveness of the model.

Figure 3 shows the standard IEEE9 node power network topology diagram and node label. Since the IEEE9 node system does not specify the line capacity, in order to determine whether the line is overloaded, based on the method in reference [10], it is assumed that the load rate of all branches is 40%.

Based on the above definition, it can be seen that:

\[
\begin{bmatrix}
1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 \\
1 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 1 & 1 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 1 \\
0 & 1 & 0 & 0 & 1 & 0 & 1 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \\
0 & 0 & 1 & 0 & 0 & 1 & 0 & 1 & 1 \\
\end{bmatrix}
\]  

(20)

Assuming that the system is in stable operation, the power flow distribution is shown in Figure 4. At k time, the line is disconnected due to permanent fault. After the fault information is transmitted to the control center through the uplink communication channel, the control command is issued through calculation and decision. The power flow is redistributed as shown in Figure 5. The line \( L_{5-9} \) and \( L_{9-8} \) power overload trip.

If the instruction is circuit breaker 5-7 reclosing, the power flow distribution of the system will return to the initial safe state; if the fault is still not eliminated, in order to prevent the system chain failure and train accident caused by line overload, the dispatching center will issue load shedding or generator load shedding instructions to make the system reach a new steady state. The power flow distribution is shown in Figure 6. The analysis of overload line data change is shown in Table 1.

It can be seen that the integration of the power information network can make the information network adjust the operation state of the power network in time, and effectively alleviate the serious accidents of the system.

| Line load rate | Normal state | \( L_{3-7} \) Open circuit | Neosteady state |
|---------------|--------------|-----------------------------|---------------|
| \( L_{8-9} \) | 40%          | 101.7%                      | 75%           |
| \( L_{5-8} \) | 40%          | 121.9%                      | 73.2%         |

5. Conclusions

With the continuous development of smart grid, it is necessary to study a power CPS model with clear architecture and good applicability. Based on the steady-state power flow equation, a three-layer model framework of power information physical system considering communication transmission factors is proposed in this paper. The whole modeling process is divided into three parts: power network, information network and communication channel. The uplink / downlink communication channel model is established to effectively associate power network and information network. Then, a mathematical model of power information physical system integration considering multi-layer coupling is proposed. The results show that the model fully considers the characteristics of power grid
operation, information transmission and information processing, and is more in line with the characteristics of power dispatching automation system.

![Figure 3. Ieee9 node system diagram.](image1)

![Figure 4. Power flow distribution under normal conditions.](image2)

![Figure 5. Power flow distribution of line 5-7 open circuit.](image3)

![Figure 6. Power flow distribution in new steady state.](image4)

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