Robustness Analysis of CPPS considering Power Flow Constraints

Zhengwei Xu,1 Yuan Ge,1 Qiyou Lin,2 Renfeng Chen,3 Jin Cao,1 and Nuo Yu1

1School of Electrical Engineering, Anhui Polytechnic University, Wuhu 241000, China
2State Grid Anhui Electric Power Co. Ltd., Wuhu Power Supply Company, Wuhu 241000, China
3Anhui Youpai Technology Co. Ltd., Wuhu 241000, China

Correspondence should be addressed to Yuan Ge; ge@ahpu.edu.cn

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Comprehensively considering the power flow constraints of the power network, the cyber-physical power system (CPPS) network integration model is established by combining with the topological structure information of the power network and information network. The Newton–Raphson method is used to solve the AC power flow distribution in the power network. Based on the interdependent network theory, a CPPS cascading fault analysis procedure considering the power flow constraints is given. Finally, the importance of CPPS network nodes is evaluated and analyzed. Simulation experiments are carried out with the IEEE39 node system as an example. The results show that some electrical components failures in the power network may lead to largescale transfer of power flow, resulting in overloading of other electrical components or transmission lines. It promotes further cascade propagation of failures in the CPPS network, which eventually leads to a sharp decrease in the robustness of CPPS.

1. Introduction

With the rapid development and application of information and communication technology, the traditional power system has become a new energy system architecture with high integration of power network and information network, which is referred to as cyber-physical power system (CPPS) [1]. When a failure occurs in the power network or information network, it may spread to another network, creating an interactive cascade of failures between the systems. It may eventually lead to a dramatic decrease in the robustness of CPPS or even lead to the collapse of the whole system [2,3]. At present, scholars mainly study the cascading failure propagation mechanism of CPPS based on the graph theory and percolation theory [4,5]. For example, References [6,7] abstract CPPS as a set of points and edges, establish a CPPS network model based on interdependent network theory, and study the robustness of CPPS from the perspective of network type, dependence direction, intentional attack, coupling strength, coupling mode, and multiple dependence [8–11]. However, it cannot truly and effectively reflect dynamic characteristics such as power flow characteristics, information network monitoring, and so on, and has a large error with the actual model.

The robustness analysis and improvement strategies of CPPS have been studied by domestic and foreign scholars from several perspectives and levels. They have revealed the interactions between the power network and the information network in CPPS through the interdependent network theory [12,13]. However, when analyzing the robustness of CPPS, not only the coupling relationship between power network and information network should be considered but also the power flow constraints should be considered to satisfy the steady state operation of the actual power network [14,15]. Some scholars have considered the power flow characteristics of the power network and proposed the modelling and analysis method based on the power flow model of the power network. For example, References [16,17] established a CPPS network model based on DC and AC power flow models and analyzed the stable operation state of the power network by solving the power flow distribution of the power network. However, it ignores the cascading failure propagation process between the power network and information network. Therefore, some scholars
consider the influence of power flow and reveal the cascading failure propagation of CPPS [18–20]. However, it does not directly reveal the cascading failure propagation mechanism of CPPS through the interdependent network theory. If the cascading failure mechanism of CPPS considering power flow constraints can be revealed on the basis of the interdependent network theory, it is more in line with the actual CPPS network model, which is convenient for CPPS robustness analysis and has more practical significance.

In this paper, simulation experiments are carried out with the IEEE39 node system as an example. Under the constraints of the feasibility and effectiveness of the steady state operation of the power network, the CPPS network integration model considering power flow constraints is constructed. Based on the interdependent network theory, the CPPS cascading failure analysis process considering the power flow constraints is given. The experimental results show that the method is feasible and can better reflect the actual CPPS operation, which is of great reference and practical value for the research of CPPS.

2. The Proposed Model

2.1. The CPPS Model. Figure 1 illustrates that a CPPS is a three-layer network structure system, including the power network, the information network, and the coupling relationship between the two networks.

