IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 3 December 2023, accepted 21 December 2023, date of publication 25 December 2023, date of current version 3 January 2024.

Digital Object Identifier 10.1109/ACCESS.2023.3346939

RESEARCH ARTICLE

A Globally Cooperative Recovery Strategy for Cyber-Physical Power System Based on Node Importance

ZHENGWEI QU[1], PENGYUE WANG[1], JINGKE LI[1,2], POPOV MAXIM GEORGIEVITCH[3], AND YUNJING WANG[1]

[1]Key Laboratory of Power Electronics for Energy Conservation and Drive Control, Yanshan University, Qinhuangdao 066004, China
[2]Henan Pinggao Electric Company Ltd., Pingdingshan 467000, China
[3]Department of Electric Power Station and Automation of Power Systems, Peter the Great Saint-Petersburg Polytechnic University, 195251 Saint Petersburg, Russia

Corresponding author: Yunjing Wang (wyj@ysu.edu.cn)

ABSTRACT With the development of cyber technology, the intelligence of power systems has increased, and cyber-physics is highly integrated and mutually constrained. In this paper, a globalized cyber-physical cooperative recovery strategy based on node importance is proposed for the failure of a cyber-physical power system under communication failure. First, the static importance of communication nodes and the importance of services are comprehensively analyzed based on the structural business transmission function characteristics of the network. Secondly, based on the fault characteristics of generators, power lines, and loads, the recovery model of the physical system is constructed by considering the safety constraints such as system frequency, node voltage, and line capacity. Finally, considering the possible delay caused by the cyber system failure to the generator output regulation, power line commissioning, and load recovery, the interaction model of physical system recovery and cyber system recovery is established and solved by using the solver after linearizing it. The results show that the cyber-physical recovery strategy can effectively reduce outage losses and improve recovery efficiency.

INDEX TERMS Cooperative recovery strategy, cyber-physical power system, node importance, physical system recovery, cyber system recovery.

I. INTRODUCTION

At present, the concept of cyber-physical systems has frequently appeared in academic fields and industrial fields, and has promoted the development and progress of power systems, production systems and energy management systems. Cyber-physical power system (CPPS) is a kind of cyber-physical system developed by the combination of traditional physical power system and cyber power system. In CPPSs, a large amount of complex data needs to be generated, processed, and exchanged, which presents a huge challenge for computer monitoring, protection, and real-time control [2]. Although combining physical systems with cyber systems can bring many benefits to electromechanical systems, it also makes systems more vulnerable to damage and threats from more advanced and covert cyber-attacks [1].

Cyber-attacks against CPPS are mainly divided into integrity attacks, availability attacks and confidentiality attacks. Confidentiality attack is a type of attack in which an unauthorized party obtains information illegally. Integrity attack is a kind of attack that tampers the information content of CPPS. The typical attack mode is false data injection attack (FDIA). The purpose of availability attacks is to prevent the system from getting the required data or signals in time, including denial of service (DoS) attacks and the introduction of control signal delay.

In recent years, several major outages around the world have demonstrated the significant impact of cyber systems on grid operations. 2003, the U.S. blackout was caused by a

The associate editor coordinating the review of this manuscript and approving it for publication was Peng-Yong Kong.

software failure in the cyber system that affected the controllability of the grid, and the emergency measures that should have been triggered in the event of a change in primary-side operation were not triggered, leading to the development of the incident. In the same year as the Italian blackout, inadequate cyber acquisition capabilities led to a system collapse when a tree flash occurred on a critical transmission line due to the dispatcher's incorrect estimation of the system's power angle and failure to take timely FM measures [3]. In 2019 a power company in the western U.S. was attacked by a hacker group due to a Dos attack, causing the power plant and its equipment and regulators to shut down. This caused a short interruption of communication between the power plant and its equipment and the regulation center; in the same year, cyber-attacks caused Venezuela to suffer multiple cyber virus attacks and physical attacks such as electromagnetic damage and substation explosions, disintegrating the hydroelectric power grid and causing widespread power outages across the country for more than five days [5].

Over time, cyber and physics have become more and more closely linked, integrating and influencing each other. In recent years, the power system has been subject to frequent cyber-attacks, and the recovery of the cyber-physical system has attracted a lot of attention from the academic community.

In order to face the impact of typhoon and reduce the outage cost, literature [6] carried out collaborative optimization on the emergency repair of fault lines, the pre-adjustment of generator output and the urgent load control, and proposed a three-order toughness improvement strategy of prevention, response and recovery. A strategy for fault component recovery based on Q-Learning algorithm was proposed in literature [7]. Literature [8] established the emergency cooperative maintenance model of transmission network after disaster according to the uncertainty of the time required by the maintenance team to shift and other actions in the fault maintenance process and the constraints of maintenance resources and road stiffness planning. Most of the above studies are traditional restoration methods, focusing on the physical system without considering the case of cyber-physical compound failures. In 2022, a two-layer network islanding method is proposed, which is based on the theory of phase-dependent networks from the perspective of the CPPS topology and achieves simultaneous recovery of physical cyber nodes for regional grid failures, improving the load response rate [9]. However, the disadvantages of this method are that the two-layer island division makes the algorithm converge slowly in the later stage, and the coupling mechanism between the cyber network and the physical network is relatively simple. Considering the facilitating role played by the measurement and monitoring side function of cyber devices in the maintenance process of transmission lines, a framework for power system defense against natural disasters is proposed from three perspectives proving that cyber-physical synergistic restoration can effectively improve the line restoration rate and reduce the losses caused by power outages [10]. But the shortcoming is that the model of each process is not fine enough, and the accuracy of the overall recovery of the network line is not high. The literature [11] established a geographic grid based on the corresponding characteristics of communication nodes and power nodes in the distribution network and established a quantitative index of resilience, as a basis for proposing a two-layer repair model for power faults and communication faults. The above research proves the feasibility and effectiveness of cyber-physical collaborative recovery in the process of fault repair, and mainly includes three methods to solve the current problem of cyber-physical power system recovery. The first method is Markov decision process, which has the advantage of dynamic scheduling of recovery resources. However, the computational complexity of this method increases significantly with the exponential growth of the state space. The second method is Q-learning algorithm, which has the advantage of good performance and effect on the system with high complexity and large search space. However, the disadvantage is that if the length of the repair sequence is uncertain, the implementation of this method will become difficult. The third method is some heuristic optimization algorithms, such as particle swarm algorithm, fish swarm algorithm and so on. The advantages of this algorithm are that it can solve the characteristics of many dimensions and strong randomness in the actual power grid fault recovery, and can improve the recovery efficiency. However, the disadvantage of this algorithm is that it is more effective only for the recovery of physical network, and it is not dominant when the cyber network and physical network cooperate to recover.

To sum up, the deep integration of cyber and physics is the basis of realizing smart grid, but it also makes the stable operation of the power system face more challenges and risks. How to quickly restore the normal operation state of power system in the case of communication failure is an important research topic. Against this background, a globally cooperative recovery strategy of CPPS based on the network topology of communication system and transmission characteristics of power business is proposed to minimize the loss of power outage and effectively improve the recovery efficiency.

II. STUDY OF THE IMPORTANCE OF COMMUNICATION NODES

A. STUDY OF THE IMPACT OF COMMUNICATION FAILURE ON THE GRID

In recent years, with the continuous development of communication systems, the number of various services controlled and managed through statistical analysis of cyber has been growing, and the dependence on cyber in the huge power system has been deepening. The recovery in this paper is after the role of power system communication system failures and network attacks. The importance of the communication side system nodes is used as an indicator to develop the recovery strategy. For communication failures, this paper develops a recovery plan by considering the importance of nodes in the power network and the allocation of resources for recovery, respectively.

The research of power communication systems mainly focuses on the cyber level, and the configuration of services is generally from the perspective of time delay, bit error rate, reliability, bandwidth, and other such communication performance, lacking consideration of system coupling perspective, real-time production control services are distributed in the communication network, and there is a certain variability in the impact on the stable and safe operation of the system after it suffers from cyber-attacks, resulting in some more important services cannot get The priority of the processing should have, that is, the security of the communication link and the business importance of the mismatch situation. Specifically, some of the services that have a significant impact on the power system may be centrally assigned to high-risk communication links, but the less influential part of the service can be reliably transmitted, a situation that increases the risk of power outages when the service is transmitted in extreme situations such as integrity network attacks. As one of the core businesses of power communication networks when it comes to real-time control services for production, this paper establishes quantitative indicators for assessing the importance of cyber nodes from the business perspective by combining network structure, node degree, and clustering coefficients.

