Received December 23, 2020, accepted January 2, 2021, date of publication January 13, 2021, date of current version January 22, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3051502

Analysis of Resilience Under Repair Strategy in Interdependent Mechatronic System

YUCHENG HAO[1,2], YANHUI WANG[1,2,3], LIMIN JIA[1,2,3], AND ZHICHAO HE[1,2]

[1]State Key Laboratory of Rail Traffic Control and Safety, Beijing Jiaotong University, Beijing 100044, China
[2]School of Traffic and Transportation, Beijing Jiaotong University, Beijing 100044, China
[3]Beijing Research Center of Urban Traffic Information Sensing and Service Technology, Beijing Jiaotong University, Beijing 100044, China

Corresponding author: Yanhui Wang (18801007426@163.com; wangyanhui@bjtu.edu.cn)

This work was supported in part by the State Key Laboratory Traffic Control and Safety, Beijing Jiaotong University under Grant RCS2021ZZ003.

ABSTRACT Existing works on the interdependent system have come to fruition based on the percolation theory and revealed that it possesses the great vulnerability due to the essential interdependency. However, how to effectively recover the performance of the interdependent system after cascading failures is still under research. In this article, we define an interdependent mechatronic system as an interdependent machine-electricity-communication network. By considering the behavior of the real-world system, we put forward an extended cascading failure model in which the non-giant component is also functional when its size proportion is not smaller than the proportion threshold δ and it has the interdependent links from the other two subnetworks. Then, according to the measures of a node (i.e., single measures), the interdependent measures are proposed and the repair strategies are obtained by these measures to determine the order of repaired nodes. In order to accurately reflect the resilience in the interdependent mechatronic system, we adopt three metrics to quantify it, i.e., the change of the robustness, the recovery ability, and the critical number of repaired nodes. Finally, we study the relationship between δ and the robustness, and apply different repair strategies to the analysis of the resilience in a real mechatronic system. The experiments show that the non-giant component plays a key role in the robustness and the resilience is affected by δ when a few nodes fail to work. In addition, we obtain the optimal repair strategy from different aspects of the resilience. A striking finding is that in most instances, the repair strategies concerning the interdependent measures lead to the higher resilience compared with the ones concerning the single measures. Our work may provide insights to make a plan for repairing equipment so as to enhance the resilience of the interdependent mechatronic system.

INDEX TERMS Resilience, robustness, interdependent network, interdependent measure, mechatronic system, cascading failure.

I. INTRODUCTION

With the development of engineering, infrastructure systems increasingly rely on each other to satisfy the demand for a certain function, which results in an increased interaction between these systems. For this reason, failures of one or more nodes may cause an extremely negative effect on the operations of the subsystem and the entire system. A classic example is the large-scale blackout that took place in Italy in 2003 [1]. This event was triggered by a malfunction of one power station so that several servers shut off, which further made other servers inactive. In the end, a cascade of events happened. Due to the serious impact, the cascading failure in the interdependent network has received a lot of attention.

The associate editor coordinating the review of this manuscript and approving it for publication was Chao Tong.

According to the work [1], analytical frameworks to investigate the percolation process for networks of networks were put forward [2], [3]. Owing to the key role of the interdependency links, the impact of the coupling strength on the robustness was analyzed and it was found that a first order percolation phase transition changes to a second order percolation phase transition as the coupling strength decreases [4]. Similarly, for different coupling strengths, the cascading failures induced by the overload [5] and the effect of clustering on the robustness [6], [7] were studied, respectively. In addition to the coupling strength, Parshani *et al.* investigated how to couple the nodes between two networks and found that the inter-similarity can improve the robustness against cascading failures triggered by the random attack. In the same way, the robustness of the interdependent networks under different coupling preferences [8]–[11] was investigated. Taking into account that it is likely to intentionally remove the node in reality, Huang *et al.* developed a general framework to investigate the cascading failure triggered by attacks on the nodes with either high or low degrees [12]. Due to the fact that the interdependent network is vulnerable to random attacks, the targeted attack in networks of networks [13] and the edge attack strategy in interdependent networks [14] have also been explored.