CPPS is a three-layer network structure system including power network, information network, and coupling relationship between the two networks. According to the CPPS topology information, CPPS can be abstracted as a weighted undirected graph, and the adjacency matrix and the dependency matrix are used to represent the connection relationship between intranetwork nodes and internetwork nodes. The CPPS topology is shown in Figure 1. In CPPS, the power network and the information network interact in real time and the information network completes the monitoring and control of the power network by collecting the operating status information of the power network. Considering the monitoring function of information network and the power flow characteristics of the power network, it is necessary to calculate the power flow distribution of the power network to determine whether the power network satisfies the stable operation state.

2.2. Basic Process of Power Flow Calculation. The power flow calculation of the power network is a basic electrical calculation that determines the steady operation state of the system for a given operating condition and network structure [21,22]. Its significance is to check whether the electrical components and transmission lines in the system are overloaded, whether the power distribution and power loss in the network are reasonable, and whether the voltage of each node is stable [23]. At present, the main methods of power flow calculation are the Newton–Raphson algorithm, PQ decomposition method, and Gauss–Seidel method. The Newton–Raphson algorithm has the advantages of fast convergence and good convergence and is a commonly used method in power flow calculation. Thus, this paper adopts the Newton–Raphson algorithm to calculate the power flow of the power network [13,24]. (see Figure 2)

(i) Step 1: The first step of power flow calculation is to form the nodal admittance matrix of the power system.

(ii) Step 2: Set the initial value of the voltage of each node to $U_i$, the initial value of the phase angle to $\epsilon_i$, and the initial value of the number of iterations to be 0.

(iii) Step 3: Calculate the active power variation $\Delta P_i$ and reactive power variation $\Delta Q_i$ of each node.

(iv) Step 4: Determine whether the convergence condition is satisfied or not, if not, proceed downward.

(v) Step 5: Solve the coefficient matrix of the modified equation-each element of the Jacobian matrix, solve the correction equation, and find the variation of the voltage of each node, namely, the correction amount $\Delta e_i^{(0)}$, $\Delta f_i^{(0)}$.

(vi) Step 6: Calculate the new value of each node voltage, i.e., the corrected node voltage value, and use the new value of each node voltage to enter the next iteration from the third step.

(vii) Step 7: Finally, the generator output power and line power results are calculated.

3. CPPS Cascading Failure Analysis considering Power Flow Constraints

In the cyber-physical power system, the information network node measures, controls, and protects the power network node. Failure of the information network node may cause the power network node to fail or not work properly [25,26]. Similarly, the power network node supplies power to the corresponding information network node. When a power network node fails, the corresponding information network node may directly withdraw from the operation state [27,28]. Under the constraints of the feasibility and effectiveness of the steady state operation of the
power network, the cascading fault propagation mechanism in the CPPS network is revealed using the interdependent network theory [29–32]. Therefore, this paper presents the CPPS cascade failure analysis procedure considering the power flow constraints:

(i) Step 1: After the initialization of CPPS is completed, the initial power flow distribution of the power network is calculated according to the Newton–Raphson method. Then, we set the upper and lower limit of node voltage, the upper and lower limit of node power, and the maximum transmission power of the line under the stable operation state of the power network.

(ii) Step 2: The power network node suffers a malicious attack and thus malfunctions.

(iii) Step 3: Delete the row and column corresponding to the failure node in the power network adjacency matrix A.

(iv) Step 4: Update the adjacency matrix A and nodal admittance matrix Y of the power network and calculate the power flow distribution of the power network at this time according to the Newton–Raphson method. If the power flow satisfies the constraints, go to step 5. Otherwise, go to step 9.

(v) Step 5: Based on the deleted rows and columns in the power network adjacency matrix B, the faulty nodes of the information network are determined by the attached matrix. If a node in the information network fails, go to step 6. Otherwise, go to step 8.