Most of the current recovery studies are based on scenarios where the cyber is fully accessible. Once the communication of the system fails, the command-and-control personnel may not be able to obtain the status cyber of the power grid in time, failing to make optimal decisions. Along with the development of cyber technology, the power grid has been highly digitalized, and the traditional power grid has gradually evolved into a system with deep cyber-physical integration. The literature [21] analyzes and studies the power system control of real-time load-making based on the communication system, i.e., the communication system has an indelible impact on the power system. Most of the actual restoration of the current grid is aligned to the restoration under extreme disasters, and after a disaster, there are two main options, one is to use the importance of the load as the basis for the order of repair, and the other is to take a random repair approach. After an extreme disaster, network reconfiguration is an important measure to quickly restore the load in non-faulty areas [22]. When the communication system fails, the planned nature of the recovery process is disrupted and is carried out randomly, i.e., by using a maximum to minimum load. In this process, the recovery speed cannot be determined and there will be cases when repairing a particular fault does not restore the load. That is some faults that are not connected to the busbar or distributed power supply, whose inability to provide a load to the system.

In the case of random recovery, the randomness can lead to a situation of ineffective recovery.

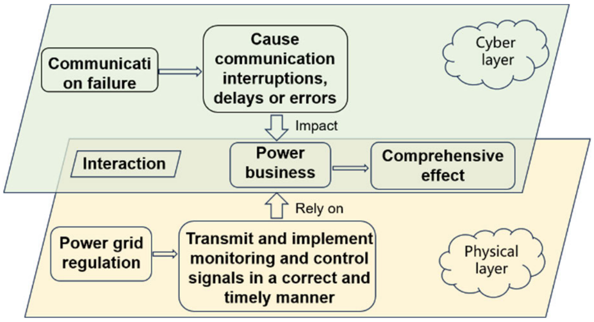


FIGURE 1. Framework of communication failure impact study.

As shown in Figure 1, when the power system is under network attack in the case of communication failure, the fault occurs and cannot be recovered in a planned manner. If the recovery is just carried out in a random recovery manner, it will not only increase the recovery time but also may cause secondary outages of the system and greater losses in the assembly because of the improper recovery sequence. To cope with this situation and improve the recovery efficiency of the power system, this paper proposes a cyber-physical cooperative recovery strategy based on node importance.

B. STATIC IMPORTANCE OF COMMUNICATION NODES

When calculating the importance of communication nodes, this paper selects degree centrality as an indicator. Only the information of the nodes themselves needs to be analyzed, and the calculation is simple, convenient, and low complexity, which is more suitable for large-scale network calculation.

In the network structure of power communication networks, the aggregation characteristics of nodes are crucial to the degree of influence of network nodes. Representing the power communication network abstractly as an undirected connectivity graph, the cohesiveness of the nodes can be judged based on the degree of contraction of the nodes in the network topology. Since the most common in our current power cyber network is a stable triangular structure, assuming that no weights are considered and only the mesoscopic number is used as a measure, most of the nodes have degree 2, while the shortest path of the network generally does not include these nodes with degree 2. This will affect the measurement of the importance of the nodes. Again, because it is difficult to form a triangular structure at the edge positions of the network, the influence of the clustering coefficient will become greater. Although the clustering coefficient cannot indicate the number of nodes around that node and the country mode size of the network, it can be used as a measure of the topological closeness around the node.

From the above analysis, when calculating the static importance of a node, this paper will use the metric of node degree combined with the clustering coefficient to measure the importance of a node T. The larger the value of T, the greater the risk to the network topology when the node fails, i.e., this node has a greater importance in the network topology, and in the recovery after failure, restoring this node will bring a more positive effect to the next step of recovery.

The value of T for node i is

$$T(i) = \frac{k(i)}{\sqrt{\sum_{j=1}^{N} [k(j)]^2}} + \frac{f(i)}{\sqrt{\sum_{j=1}^{N} [f(j)]^2}} \tag{1}$$

where $k(i)$ represents the node degree of node i.

$$f(i) = \frac{\max_{j \in N}\left[\frac{c(j)}{k(j)}\right] - \frac{c(j)}{k(j)}}{\max_{j \in N}\left[\frac{c(j)}{k(j)}\right] - \min_{j \in N}\left[\frac{c(j)}{k(j)}\right]} \tag{2}$$

where $c(i)$ denotes the clustering coefficient of node i.

$$c(i) = \frac{2e(i)}{[k(i)]^2 - k(i)} \tag{3}$$

where $e(i)$ is the number of edges between all neighboring nodes of node i.

The static importance index of node i in the power communication network depends on two important factors, one is the number of nodes N connected to node i, and the other is the position of node i in the power communication network. Under the same condition, the more the number of nodes connected to node i, the less the number of nodes left in the network after shrinking the node, that is, the greater the cohesiveness of the network, the greater the static importance of the node. The greater the degree of centrality and cohesion of the node, the more important its position in the power communication network, the greater the role it plays, and the more important the priority recovery of the node with high importance when the network is restored after a failure. When the network is restored, the first node to be restored is necessarily the part of the node connected to the dispatch center, and secondly, considering the mutual influence between the nodes, to minimize the loss of power outage, the key nodes are determined according to the importance of the nodes, i.e., considering the impact of the nodes on the network topology and operational functions, and these nodes should have certain priority in the restoration process.

C. SERVICE IMPORTANCE OF COMMUNICATION NODES

In practice, each node in the power communication network structure is responsible for its various services related to the safe operation of the power grid, including line relay protection, security and stability systems, wide area measurement, scheduling automation, and power plant and substation video monitoring and other transmission services, commonly used communication business importance indicators are shown in Figure 2. For the node, the type of services it undertakes is different, and the impact on the safe operation of the power communication network is also different. The business importance of a node refers to the degree of impact on the safe and stable operation of the power grid when a service is interrupted or defective, and the higher the business importance, the greater the impact on the safe operation of the power grid, i.e., the two are positively correlated. Therefore, the business importance of the node is used as an indicator to measure the importance of the node in the power communication network.

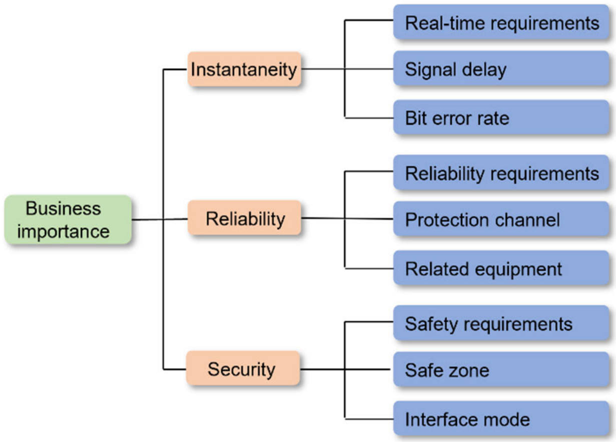


FIGURE 2. Framework of communication failure impact study.

When a communication node of the power network undertakes more types and a greater number of services, the greater the impact on the safe and stable operation of the power system after its failure, i.e., the higher the importance of the node. When the power system is recovered after a failure, the nodes with high service importance are restored as a priority to facilitate the next step of system recovery.

Since the security requirements for different types of services and cyber transmission are of different levels, the importance of various types of services that have appeared in various types of literature so far are summarized and classified into a total of five categories, and their average values are taken into the calculation to obtain the business classification importance of communication nodes, as shown in the following table.

TABLE 1. Types of communication node services and their importance.

Business type / Business number	Importance / Ranking
Relay Protection/I	0.99/1
Stabilization System/II	0.94/2
Wide area measurement, dispatch automation, dispatch telephony, etc./III	0.62/3
Cyber Management, Power Plant and Substation Video Monitoring/IV	0.29/4
Lightning location monitoring, office automation / V	0.13/5

Table 1 shows the service types of communication nodes in the physical system and their importance, and these five services in the table are all services for the power system, which will have an impact on the restoration of the physical system. It can be seen from the table that these five service types have different importance degrees according to their different influence degrees on the power system.

As shown in Table 1, the business importance of line relay protection is the highest among the five types, and in practical application, the importance increases with the voltage level, and the voltage level is unified in the research object of this paper, so it importance is calculated with a determined unified value. The importance of business such as stability control systems and dispatching automation is lower than the importance of urgent you to protection, but its direct impact on the safe and stable operation of the power system. The business of lightning positioning monitoring and office automation, on the other hand, has limited impact on the operation of power production, so its importance is the lowest.