It is well-known that the operation of the infrastructure system is crucial for a normal life. Therefore, how to assess its robustness and design the optimal structure has been an attractive research topic. By characterizing the features of the cyber-physical system, the failure propagation process between networks was analyzed and the corresponding strategies to enhance its robustness were given [15]–[18]. Because the removal of a part of critical nodes or edges is prone to greatly impair the ability to normally operate in real-world systems, especially for the interdependent infrastructure network, the approaches regarding the identification of key nodes and edges for the interdependent power-communication network were proposed [19], [20], respectively. In order to understand the response of the interdependent system composed of the power grid, the corresponding cascading failure models were built for interdependent power-transportation networks [21]–[23], interdependent power-telecom-water networks [24], and interdependent energy-power networks [25], [26], respectively. Additionally, Marzuoli *et al.* gave a case report with respect to the Asiana crash in San Francisco International Airport, finding that cancelations and delays in the aerospace lead to the occurrence of a traffic jam in the road near the airport, and the increased transit passenger demand [27]. This is an appropriate instance to illustrate the propagation of disturbances between different real-world systems.

Shekhtman *et al.* have reviewed the recent works on the robustness and the resilience, and pointed out that these two aspects in interdependent networks may obtain more interesting discoveries [28]. In contrast to the robustness, the resilience is used to assess the recovery of the system performance under extreme perturbations, which is a more comprehensive concept. In the realm of complex networks, because some systems are able to spontaneously recover their functions, such as brain seizures in neuroscience or market crashes in finance, Majdandzic *et al.* proposed a framework for understanding the resilience of networks in which the failed node spontaneously recovered from the failure to the operation [29]. However, the node without the external repair hardly bounces back in infrastructure systems (e.g., the power grid, communication networks, and transportation systems). To this end, the recovery processes considering the reconstruction of the inactive node were analyzed [30]–[32]. Di Muro *et al.* introduced an analytic framework to understand the recovery of interdependent networks where the broken node that connected with the giant component was recovered under a certain probability [33]. In addition, Gao *et al.* developed a set of analytical tools for assessing the resilience of the network, which can describe the network state by coupled nonlinear equations [34]. In the field of engineering, by adopting the classic measures for nodes, based on different orders of repaired nodes, the researches on the resilience of Railways Network and National Airspace System Airport Network were conducted [35], [36], respectively. Moreover, it is worth mentioning that Bruneau *et al.* first gave a conceptual framework to quantify the resilience [37], which provides insights on the research on the resilience in real-life systems. Motivated by this work, a three-stage framework including the disaster prevention, the damage propagation and the recovery process for the resilience analysis was proposed [38]. The studies on the resilience in infrastructure systems have been performed, e.g., the evaluation [39]–[44] and the optimization [23], [45], [46]. By reviewing the previous studies, Ouyang divided them into six types, i.e., empirical methods, agent based methods, system dynamics based methods, economic theory based methods, network based methods, and others [47].

As discussed above, it can be seen that most of the existing works based on the percolation theory neglect the role of the non-giant component. However, the small size component is likely also to be active for a certain condition in real-world systems. Thus, exploring the effect of the small size component on the robustness and the resilience is meaningful. In addition, it is natural that the quicker the repair strategy makes the recovery of the performance, the higher the resilience of the system is. Although there exist researches [31], [33], [35], [36] that adopt the simple measures for nodes to determine the order of repaired nodes, the existing measure for a node can only reflect its importance within a network, rather than that within an interdependent network, which means that the resilience of the interdependent network is not the highest according to the order obtained by these measures. Therefore, it is necessary to develop a more effective approach in the consideration of the characteristic of interdependent networks to obtain the order of repaired nodes. Besides, subjects in these studies are mainly interdependent power-communication systems, but some mechatronic systems containing the mechanical equipment (e.g., a high-speed train, an airplane, and so on) do not receive enough attention.