(vi) Step 6: Delete the rows and columns corresponding to the failure nodes in the information network adjacency matrix B and update the adjacency matrix B of the information network.

(vii) Step 7: Based on the rows and columns deleted in the information network adjacency matrix B, determine the failure nodes of the power network through the attached matrix. If a node in the power network fails, go to step 3. Otherwise, go to step 8.

(viii) Step 8: Both the power network and the information network reach a steady state and output the system state.

(ix) Step 9: The system is completely decoupling, the cascading failure simulation process ends, and the number of failure nodes is the number of all nodes in the CPPS.

The flowchart of CPPS cascading failure analysis considering power flow constraints is shown in Figure 3:

Remark 1. The adjacency matrix A represents whether there is a connection relationship between any two nodes in the power network. The adjacency matrix B represents whether there is a connection relationship between any two nodes in the information network. The adjacency matrix E is defined as follows:

$$ E = \begin{bmatrix} e_{1,1} & e_{1,2} & \cdots & e_{1,n} \\ e_{2,1} & e_{2,2} & \cdots & e_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ e_{n,1} & e_{n,2} & \cdots & e_{n,n} \end{bmatrix} $$

(1)

When there is no connection relationship between two nodes in the network, $e_{i,j} = 0$; when there is a connection relationship between two nodes in the network, $e_{i,j} = 1$.

4. Example Analysis

4.1. Simulation Model Construction. First, the initialization of the power network is completed based on the load data, generator data, line parameters, and transformer parameters in the power network under known initial conditions. Then, the power flow distribution of the power network at this time is solved based on the Newton–Raphson method.

Based on the initial power flow calculation results, the maximum active power transmission power of the line determined at this time is $830 MW$. Therefore, the maximum transmission capacity of each line (transmission line) of the power network at stable operation can be set as $P(MW)$, which can be expressed by Equation 2.

$$ |P(MW)| \leq 1200 MW. \quad (2) $$

Equation 2: when the effective transmitted power of the line (transmission line) exceeds its maximum transmission
capacity, it means that the line is failed and the line is disconnected.

Setting the upper and lower limits of the node voltage of the power network under stable operation can be expressed as Equation 3.

\[ 0.95 \leq |V| \leq 1.1. \]  

Equation 3: When the node voltage value is not within its limit, it indicates the node is faulty and thus exits the operation state.

Generally, only one balance node is set in the IEEE39 node system, and the No.31 node is the balancing node. The upper and lower limits of the active power of the balance node are set, which can be expressed by Equation 4.

\[ |P(MW)| \leq 1200 MW. \]  

Equation 4: if the active power output of the balance node is not within the limit, it means that the balancing node is faulty. The failure of the balancing node may cause the power flow to fail to converge. Namely, when the balancing node is unable to withstand the power loss and active power deficit of the system, the active power imbalance in the system will cause the power flow to fail to converge, resulting in cascading failures in the power network.

The propagation process of CPPS cascade faults is derived quantitatively based on the CPPS cascade fault analysis process proposed in the previous section considering the power flow constraints. This part is based on the CPPS established by the IEEE39 node system in Figure 4. The red node represents the power network node, the green node represents the information network node, and the information network structure is the same as the power network structure. The nodes between the two networks are connected in a one-to-one correspondence, thus forming a complete one-to-one correspondence CPPS network. CPPS network model is shown in Figure 5.

In the initial CPPS network model established in this paper, the total number of nodes is 78 and the sum of node degrees is 262. In this paper, the initial failure of the No.16 node in the power network is taken as an example for deduction analysis. Based on the graph theory, the change of the CPPS network structure without considering the power flow constraints is analyzed from the perspective of connectivity. At this time, CPPS is divided into three subnetworks. The maximum subnetwork result of CPPS is shown in Figure 6. The number of nodes is 56 and the sum of node degrees is 188.

\[ E_{p1}, E_{p2}, \text{ and } E_{p3} \] are used to represent the adjacency matrix corresponding to each power subnet, and \( Y_{p1}, Y_{p2}, \) and \( Y_{p3} \) are used to represent the corresponding nodal admittance matrix.