The business importance of each node in the power communication network depends on the number of lines connected to the node and the business undertaken on this line. The more the number of lines connected to the node means that the node needs to undertake the transmission of more business, and the type and number of services are also more, i.e., the node is restored first, then the work is restored first, and the recovery process is faster and the loss is minimized. To make a full and comprehensive consideration of the node importance, the type of service, the number of various types of services, and the number of lines connected to the node all need to be taken into account, as follows

$$B(i) = \sum_{i=1}^{n} b_{kj} n_{kj} \tag{4}$$

where $B(i)$ denotes the value of the business importance of node i, n denotes the number of lines connected to node i, b_{kj} is the value of the importance of the kth type of business undertaken by the jth line connected to node i, *and* n_{kj} is the number of the kth type of business running on line j. The larger the calculated value of $B(i)$, the higher the business importance of this node, and the more important and more numerous the business undertaken. When the system fails, the node with high importance is restored first in the process of recovery, and the business undertaken by the node is also restored, and the more business is restored the less damage is caused.

From the two aspects of the node's static importance index and business importance index, the two are integrated and the importance quantification value of the power system communication node is obtained, namely.

$$I(i) = \frac{(B(i) - 1)(T(i) - 1)}{1 - T(i) - B(i) + 2T(i)B(i)} \tag{5}$$

III. GLOBALIZED RECOVERY STRATEGY BASED ON NODE IMPORTANCE

To meet the research needs and challenges brought by the deep cyber-physical convergence, reduce outage losses, and improve recovery efficiency after power system failures, this paper proposes a globalized cyber-physical cooperative recovery strategy based on node importance from the perspective of the power system communication system itself by analyzing the impact of communication failures on power system power recovery.

A. OBJECTIVE FUNCTION

From the perspective of an electric utility, to ensure the rapid restoration of critical loads, the recovery strategy after a power system failure is optimized to minimize the loss of power due to outages caused by the failure.

$$\min \sum_{l \in \Omega^D} c_l P_l^D t_l^D \tag{6}$$

In the above equation, Ω^D denotes the set of all loads in the system; cl denotes the outage loss per unit of power for load l, i.e., the number of dollars lost per kWh for load l; P_l^D denotes the active power demand for load l; t_l^D denotes the moment when load l is restored, and t_l^D is the optimization variable.

Depending on the load level, a variety of factors such as the size of the load, the socio-economic value of the load, and the different impacts of the load on security, medical care, and people's lives are taken into account, and historical outage data as well as the outage losses per unit of electricity for different types of loads set by the government are also included in the analysis to provide indicators for the development of the sequence of load restoration.

B. PHYSICAL SYSTEM RECOVERY MODEL

When the system communication fails, the generator's economic dispatch control function fails to accept the regulation instructions from the regulation center, thus it cannot automatically respond to the dispatch instructions and has to rely on the manual regulation method to change the output, resulting in the prolongation of the whole recovery process.

As shown in (7), when the generator economic dispatch control fails, the upper and lower limits of the power achieved by generator g at the recovery moment t are expressed by $P_{g,t}^{G,\max}$ and $P_{g,t}^{G,\min}$; G denotes the set of generators in the system; R_g is used to represent the active power regulation speed of generator g; the time required to manually regulate the generator output is expressed by ΔT_G; then the range of the active power output P of generator g at its recovery moment at this time is expressed as t. The range of the active power output $P_{g,t}^G$ of generator g at its recovery time is expressed as

$$P_{g,t}^{G,\min} + R_g \Delta T_G \leq P_{g,t}^G \leq P_{g,t}^{G,\max} - R_g \Delta T_G \tag{7}$$

From the above equation, when the economic dispatch control of the generator with normal system communication is intact, there is no delay ΔT_G caused by manual regulation, ΔT_G is zero, and the regulation range of the generator g at this time is significantly larger than that of the generator when the system communication fails. From this, it is clear that after the cyber failure of the generator, its active regulation range at the next recovery moment will become smaller. To facilitate the computational analysis, (7) is written in discrete form as

$$P_{g,t}^G \geq \max\left\{P_{g,t}^G - R_g\left[L_T - (1 - u_{g,t-1}^{CB})\Delta T_G\right], P_{g,\min}^G\right\} \quad \forall g \in \Omega^G, t \in T \tag{8}$$

$$P_{g,t}^G \leq \min\left\{P_{g,t}^G + R_g\left[L_T - (1 - u_{g,t-1}^{CB})\Delta T_G\right], P_{g,\max}^G\right\} \quad \forall g \in \Omega^G, t \in T \tag{9}$$

where $P_{g,\min}^{G}$ denotes the minimum active output of generator g and $P_{g,\max}^{G}$ denotes the maximum active output of generator g. L_T is the specific length of the discrete recovery interval at recovery time; T denotes the set of discrete recovery time intervals; the state variable $u_{g,t-1}^{CB}$ denotes the real-time state of the cyber system of the node where generator g is located at time $t-1$; to facilitate the modeling calculation, 0/1 is used to recognize the two different states, $u_{g,t-1}^{CB}=0$ indicates that the node is faulty, and $u_{g,t-1}^{CB}=1$ indicates that the node is in a normal state in the system. As the above equation shows, if the cyber node of the node where the generator g is located is faulty, it cannot automatically adjust the active output, and at this time the generator needs to adjust its output by manual adjustment, resulting in a longer time for the start of the adjustment and a consequent smaller adjustment range of the active output.

At the same time, to avoid secondary system outages during the restoration process, the generator output needs to comply with the system safety constraint, i.e., the output value of generator g should not exceed its maximum capacity value, as expressed in (10).

$$\left(P_{g,t}^{G}\right)^{2}+\left(Q_{g,t}^{G}\right)^{2}\leq S_{g,\max}^{2}\quad \forall g\in\Omega^{G},t\in T \tag{10}$$

where $S_{g,\max}$ represents the maximum apparent capacity of generator g and $Q_{g,t}^{G}$ represents the reactive power output of generator g at moment t.

After a failure occurs, the system's recovery process is not only limited by the system network topology but also by the recovery resources. The following equation describes the situation where the repair process is limited. In the case of power line recovery, when the lines adjacent to a particular line are in a fault state and cannot operate normally, this line cannot be recovered and cannot operate normally, and (11) describes this situation. In this equation, the set of power lines in the system is represented by Ω^{L}, while ψ_{mn} represents the set of all lines adjacent to line (m,n); the state variable $u_{mn,t}^{L}$ represents the state of power line (m,n) not restored/restored at moment t with a value of 0/1.

$$u_{mn,t}^{L}\leq\sum_{(\alpha,\beta)\in\psi_{mn}}u_{\alpha\beta,t}^{L} \tag{11}$$

$$u_{mn,t}^{L}=\begin{cases}0, u_{m,t}^{L}+u_{n,t}^{L}<2\\ 1, u_{m,t}^{L}+u_{n,t}^{L}=2\end{cases},\ \forall(m,n)\in\Omega^{L},t\in T \tag{12}$$

$$u_{i,t}^{L}=\begin{cases}1, x_i=\max\left\{x_1,\cdots,x_i,\cdots,x_{30}\right\}\\ 0, x_i\neq\max\left\{x_1,\cdots,x_i,\cdots,x_{30}\right\}\end{cases},\ \forall i\in\psi_{zx} \tag{13}$$

In the recovery process, node importance x determines the sequence of node recovery. The higher the node importance, the higher the priority of node recovery, as shown in equation (13), x_i represents the node importance of node i and ψ_{zx} represents the set of communication nodes that have not been recovered.

The limited resources in the recovery process of the repair are represented by R_P to denote the number of recovery resources of the physical system, and (14) bounds the number of lines recovered in each discrete time interval. $u_{mn,t}^{L}$ and $u_{mn,t-1}^{L}$ sub-tables represent the recovery status of the lines at moment t and moment $t-1$.

$$\sum_{(m,n)\in\Omega^{L}}\left(u_{mn,t}^{L}-u_{mn,t-1}^{L}\right)\leq R_P\quad\forall t\in T \tag{14}$$

However, in the actual recovery process, due to the high degree of integration of power cyber and physical systems, the recovery of power lines is not only affected by the state of adjacent lines but also by the state of cyber systems. The cyber nodes at both ends of any line, if they are not in the same normal communication state, the operation of equipment such as contact switches on this line cannot be quickly adjusted automatically, and can only rely on manual dispatch adjustment, while the manual operation will produce a certain time difference. In (15), t_{mn}^{L} represent the line (m,n) specific recovery moment; manual operation to put the line into operation the time spent by ΔT_L to represent; state variable $u_{mn,t}^{CB}=0$ is representative of the line (m,n) at least one of the two ends of the cyber node is not back in operation, state variable $u_{mn,t}^{CB}=1$ is representative of the line (m,n) two ends of the cyber node all back to normal.