With consideration of the improved cascading failure mechanism, our aim is to analyze the resilience (i.e., the recovery of the robustness after attacks) in the interdependent mechatronic system under repair strategies defined by the single and interdependent measures. In order to address the existing issues and achieve the goal, we model the mechatronic system as an interdependent machine-electricity-communication network. Then, by considering the feature in real-world systems, we put forward a cascading failure model where the non-giant component is likely to be functional. By means of the measure of a node (i.e., the degree, the betweenness centrality, the harmonic closeness centrality, the PageRank, the eigenvector centrality and the subgraph centrality), called the single measures, the interdependent measures are defined by these corresponding single measures in this article so that the repair strategies are obtained by the single measures and the interdependent measures. The methodology is applied to a case study in a real-world mechatronic system. Experiments show that the small size component is related to the robustness and the resilience, and the repair strategies concerning the interdependent measures make the network resilience stronger.

II. MODEL

A. INTERDEPENDENT MACHINE-ELECTRICITY-COMMUNICATION NETWORKS

A complex network is an efficient analysis tool to explore the performance of the real-life complex system. Recently, the studies on interdependent networks have attracted a lot of attention for exploring the cascading failure, which majorly focuses on the robustness of interdependent power-communication networks, interdependent power-transportation networks, and so on. However, in reality, different from the existing interdependent networks, many real systems (e.g., interdependent mechatronic systems) are comprised of mechanical and electronic equipment, and communication devices for the specific function. For this purpose, in this article, we build an interdependent machine-electricity-communication network (IMECN) with three subnetworks which are a machine network (MN), an electricity network (EN), and a communication network (CN) and denoted as $G_m = (V_m, E_m)$, $G_e = (V_e, E_e)$, and $G_c = (V_c, E_c)$, respectively. In a subnetwork, a node represents the minimum maintenance equipment. If fasteners (e.g., bolt, screw, welding and so on) connect equipment p (corresponding node i) with equipment q (corresponding node j), there exists an edge between nodes i and j within the machine network. In this same way, if the equipment needs the power supply (the control signal) to work, the corresponding node is also in the electricity network (the communication network). When there exists an electric current (a packet) between two components, corresponding nodes have an edge with each other within the electricity network (the communication network). When nodes i and j from different subnetworks refer to the same equipment, node i has an interdependency link with node j, and node i is the dependent node of node j and vice versa. Namely, a one-to-one correspondence between any two subnetworks is established.

B. CASCADING FAILURE MODEL IN IMECN

Most of the previous works with regard to the cascading failure in the interdependent network utilize the percolation theory to decide whether the failure propagation is triggered [1]–[4], [6], [7], [10], [12]–[14], [17], [18]. In terms of the percolation theory, it is assumed that the component containing the most nodes, namely the giant component, can keep the normal function, which means that the nodes belonging to the component with the fewer nodes fail to work. Obviously, it is not reasonable for real-world systems because the nodes in the non-giant component are able to work normally under specific conditions. For example, a communication network may break into some clusters if a node malfunctions in it, but the nodes in these clusters still have the ability to receive and send data. The phenomenon shows that the small size cluster cannot be ignored in the cascading failure model for real systems.

Considering the above reason, in the interdependent machine-electricity-communication network, we propose a more reasonable cascading failure model where for the active non-giant component c_i in a subnetwork, two conditions need to be satisfied: (1) it has at least an interdependency link with the other two subnetworks, respectively, and (2) its size proportion p_{c_i} is not smaller than the proportion threshold δ, where the size proportion p_{c_i} of the component c_i equals the proportion of its size in the subnetwork size. Note that the giant component having interdependency links with different subnetworks is considered to be active regardless of the proportion threshold δ. The assumption is more reasonable because it takes into account the role of the small size component and the fact that a mechatronic system needs the power supply and the control sign to conduct a certain function. Once a component fails to work, all nodes within the component malfunction, which causes all edges of these nodes (including the intra-link within the subnetwork and the interdependency link between subnetworks) and their dependent nodes to be removed. This may break the subnetwork into some small components and trigger the cascading failure. The dynamical process of cascading failures in the IMECN is described in Fig.1.