As shown in Figure 7, the initial failure of the No.16 node causes the power network to split into three power subnetworks. Based on the subnetwork adjacency matrix and the nodal admittance matrix, the Newton–Raphson method

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**Figure 3:** Flowchart of CPPS cascading failure analysis considering power flow constraints. Based on the interdependent network theory, a CPPS cascading fault analysis procedure considering the power flow constraints is given.
is used to calculate the power flow distribution of each power subnetwork at this time. The power flow calculation results show that the power flow of the three power subnetworks split in the power network is not convergent. Therefore, all the power network nodes are subject to failures. The failure of the power network nodes leads to the failure of the corresponding information network nodes, ending the cascading failure simulation. The total number of fault nodes is the number of all nodes in the CPPS.

4.2. Robustness Analysis. Randomly selected nodes in the power network are attacked to give the results of the CPPS network structure changes without considering the power flow constraints as shown in Table 1:

Randomly select nodes from the power network are attacked and given the results of the CPPS network structure changes considering the power flow constraints. The results are shown in Table 2:

The results of comparing the number of CPPS loss nodes without considering the power flow constraint and the number of CPPS loss nodes considering the power flow constraint are shown in Figure 7.

The parameters of each node in the CPPS network are calculated, and the nodes are sorted according to the node degree and node betweenness. Some sorting results are shown in Tables 3 and 4.

Considering the power flow constraints, the robustness curves of CPPS under node degree attack and node betweenness attack are plotted as shown in Figures 8 and 9.
By observing the data in Tables 1 and 2 and the simulation results in Figure 10, we can observe the following findings:

The No.38 node failure caused the entire CPPS paralysis. The reason is that the failure of the No.38 node in the power network causes the active power output of
the No. 31 balanced node to exceed its upper limit, i.e., the failure of the No.31 balance node. Due to the lack of balancing nodes in the whole power network, the output of each node in the power network is unbalanced and the power flow does not converge.

The No.16 node caused a complete collapse of the entire CPPS. The reason is that the No.16 node fault divides the power network into three power subnetworks. Through the power flow calculation, the output of each node of the three power subnetworks is unbalanced and...
the power flow does not converge. In other words, all the power network nodes fail, resulting in the complete collapse of CPPS.

By observing the data in Tables 3 and 4 and the simulation results in Figures 8 and 9, we can see that some nodes in CPPS not only have a high node degree but also high node betweenness. In the case of considering power flow constraints, attacking these important nodes in CPPS can easily lead to CPPS collapse.

In summary, the failure of balancing nodes may lead to the imbalance of active power output of each node in the power network and increase the further propagation of cascading failures in the CPPS network, leading to a sharp decrease in the robustness of CPPS. When attacking nodes with a high node degree, it may also lead to a drastic change in the network structure, resulting in a large area of power network faults and cascading propagation of failures, which makes the robustness of CPPS decrease sharply.

5. Conclusion

In this paper, a CPPS network integration model is established by combining the topological structure information of the power network and information network, and the CPPS cascading fault analysis process considering the power flow constraint is given. A simulation experiment of the IEEE39 node system is carried out to quantitatively deduce the cascading failure propagation process under the influence of network node attacks. Finally, the importance of network nodes in the cyber-physical power system is evaluated. Simulation results show that failure of some power nodes in the power network may lead to nonconvergence of power flow, overloading of other electric components, or transmission lines, and eventually lead to large-scale cascading failures or even collapse of CPPS. Therefore, we should combine the power flow characteristics and CPPS network structure characteristics to evaluate the importance of nodes.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request. Please visit https://github.com/B1547/IEEE39-node-system.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References