$$t_{mn}^{L}\geq\sum_{t\in T}\left(1-u_{mn,t}^{L}\right)L_T+\left(1-u_{mn}^{CB}\right)\Delta T_L$$
$$\forall(m,n)\in\Omega^{L} \tag{15}$$

$$u_{mn,t}^{CB}=\begin{cases}0, u_{m,t}^{CB}+u_{n,t}^{CB}<2\\ 1, u_{m,t}^{CB}+u_{n,t}^{CB}=2\end{cases},\ \forall(m,n)\in\Omega^{L} \tag{16}$$

$$u_{n,t}^{CB}=\begin{cases}1, x_n=\max\left\{x_1,\cdots,x_n,\cdots,x_{30}\right\}\\ 0, x_n\neq\max\left\{x_1,\cdots,x_n,\cdots,x_{30}\right\}\end{cases},\ \forall n\in\psi_{zx} \tag{17}$$

To circumvent the secondary faults that may be caused during the recovery process, the recovery of line (m,n) needs to comply with the maximum allowable power constraint. As shown in formula below

$$P_{mn}^{2}+Q_{mn}^{2}\leq S_{mn,\max}^{2}\quad\forall(m,n)\in\Omega^{L},t\in T \tag{18}$$

where P_{mn}, Q_{mn} and $S_{mn,\max}$ denote the active power, reactive power and the maximum allowable apparent power transmitted on the line (m,n), respectively.

When a load is restored in the system, a load can be restored if at least one of the lines adjacent to the node where the load is located has been restored.

$$u_{l,t}^{D}\leq\sum_{(m,n)\in\psi_{l}}u_{mn,t}^{L}\quad\forall l\in\Omega^{D},t\in T \tag{19}$$

where ψ_l is the set of lines adjacent to the node where load l is located; the state variable $u_{l,t}^{D}$ represents the recovery state of load l at moment t, $u_{l,t}^{D}=1$ means the load has been recovered, and $u_{l,t}^{D}=0$ means the load has not been recovered; Ω^{D} represents the set of loads in the system.

In the same way as line restoration, load restoration is also affected by the state of the cyber nodes. However, the recovery of load needs to take into account the frequency overrun of the system that may be triggered by the generator power adjustment. When the recovery of load is small and the generator communication is normal with sufficient regulation, the commissioning of the system load does not cause the frequency overrun to occur. These small amounts of load can be automatically restored by the generator's regulation without waiting for manual regulation orders. On the contrary, when the load is large and the regulation capacity of the generators with normal communication is insufficient, the recovery of the load needs to wait for the other generators with communication failure to receive the manual regulation order to recover. Therefore, when judging the recovery time of the load, the regulation capacity of the generators in the system needs to be calibrated.

$$\begin{aligned} t_l^D \geq & \sum_{t \in T} \left(1 - u_{l,t}^D\right) L_T \\ & + \max\left\{(1 - u_l^{CB})\Delta T_D,\ \left(1 - u_l^G\right) \Delta T_G\right\} \\ & \forall l \in \Omega^D \end{aligned} \tag{20}$$

In this case, the time taken for the manual operation to put the load into operation is represented by ΔT_D; the state variable $u_l^{CB} = 0$ means that the communication of the node where the load l is located is not restored, and the state variable $u_l^{CB} = 1$ means that the communication of the node where the load l is located has been restored to the normal state; u_l^G represents the relationship between the load l and the generator receiving the manual order, $u_l^G = 1$ means that the load is restored before the generator unable to communicate receives the manual order, and $u = 0$ means that the load is restored after the generator unable to communicate receives the manual order. $u_l^G = 0$ means that the load is restored after the uncommunicative generator receives the manual order. u_l^G then requires the following constraints to be satisfied.

$$\sum_{l \in \Omega^D} \left(u_{l,t}^D - u_{l,t-1}^D\right) P_l^D \leq \sum_{g \in \Omega^G} u_{g,t-1}^{CB} R_g L_T \quad \forall t \in T \tag{21}$$

The formula indicates that the amount of load that can be restored without waiting for a manually regulated generator during the recovery interval cannot exceed the regulation capacity of a generator with intact and fault-free communication. At this point, the voltage and system frequency of each node in the system should satisfy the following constraints.

$$V_{i,\min} \leq V_{i,t} \leq V_{i,\max} \quad \forall i \in \Omega^{PB}, t \in T \tag{22}$$

$$\left| \frac{\sum\limits_{l \in \Omega^D} \left(u_{l,t}^D - u_{l,t-1}^D\right) P_l^D}{\sum\limits_{g \in \Omega^G} \frac{P_{gN}^G}{\delta_g}} \right| \leq \frac{\Delta f_{\max}}{f_N} \quad \forall t \in T \tag{23}$$

where Ω^{PB} denotes the set of nodes in the system; $V_{i,\min}$, $V_{i,t}$, $V_{i,\max}$ denote the minimum value of voltage amplitude allowed at node i, the voltage value at moment t, and the maximum value of allowed voltage amplitude, respectively. P_{gN}^G, δ_g denote the rated active output and power angle of generator g, respectively; $\Delta f_{\max}$, f_N denote the maximum frequency deviation allowed in the recovery process and the rated frequency of the system.

C. CYBER SYSTEM RECOVERY MODEL

The development of communication technology has led to the increasing application of more reliable methods such as power IoT, 5G communication, and fiber optic communication in power cyber systems. Therefore, for the construction of the power communication network in this paper, the traditional carrier communication is not considered but the fiber optic link is the main one. The erection of the fiber composite overhead ground line is established with the erection of transmission lines, so the restoration of transmission lines is a prerequisite for the restoration of their corresponding fiber links. Therefore, the time of fiber recovery should be later than the recovery of the corresponding transmission line in the physical system. As shown in (24).

$$u_{mn,t}^{CL} \leq u_{mn,t}^{L} \quad \forall (m, n) \in \Omega^O, t \in T \tag{24}$$

where the state variable $u_{mn,t}^{CL}$ indicates the recovery state of the communication link (m, n) at moment t. Its value of 0 indicates that the link is not recovered, and its value of 1 indicates that the link is recovered; Ω^O indicates the fiber optic link built with the transmission line.

The recovery of the communication link presupposes that the link connected to at least one end of the node being recovered at a certain moment is functioning normally or has been recovered so that the communication between it and the regulation center can be guaranteed. This problem is considered in this paper for the recovery of cyber systems. To solve this problem, the recovery priority of the node connected to the normally operating equipment is proposed to ensure communication between the recovered node and the regulation and control center. The abstraction of the power communication network is simplified and transformed into a directed graph consisting of cyber nodes and communication links. Recovery models are established for both of them respectively, corresponding to different fault cases. The recovery-constrained case of communication links is similar to the constrained case of power line recovery, and the network topology and the number of recovery resources have an impact on the speed of repair. Formula (25) indicates that a communication link can be recovered only if at least one of the nodes at both ends of the link has been recovered. Formula (26) indicates that the number of restored links in each restoration interval cannot be more than the number of restored resources.

$$u_{mn,t}^{CL} \leq u_{m,t-1}^{CB} + u_{n,t-1}^{CB} \quad \forall (m, n) \in \Omega^{CL}, t \in T \tag{25}$$

$$\sum_{(m,n) \in \Omega} \left(u_{mn,t}^{CL} - u_{mn,t-1}^{CL}\right) \leq R_{CL} \quad \forall t \in T \tag{26}$$

In this case, the set of all communication links in the cyber system is represented by Ω^{CL}; the state variables $u^{CB}_{m,t-1}$ and $u^{CB}_{n,t-1}$ indicate the recovery status of communication node m and communication node n at time $t-1$, respectively, and its value of 0 means that the node has not recovered, and its value of 1 means that the node has been recovered; R_{CL} indicates the number of repair resources that can be mobilized when the communication link is recovered.

According to the description above, the recovery of a communication node is influenced by the state of the communication links connected to it. Formula (27) expresses the meaning that the node can be recovered only if at least one of the communication links connected to the cyber node has been recovered. Formula (28) describes the constraint on the number of salvage resources when the cyber node is restored.

$$u^{CB}_{mn,t} \leq \sum_{(\alpha,\beta)\in\psi_i^{CL}} u^{CL}_{\alpha\beta,t-1} \quad \forall i\in\Omega^{CB}, t\in T \tag{27}$$

$$\sum_{(m,n)\in\Omega^{CB}} \left(u^{CB}_{i,t} - u^{CB}_{i,t-1}\right) \leq R_{CB} \quad \forall t\in T \tag{28}$$

where Ω^{CB} denotes the set of all communication nodes in the cyber system; ψ_i^{CL} denotes the set of all communication links adjacent to node i in the cyber system; and R_{CB} denotes the number of repair resources that can be mobilized when the communication node is restored.