As shown in Fig.1, when node M1 is attacked at stage1, all its edges and the dependent node (E1) are removed at stage2. Due to the failure of E1, this causes its intra-link, interdependency link, and dependent node (C1) to be deleted. Therefore, there are two components in every subnetwork at stage 2. Because the size proportion of the component (E2 and E3) is smaller than the proportion threshold δ, it also breaks down and the nodes within it are also removed at stage 3, which leads to the malfunctions of M3 and C4. Then, M3, C4, and the single node (M2) are removed at stage4. Owing to the absence of the interdependency link in the component (C2, C3, and C5), this component also malfunctions, which results in the failure of E4. In the end, cascading failures stop and the component (M4, M5, and M6), the component (E5, E6, and E7), and the component (C6, C7, and C8) are functional.

C. RECOVERY MODEL IN IMECN

In order to investigate the resilience of IMECN, we also give the recovery model by repairing the failed node. It is assumed that when node i is repaired, according to the topology structure of interdependent networks without attacks, the edge ij linking up the active node j is restored. On the contrary, if the repaired node i has an edge with node k before attacks, the edge ik between these two nodes cannot be recovered temporarily in the case of the failure of node k. Until the failed node k is repaired, the edge ik also recovers. It is worth mentioning that after the repair of the node, in consideration of the above assumption of the active component, there may exist some single repaired nodes or inactive components

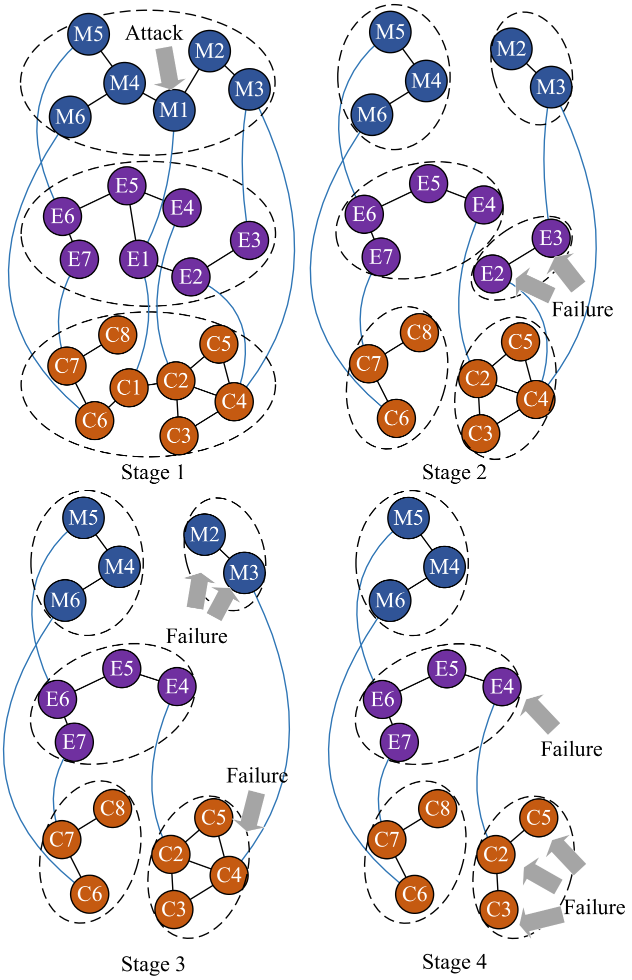

FIGURE 1. The dynamical process of cascading failures under $\delta = 0.3$ in the IMECN. The blue nodes (M1, M2, M3, M4, M5, and M6), the purple nodes (E1, E2, E3, E4, E5, E6, and E7), and the orange nodes (C1, C2, C3, C4, C5, C6, C7, and C8) represent the nodes in the machine, electricity, and communication networks, respectively. The black and blue lines represent the intra-link within subnetworks and the interdependency link between subnetworks.