To simplify the model for computational analysis, the "hardware" and "software" failures of cyber systems are not specifically distinguished in the recovery model. According to the specific type of failure, the communication link recovery resource R_{CL} and communication node recovery resource R_{CB} can be used as both a line repair team for repairing "physical hardware" and an engineering team for repairing "cyber software" when performing recovery repair. The team can be used as either a line repair team to repair "physical hardware" or as an engineer to repair "cyber software".

D. MODEL SOLVING

The recovery optimization model in this paper is a nonlinear optimization problem, which is difficult to solve directly, so it is solved by AC linearization method by converting it into a mixed integer second-order cone programming model and then using a commercial solver GUROBI 9.0.

Formulas (29) to (34) represent the AC constraint of the power system in discrete time, where (29) and (30) represent the relationship between the power injected into each node and the generator output and load power demand; formulas (31) and (32) are the relationships between the line tide distribution and the power injected into the nodes; formulas (29) and (30) are the relationships between the line tide and the voltage at both ends description.

$$P_{i,t} = \sum_{g\in\Omega_i^G} P^G_{g,t} - \sum_{l\in\Omega_i^D} u^D_{l,t}P^D_l \quad \forall i\in\Omega^{PB}, t\in T \tag{29}$$

$$Q_{i,t} = \sum_{g\in\Omega_i^G} Q^G_{g,t} - \sum_{l\in\Omega_i^D} u^D_{l,t}Q^D_l + Q^R_{i,t} \quad \forall i\in\Omega^{PB}, t\in T \tag{30}$$

$$P_{i,t} = \sum_{(i,m)\in\Delta_i} P_{im,t} - \sum_{(n,i)\in\Lambda_i} P_{ni,t} \quad \forall i\in\Omega^{PB}, t\in T \tag{31}$$

$$Q_{i,t} = \sum_{(i,m)\in\Delta_i} Q_{im,t} - \sum_{(n,i)\in\Lambda_i} Q_{ni,t}\forall i\in\Omega^{PB}, t\in T \tag{32}$$

$$\begin{aligned} P_{mn,t} &= V^2_{m,t}G_{mn} \\ &\quad - V_{m,t}V_{n,t}\left(G_{mn}\cos\theta_{mn,t} + B_{mn}\sin\theta_{mn,t}\right) \\ &\quad \forall(m,n)\in\Omega^L, t\in T \end{aligned} \tag{33}$$

$$\begin{aligned} Q_{mn,t} &= -V^2_{m,t}B_{mn} \\ &\quad - V_{m,t}V_{n,t}\left(G_{mn}\sin\theta_{mn,t} - B_{mn}\cos\theta_{mn,t}\right) \\ &\quad \forall(m,n)\in\Omega^L, t\in T \end{aligned} \tag{34}$$

where the set of physical nodes is denoted by Ω^{CB}; Ω_i^G and Ω_i^D represent the set of generators and loads under node i, respectively; Δ_i and Λ_i represent the set of lines with node i as the first and last; the active and reactive power injected, the active and reactive power emitted, and the demand for reactive power at moment t by node i, generator g, and load l are denoted by $P_{i,t}$ and $Q_{i,t}$, $P^G_{g,t}$ and $Q^G_{g,t}$, and Q^D_l, respectively; the compensation provided by the reactive power device at node i is denoted by $Q^R_{i,t}$. The voltage amplitude at both ends of the line (m,n) at moment t and the active and reactive power flowing on it are $V_{m,t}$, $V_{n,t}$, $P_{mn,t}$, $Q_{mn,t}$; the voltage phase difference between the two ends of the line (m,n) is $\theta_{mn,t}$; the conductance and the conductance on the line (m,n) are G_{mn}, B_{mn}.

Linearization of (33) and (34).

$$V_{m,t} = V_m^{base} + \phi_{m,t}, \forall m\in\Omega^{PB}, t\in T \tag{35}$$

$$\begin{aligned} P_{mn,t} &= \left(V_m^{base}\right)^2 G_{mn} - V_m^{base}V_n^{base}B_{mn}\left(\theta_{m,t}-\theta_{n,t}\right) \\ &\quad - V_m^{base}V_n^{base}G_{mn}\cos^*\theta_{mn,t} \\ &\quad \forall(m,n)\in\Omega^L, t\in T \end{aligned} \tag{36}$$

$$\begin{aligned} Q_{mn,t} &= -\left(V_m^{base}\right)^2 B_{mn} - V_m^{base}V_n^{base}G_{mn}\left(\theta_{m,t}-\theta_{n,t}\right) \\ &\quad + V_m^{base}V_n^{base}B_{mn}\cos^*\theta_{mn,t} - V_m^{base}B_{mn}\left(\phi_{m,t}-\phi_{n,t}\right) \\ &\quad - \left(V_m^{base}-V_n^{base}\right)B_{mn}\phi_{m,t} \\ &\quad \forall(m,n)\in\Omega^L, t\in T \end{aligned} \tag{37}$$

$$\begin{aligned} \cos^*\theta_{mn,t} &= \frac{\cos\theta_{mn}^{\max} - \cos\theta_{mn}^{\min}}{\theta_{mn}^{\max} - \theta_{mn}^{\min}}\left(\theta_{mn,t} - \theta_{mn}^{\min}\right) + \cos\theta_{mn}^{\min} \\ &\quad \forall\,(m,n)\in\Omega^L, t\in T \end{aligned} \tag{38}$$

$$\begin{aligned} &\cos^*\theta_{mn,t} - (\sin a)\left(\theta_{mn,t} - a\right) + \cos a \\ &\quad \forall\,(m,n)\in\Omega^L, t\in T \end{aligned} \tag{39}$$

where V_m^{base} and V_n^{base} represent the voltage reference values at both ends of the line; $\phi_{m,t}$ and $\phi_{n,t}$ represent the offset variables introduced by the voltages at both ends; $\theta_{m,t}$ and $\theta_{n,t}$ represent the voltage phases at both ends of the line;

cos* represents the segmented linearization function of cos; a is the correlation constant of the segmentation function; $\theta_{mn}^{\max}$ and $\theta_{mn}^{\min}$ are the maximum and minimum values of the voltage phases at both ends of the line, respectively.

In (15) and (20), u_{mn}^{CB}, u_{l}^{CB} and u_{l}^{G} represent the states of the cyber system during the recovery operation of the physical system, respectively, and portray the interaction between the physical system and the cyber system during the recovery process.

The state variable u_{mn}^{CB} indicates the communication status of the line (m, n) at its two connected nodes when the recovery is performed, and the state variable u_{l}^{CB} then denotes the communication state of the node where the load l is located when it is recovered, and the following constraints need to be satisfied.

$$1 - u_{mn}^{CB} \geq \frac{\sum\limits_{t \in T} \left(u_{mn,t}^{L} - u_{m,t-1}^{L} \right)}{N}, \forall (m, n) \in \Omega^{L} \tag{40}$$

$$1 - u_{mn}^{CB} \geq \frac{\sum\limits_{t \in T} \left(u_{mn,t}^{L} - u_{n,t-1}^{L} \right)}{N}, \forall (m, n) \in \Omega^{L} \tag{41}$$

$$1 - u_{l}^{CB} \geq \frac{\sum\limits_{t \in T} \left(u_{l,t}^{D} - u_{l,t-1}^{CB} \right)}{N}, \forall (m, n) \in \Omega^{D} \tag{42}$$

where N denotes the number of recovery intervals. Formulas (40) and (41) indicate that the state variable u_{mn}^{CB} is 1 only when the line (m, n) has been recovered and all the nodes connected to it at both ends have also been recovered.

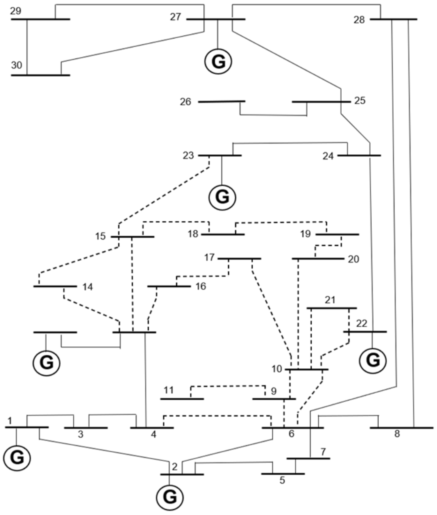
IV. EXAMPLE ANALYSIS

A. PARAMETER SETTING

The IEEE30 node standard power system is used as the basis to build a power cyber-physical system to verify the feasibility and effectiveness of the collaborative recovery strategy proposed in this paper. A cyber network corresponding to IEEE30 nodes is built and redundant communication links are added. The objective function is solved based on MATLAB programming using GUROBI 9.0. The following parameter quantities are set: during the power system recovery process, the nodes allow the maximum magnitude of the voltage standardized value of 1.1 and the minimum magnitude standardized value of 0.9; the frequency deviation allowed for power system operation is ±0.5 Hz; the time for manual generator, line, and load regulation in case of communication failure is 8min, 10min, and 10min, respectively; the recovery time interval for each discrete the details of the load parameters, voltage parameters and generator parameters of each node of the system are shown in MATPOWER 7.0.

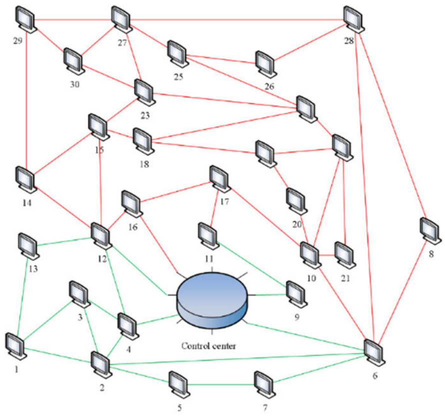
B. SIMULATION RESULTS AND ANALYSIS

The quantitative normalization results of the importance of communication nodes are shown in Figure 3, which shows that nodes 6, 10, 12, 15, and 27 not only undertake important services in the cyber system but also occupy an important position in the network structure. Combined with the analysis of the system wiring diagram, the number of lines connected to node 6 is the largest, and the number of lines connected to nodes 10, 12, 15, and 27 is also more than other nodes in the system, and in the case of cyber transmission, if its communication fails, the number of links affected is more, so priority is given to restoring these nodes when performing recovery, so that the overall process of recovery is accelerated and losses are reduced. Therefore, it can be seen that the results obtained by using a combination of static importance and service importance are more consistent with the actual situation.



-Normal operating lines --Discontinued lines

FIGURE 3. **Power network diagram of power system.**



—Normal communication lines —Faulty communication lines

FIGURE 4. **Power system communication network diagram.**

Four global recovery schemes are considered in this paper. Scheme 1 is the cooperative recovery strategy in the absence of communication failure; scheme 2 adopts the traditional recovery strategy in literature [30] to give priority to power system recovery; scheme 3 is the cooperative recovery strategy without considering node importance [25]; scheme 4 is the cooperative recovery strategy based on node importance. Table 2 lists the importance of failed communication node.

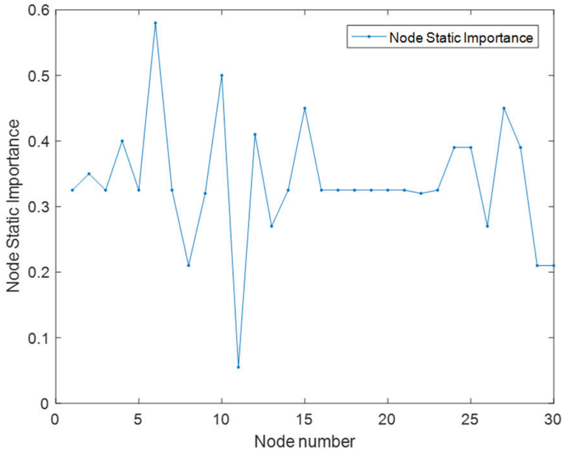


FIGURE 5. Static importance curve of communication nodes.

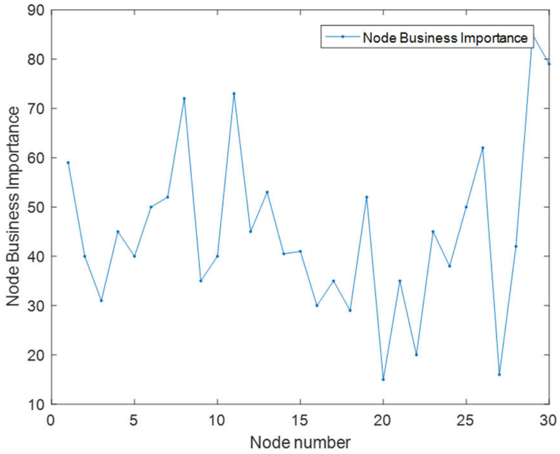


FIGURE 6. Business importance curve of communication nodes.

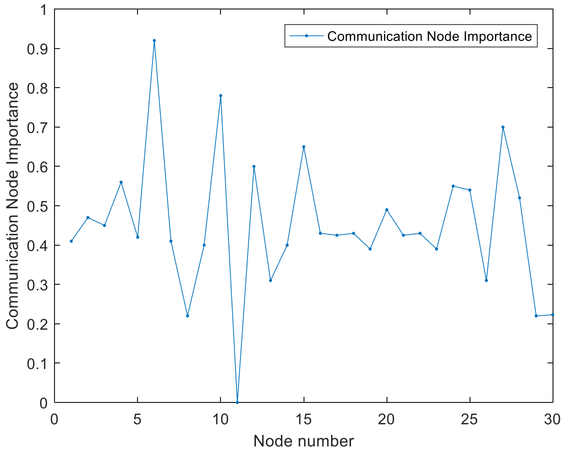


FIGURE 7. Integrated importance curve of communication nodes.

According to the importance ranking of information nodes in Table 2, the recovery strategies of communication nodes under four schemes are developed, as shown in Table 3.

TABLE 2. Importance of failed communication nodes.

Fault communication node	Importance	Sort by
10	0.7642	1
27	0.7016	2
15	0.6586	3
24	0.5444	4
28	0.5388	5
25	0.5352	6
20	0.4832	7
18	0.4431	8
22	0.4417	9
16	0.4410	10
21	0.4359	11
17	0.4356	12
14	0.4304	13
23	0.4279	14
19	0.4233	15
26	0.3175	16
8	0.2410	17
30	0.2398	18
29	0.2386	19

It can be seen from the above that the generator communication recovery will have an impact on the recovery of the power system. On the one hand, the generator communication failure will lead to the reduction of its active power output regulation range, and then lead to the decrease of the active power regulation of the entire power system, which will prolong the entire recovery process. On the other hand, when the generator communication is limited, the larger load recovery amount will cause the frequency of the system to exceed the limit, so the way of manual adjustment is adopted to avoid this situation. However, manual adjustment means that the recovery time increases, the power outage is prolonged, and the economic loss caused by power outage also increases. As can be seen from the recovery sequence of communication nodes shown in Table 2, node 22, 23 and 27 corresponding to generator nodes were recovered within the first three time-intervals, which also means that the node has a large volume of service and plays an important role in the network structure. As a result, some of the nodes recovered during the first three time-intervals were negatively affected by the generator communication failure. It can be seen from the data in column 4 of the table that nodes 4, 12, 15 and 24 are restored at the beginning of the time interval without waiting for manual instructions because of the sufficient generator adjustment capacity.

The efficient and coordinated restoration strategy of power system speeds up the recovery speed of power system and reduces the loss of power outage. Manual adjustment will increase the time of system outage, so the priority of restoring the communication system corresponding to the node can avoid the extra time of manual restoration. Therefore, as far as possible, the communication of the node should be restored

TABLE 3. Communication nodes recovery strategy.

Scheme 1		Scheme 2	
Node	Recovery time/min	Node	Recovery time/min
12	0	12	0
19	0	19	10
14	0	14	10
17	0	17	10
21	0	21	10
23	20	23	30
26	20	26	30
30	20	30	30
16	20	16	30
18	20	18	30
4	40	4	40
24	40	2	40
15	40	24	50
20	40	15	50
2	40	20	50
10	60	10	60
Scheme 3		**Scheme 4**	
Node	Recovery time/min	Node	Recovery time/min
4	0	4	0
12	0	12	0
23	10	19	10
24	10	14	10
19	10	21	10
14	20	15	20
17	20	17	30
26	30	23	30
30	30	26	30
18	30	30	30
15	40	24	40
20	40	20	40
2	40	16	40
21	40	18	40
16	50	2	40
10	60	10	60

before the load of the node is restored. As can be seen from the data in the table, except for a few individual nodes, the communication of the remaining nodes was restored before the load was put into operation. For example, the communication of load nodes 14, 17, 19, and 21 has not been restored during load recovery. Therefore, manual adjustment is required to restore the load, and the recovery time is delayed by 10 minutes. Table 4 and 5 lists the active power required by each node in the power system and the power loss per unit load.

TABLE 4. Active power required for IEEE 30-Bus standard power system.

Node	P_l^D / MW	Node	P_l^D / MW	Node	P_l^D / MW
1	16.3	11	22.3	21	17.5
2	21.7	12	11.2	22	8.2
3	2.4	13	9.8	23	3.2
4	7.6	14	6.2	24	8.7
5	12.7	15	8.2	25	10.5
6	6.1	16	3.5	26	3.5
7	22.8	17	9	27	8.6
8	30	18	3.2	28	4.5
9	18.6	19	9.5	29	2.4
10	5.8	20	2.2	30	10.6

TABLE 5. Power failure loss per unit load of IEEE 30-Bus standard power system.

Node	w_l (cent/kWh)	Node	w_l (cent/kWh)	Node	w_l (cent/kWh)
1	2.48	11	54.84	21	49.9
2	6.64	12	68.59	22	78.5
3	8.47	13	54.87	23	117.04
4	9.18	14	141.86	24	29.81
5	5.85	15	34.1	25	25.85
6	11.75	16	87.76	26	89.28
7	17.54	17	79.93	27	45.68
8	7.87	18	115.49	28	43.56
9	5.87	19	126.66	29	10.77
10	7.1	20	134.69	30	40.65

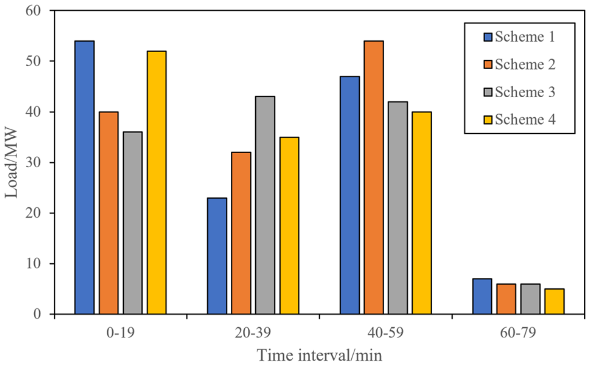


FIGURE 8. Load recovery in each time interval of the four schemes.

Figure 8 shows the load recovery of each scheme in four time-intervals. In the first time-interval, scheme 1 has the largest load recovery; scheme 4 has a slightly smaller load recovery in the first time-interval than scheme 1; scheme 2 and scheme 3 have a significantly smaller load recovery. In the second and third time-intervals, the load recovery amount between scheme 1 and scheme 2 shows an obvious difference, while the difference between scheme 3 and scheme 4 is very small. In the final interval, there was little difference in the amount of recovery between the four schemes. From the stability of load recovery speed, the recovery speed of scheme 4 is the most stable.

As shown in Table 6, the average recovery time of scheme 1, scheme 3 and scheme 4, which adopt the collaborative recovery strategy, is reduced by 19.4% and 19.4% compared with scheme 3 and scheme 4. The weighted recovery time decreased by 28.2% and 16.0%. The corresponding recovery rate is increased by more than 20%. It can be seen that when the system communication is normal, the average recovery time and weighted recovery time of the load are the shortest, and the recovery rate is the fastest, that is, the communication state of the system has a key influence on the recovery rate of the system load. In the case of communication failure, the average recovery time of scheme 2, 3 and 4 which adopts the cooperative recovery strategy is reduced by 10.1% compared with the traditional recovery scheme 2 which does not consider the coordination. The weighted recovery time increased by 10.9% and 1.5%, respectively. The corresponding recovery rate is only slightly improved.

The cyber-physical cooperative recovery strategy based on node importance proposed in this paper, that is, scheme 4 has

TABLE 6. Recovery time and recovery rate of four schemes.

Scheme	Scheme1	Scheme2	Scheme3	Scheme4
Average recovery time/min	22.5	29.6	26.88	26.88
Weight recovery time/min	21	24	26.93	24.35
Average recovery rate/(MW/min)	5.85	4.45	4.9	4.9
Weight recovery rate/(MW/min)	6.27	5.48	4.89	5.4
Total outage loss/(10^4 USD)	133.88	294.77	275.50	246.34

the same average recovery time and the weighted recovery time is reduced by 10.6% compared with scheme 3, which does not consider node importance. The corresponding recovery rate is also better than scheme 3. From the economic perspective, as shown in Row 6 of Table 6, the power failure loss of scheme 1 is reduced by 120.2%, 105.8% and 84.0% compared with that of scheme 2, 3 and 4. The power failure loss of scheme 3 and 4 is reduced by 7.0% and 19.7% compared with scheme 2. Scheme 4 had a reduction of 11.8% per cent compared with scheme 3. To sum up, the impact of communication failure on load recovery time and rate as well as power failure loss is not beneficial. However, when the system is subjected to compound attacks and communication failure, the traditional recovery mode still needs to spend a lot of time and money to restore the system. The cooperative recovery strategy can effectively improve the recovery efficiency of the system and reduce the power failure loss of the system.

IEEE 30 system is a typical and complete distribution system, and its topology and functions are sufficient to cover all the research content of this paper. Therefore, under the condition of normal topology and complete functions, the optimized model in this paper is suitable for all large node complex systems.

V. CONCLUSION

The power system is highly integrated with cyber and physics, and to cope with the risks brought by compound faults, this paper analyzes the interaction impact of cyber system and physical system, formulates the restoration order of communication nodes based on their importance, and optimizes the outage time of each load node by using mixed integer planning, i.e., to achieve the goal of minimum outage loss. The results of the algorithm show that

(1) The communication status of the generator has a critical role in the recovery of the cyber-physical system, and therefore the cyber system should be prioritized in the recovery process. Compared with the recovery strategy of ignoring the cyber system, coordinating the recovery process of the physical and cyber systems is beneficial for the recovery of the whole system.

(2) The strategy of synergistic restoration allows for proper regulation of generators and load restoration to avoid secondary outages in the power system due to frequency crossing limits. At the same time, the synergy of the two speeds up the recovery of the load and thus reduces the losses caused by power outages compared with the strategy of independent recovery of the physical system and the cyber system.

In terms of the average time and weighted average time of load recovery, the cooperative recovery strategy based on node importance of the cyber-physical system has the shortest weighted average time of load recovery, so it can effectively improve the load recovery rate and reduce the economic loss caused by system power failure. However, considering that the information is too miscellaneous in the process of power system emergency repair and restoration, the recovery strategy based on node importance will significantly increase the workload of emergency repair and restoration and is not conducive to subsequent management and maintenance. Therefore, in the follow-up research, we will further consider the introduction of grid method on the basis of global cooperative recovery, divide the power system into grids, and restore nodes in each grid according to the importance of nodes, so as to formulate a power system recovery plan from different situations and give a more efficient recovery strategy.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

REFERENCES

[1] K.-D. Lu, Z.-G. Wu, and T. Huang, "Differential evolution-based three stage dynamic cyber-attack of cyber-physical power systems," *IEEE/ASME Trans. Mechatronics*, vol. 28, no. 2, pp. 1137–1148, Apr. 2023, doi: 10.1109/TMECH.2022.3214314.

[2] K.-D. Lu, L. Zhou, and Z.-G. Wu, "Representation-learning-based CNN for intelligent attack localization and recovery of cyber-physical power systems," *IEEE Trans. Neural Netw. Learn. Syst.*, 2023, doi: 10.1109/TNNLS.2023.3257225.

[3] Y. Wang, "Research framework of strong smart grid technology standard system," *Power Syst. Autom.*, vol. 34, pp. 1–6, Jan. 2010.

[4] G. Andersson, P. Donalek, R. Farmer, N. Hatziargyriou, I. Kamwa, P. Kundur, N. Martins, J. Paserba, P. Pourbeik, J. Sanchez-Gasca, R. Schulz, A. Stankovic, C. Taylor, and V. Vittal, "Causes of the 2003 major grid blackouts in North America and Europe, and recommended means to improve system dynamic performance," *IEEE Trans. Power Syst.*, vol. 20, no. 4, pp. 1922–1928, Nov. 2005.

[5] N. Liu, X. Yu, and J. H. Zhang, "Cooperative cyber-attack: Extrapolation and insights from the Ukraine power outage," *Power Syst. Autom.*, vol. 40, pp. 144–147, 2016.

[6] J. Yan, B. Hu, K. Xie, T. Niu, C. Li, and H.-M. Tai, "Dynamic repair scheduling for transmission systems based on look-ahead strategy approximation," *IEEE Trans. Power Syst.*, vol. 36, no. 4, pp. 2918–2933, Jul. 2021.

[7] T. Ding, M. Qu, Z. Wang, B. Chen, C. Chen, and M. Shahidehpour, "Power system resilience enhancement in typhoons using a three-stage day-ahead unit commitment," *IEEE Trans. Smart Grid*, vol. 12, no. 3, pp. 2153–2164, May 2021.

[8] Y. Zhang, J. Wu, Z. Chen, Y. Huang, and Z. Zheng, "Sequential node/link recovery strategy of power grids based on Q-learning approach," in *Proc. IEEE Int. Symp. Circuits Syst. (ISCAS)*, May 2019, pp. 1–5.

[9] S. H. Y. Liang, Y. Y. Wang, Y. P. Liu, and X. M. Wang, "Optimization of post-disaster emergency maintenance strategies for transmission networks based on improving resilience," *China Electr. Power*, vol. 55, pp. 142–151, 2022.

[10] X. Li, "Research on islanding of power cyber physical system based on common edge nodes," North China Electr. Power Univ., Beijing, China, Tech. Rep., 2019.

[11] F. L. Y. Tang, Q. Wang, and M. Ni, "A quantitative evaluation method for the impact of communication system failure on real-time load control of power system," *Power Autom. Equip.*, vol. 37, pp. 90–96, 2017, doi: 10.16081.

[12] L. Xu, Q. Guo, T. Yang, and H. Sun, "Robust routing optimization for smart grids considering cyber-physical interdependence," in *Proc. IEEE Power Energy Soc. Gen. Meeting (PESGM)*, Aug. 2020, p. 1.

[13] Q. W. Y. Tang, M. Ni, and Y. Liang, "Analysis of cyber-attacks in power cyber-physical convergence systems," *Power Syst. Autom.*, vol. 40, pp. 148–151, Jan. 2016.

[14] Y. Wang, "Power cyber physical system modeling and vulnerability research in cyber-attack environment," Zhejiang Univ., Hangzhou, China, Tech. Rep., 2019.

[15] K. Jiang, *Network Analysis of Power communication Networks*. Beijing, China: China Electric Power Publishing House, 2014.

[16] L. Sun, Z. Lin, Y. Xu, F. Wen, C. Zhang, and Y. Xue, "Optimal skeleton-network restoration considering generator start-up sequence and load pickup," *IEEE Trans. Smart Grid*, vol. 10, no. 3, pp. 3174–3185, May 2019.

[17] X. J. X. Xiaohai, "Application of fiber optic communication technology in power system dispatching automation," *Commun. Power Technol.*, vol. 36, pp. 180–181, Jan. 2019.

[18] "Research on the application of 5G mobile communication technology in power communication system," *Commun. Power Technol.*, vol. 37, pp. 178–179, Jan. 2020.

[19] Z. Li, M. Shahidehpour, R. W. Galvin, and Y. Li, "Collaborative cyber-physical restoration for enhancing the resilience of power distribution systems," in *Proc. IEEE Power Energy Soc. Gen. Meeting (PESGM)*, Aug. 2018, pp. 1–5.

[20] Z. Bie, Y. Lin, G. Li, and F. Li, "Battling the extreme: A study on the power system resilience," *Proc. IEEE*, vol. 105, no. 7, pp. 1253–1266, Jul. 2017.

[21] J. Fan, "Design of backup power management system for mobile communication base stations," Liaoning Univ. Sci. Technol., Anshan, China, Tech. Rep., 2013.

[22] T. W. M. Li and J. Hsienji, "Smart grid cyber security defense system and cyber security test system construction: Reflections and insights from the cyber-attacks on the national grid of Ukraine and Israel," *Power Syst. Autom.*, vol. 40, pp. 147–151, 2016.

[23] T. L. F. Bing, "Vulnerability analysis of power communication network," *Chin. J. Electr. Eng.*, vol. 34, pp. 1191–1197, 2014.

[24] C. Zhang, Z. Lin, F. Wen, G. Ledwich, and Y. Xue, "Two-stage power network reconfiguration strategy considering node importance and restored generation capacity," *IET Gener., Transmiss. Distrib.*, vol. 8, no. 1, pp. 91–103, Jan. 2014.

[25] Y. W. K. Pang, F. Wen, C. Wang, J. Zhao, and Y. Liu, "A physical cooperative recovery strategy for transmission system information taking into account communication failures," *Autom. Electr. Power Syst.*, vol. 45, pp. 58–67, 2021, doi: 10.7500/AEPS20200811001.

[26] Y. Chen, L. Cheng, M. Li, J. Wang, L. Tong, and K. Yang, "Multiscale grid method for detection and reconstruction of building roofs from airborne LiDAR data," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 7, no. 10, pp. 4081–4094, Oct. 2014.

[27] A. Arab, A. Khodaei, Z. Han, and S. K. Khator, "Proactive recovery of electric power assets for resiliency enhancement," *IEEE Access*, vol. 3, pp. 99–109, 2015.

[28] A. Anmar and Z. Yu, "Power distribution system outage management with co-optimization of repairs, reconfiguration, and DG dispatch," *IEEE Trans. Smart Grid*, vol. 9, no. 5, pp. 4109–4118, Jan. 2017.

[29] S. Lei, C. Chen, Y. Li, and Y. Hou, "Resilient disaster recovery logistics of distribution systems: Co-optimize service restoration with repair crew and mobile power source dispatch," *IEEE Trans. Smart Grid*, vol. 10, no. 6, pp. 6187–6202, Nov. 2019.

[30] F. Aminifar, M. Fotuhi-Firuzabad, M. Shahidehpour, and A. Safdarian, "Impact of WAMS malfunction on power system reliability assessment," *IEEE Trans. Smart Grid*, vol. 3, no. 3, pp. 1302–1309, Sep. 2012.

[31] S. S. C. Shuyong, Li Lanxin, and J. Shen, "Review of smart grid technology," *Power Grid Technol.*, vol. 33, pp. 1–7, 2009.

[32] H. Li, A. Dimitrovski, J. B. Song, Z. Han, and L. Qian, "Communication infrastructure design in cyber physical systems with applications in smart grids: A hybrid system framework," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 3, pp. 1689–1708, 3rd Quart., 2014, doi: 10.1109/SURV.2014.052914.00130.

[33] C. Qu, W. Chen, J. B. Song, and H. Li, "Distributed data traffic scheduling with awareness of dynamics state in cyber physical systems with application in smart grid," *IEEE Trans. Smart Grid*, vol. 6, no. 6, pp. 2895–2905, Nov. 2015.

[34] X. Shijie, "Thinking about building China's smart grid technology," *Power Syst. Autom.*, vol. 33, pp. 1–4, 2009.

ZHENGWEI QU received the B.Sc. degree in power system and automation and the M.S. degree in power electronics and power drives from Yanshan University, Qinhuangdao, China, in 2000 and 2003, respectively, and the Ph.D. degree in electrical engineering from Tsinghua University, Beijing, China, in 2010. He is currently a Professor with the School of Electrical Engineering, Yanshan University. His research interests include situational awareness and intelligent measurement technology in smart grids.

PENGYUE WANG was born in Yantai, Shandong, China, in 1999. He received the B.Sc. degree in electrical engineering and automation from the Xi'an University of Technology, China, in 2021, and the M.S. degree in emerging power systems from Curtin University, Perth, WA, USA, in 2023. He is currently pursuing the M.S. degree in electrical engineering with Yanshan University, Qinhuangdao, China. His research interests include defense resource allocation and failure recovery of cyber-physical power systems.

JINGKE LI received the B.Sc. degree in agricultural electrification from North China Electric Power University, Baoding, China, in 2020, and the M.S. degree in electrical engineering from Yanshan University, Qinhuangdao, China, in 2023. She is currently with Henan Pinggao Electric Company Ltd.

POPOV MAXIM GEORGIEVITCH received the master's degree, in 2001. He did the master's thesis, in 2001. Since 1999, he has been in scientific and pedagogical experience with SPBPU. From 2002 to 2014, he was an Associate Professor and the Deputy Head of scientific work with the Department of Electric Power Station and Automation of Power Systems. Since 2014, he has been the Head of the Department of Electric Power Station and Automation of Power Systems. He is a member of the B5 RNA CIGRE Working Group; a member of the editorial board of two journals; an expert in the scientific and technical sphere and science; and a member of the Scientific and Technical Council (NTS) of FGC UES, RusHydro, and Rosenergoatom.

YUNJING WANG received the B.Sc. degree in power system and automation, the M.S. degree in power electronics and power drives, and the Ph.D. degree in instrument science and technology from Yanshan University, Hebei, China, in 2000, 2003, and 2014, respectively. She is currently an Associate Professor with the Department of Electrical Power Engineering, Yanshan University. Her research interest includes the application of intelligent algorithms in power systems.

• • •