that lack interdependency links from the other two subnetworks or have the size proportion smaller than the proportion threshold. For simplicity, the node belonging to this inactive component during the recovery process is called the limited functional node. In this case, these single repaired nodes, limited functional nodes, and their repaired edges cannot be removed. However, we do not count these two kinds of nodes in active nodes. As long as the single repaired node connects with the active component, this node is considered to be functional again and counted in functional nodes. In a similar manner, when the inactive component satisfies the demands for the interdependency links from two subnetworks and the larger size proportion, the limited functional node also has the ability to operate.

Generally speaking, after cascading failures caused by attacking nodes, repairing the important broken node is prone to greatly recover the robustness, indicating that the importance of the node is closely related to the resilience of IMECN. There are a lot of measures for nodes, such as the degree, the betweenness centrality, the harmonic closeness centrality, the PageRank, the eigenvector centrality, and the subgraph centrality. The degree k_i of node i can reflect its local information, which is defined as,

$$k_i = \sum_{i=1}^{n} a_{ij} \tag{1}$$

where a_{ij} represents the element of adjacent matrix A, which equals 1 when node i connects with node j, and 0 otherwise. n is the number of nodes in a subnetwork.

The betweenness centrality bc_i of node i can reflect its importance in the subnetwork, which is expressed as,

$$bc_i = \sum_{s \neq i \neq t} \frac{\sigma_{st}(i)}{\sigma_{st}} \tag{2}$$

where $\sigma_{st}(i)$ is the number of shortest paths from node s to node t through node i and σ_{st} is the total number of shortest paths between node s and node t.

The harmonic closeness centrality hcc_i of node i quantifies the distance between it and the centre of the network, which is defined as,

$$hcc_i = \frac{1}{n-1} \sum_{i \neq j} \frac{1}{d_{ij}} \tag{3}$$

where d_{ij} stands for the shortest distance between node i and node j.

The PageRank of a node is dependent on not only the one of the adjacent node but also the degree of the adjacent node, which is similar to the definition of the eigenvector centrality. The PageRank pr_i of node i is defined as,

$$pr_i = (1-d) + d \sum_{i=1}^{n} a_{ij} \frac{pr_j}{k_j} \tag{4}$$

where d is a damping factor and equals 0.85 usually.

The eigenvector centrality takes into account the importance of the adjacent nodes. The eigenvector centrality ec_i of node i is defined as,

$$ec_i = \frac{1}{\lambda} \sum_{j=1}^{n} a_{ij} ec_j \tag{5}$$

where λ is the largest eigenvalue of the adjacency matrix A.

The subgraph centrality of a node characterizes its participation in structural subgraphs and gives higher weights to the smaller subgraph. The subgraph centrality sc_i of node i is defined as,

$$sc_i = \sum_{k=0}^{\infty} \frac{\mu_k(i)}{k!} \tag{6}$$

where $\mu_k(i) = (A^k)_{ii}$.

Due to the fact that the active component needs at least two interdependency links from different subnetworks, it is natural to preferentially restore the node with the interdependency link. In general, repairing a node whose dependent node has the large measure is likely to quickly recover the robustness in the interdependent network even though this node is not a hub node. This is because the operation of a node is decided by its dependent node. On the contrary, the restoration of a critical node with the high measure may not lead to a significant recovery of the robustness when its dependent node has the small measure. Therefore, it is necessary to take into account the measures of the single node and its dependent node so that the importance of the node can be accurately quantified. It should be noted that we normalize these single measures due to their differences in three subnetworks. To this end, we propose interdependent measures that equal the sum of the normalized single measures of the node and its dependent node, i.e., the interdependent degree, the interdependent betweenness centrality, the interdependent harmonic closeness centrality, the interdependent PageRank, the interdependent eigenvector centrality and the interdependent subgraph centrality in the light of the feature of the interdependent network. The interdependent degree id_{A_i} of node A_i in subnetwork A is defined as:

$$id_{A_i} = \frac{d_{A_i} - d_A \min}{d_A \max - d_A \max} + \sum_{B_j \in \Phi_{A_i}} \frac{d_{B_j} - d_B \min}{d_B \max - d_B \min} \tag{7}$$

where d_{A_i} represents the degree of node A_i in subnetwork A. $d_A \min$ and $d_A \max$ represent the minimum and maximum degrees in subnetwork A, respectively. Φ_{A_i} denotes the set of the dependent node from different subnetworks for node A_i. B_j denotes the dependent node of node A_i in subnetwork B. Similarly, the interdependent betweenness centrality ibc_{A_i}, the interdependent harmonic closeness centrality $ihcc_{A_i}$, the interdependent PageRank ipr_{A_i}, the interdependent eigenvector centrality iec_{A_i}, and the interdependent subgraph centrality isc_{A_i} in subnetwork A are respectively defined as,

$$ibc_{A_i} = \frac{bc_{A_i} - bc_A \min}{bc_A \max - bc_A \min} + \sum_{B_j \in \Phi_{A_i}} \frac{bc_{B_j} - bc_B \min}{bc_B \max - bc_B \min} \tag{8}$$

$$ihcc_{A_i} = \frac{hcc_{A_i} - hcc_A \min}{hcc_A \max - hcc_A \min} + \sum_{B_j \in \Phi_{A_i}} \frac{hcc_{B_j} - hcc_B \min}{hcc_B \max - hcc_B \min} \tag{9}$$

$$ipr_{A_i} = \frac{pr_{A_i} - pr_A \min}{pr_A \max - pr_A \min} + \sum_{B_j \in \Phi_{A_i}} \frac{pr_{B_j} - pr_B \min}{pr_B \max - pr_B \min} \tag{10}$$

$$iec_{A_i} = \frac{ec_{A_i} - ec_A \min}{ec_A \max - ec_A \min} + \sum_{B_j \in \Phi_{A_i}} \frac{ec_{B_j} - ec_B \min}{ec_B \max - ec_B \min} \tag{11}$$

$$isc_{A_i} = \frac{sc_{A_i} - sc_A \min}{sc_A \max - sc_A \min} + \sum_{B_j \in \Phi_{A_i}} \frac{sc_{B_j} - sc_B \min}{sc_B \max - sc_B \min} \tag{12}$$

where bc_{A_i}, hcc_{A_i}, pr_{A_i}, ec_{A_i}, and sc_{A_i} represent the betweenness centrality, the harmonic closeness centrality, the PageRank, the eigenvector centrality and the subgraph centrality of node A_i in subnetwork A, respectively. $bc_A \min$, $hcc_A \min$, $pr_A \min$, $ec_A \min$, and $sc_A \min$ represent the minimum values of the betweenness centrality, the harmonic closeness centrality, the PageRank, the eigenvector centrality, and the subgraph centrality in subnetwork A, respectively. $bc_A \max$, $hcc_A \max$, $pr_A \max$, $ec_A \max$, and $sc_A \max$ represent the maximum values of these five measures in subnetwork A, respectively.

According to the difference of the definitions, repair strategies could be divided into two cases, i.e., the repair strategies regarding the single measures and the ones regarding the interdependent measures. By means of these single measures (i.e., the degree, the betweenness centrality, the harmonic closeness centrality, the PageRank, the eigenvector centrality, and the subgraph centrality), we propose six repair strategies to obtain the effective order of the repaired node. Without loss of generality, we also take into account the random repair. Repair strategies concerning single measures are defined as follows:

1) Random repair strategy (RRS). The failed node in the IMECN is sorted randomly.
2) Degree repair strategy (DRS). The failed node in the IMECN is sorted in the descending order of its degree.
3) Betweenness centrality repair strategy (BCRS). The failed node in the IMECN is sorted in the descending order of its betweenness centrality.
4) Harmonic closeness centrality repair strategy (HCCRS). The failed node in the IMECN is sorted in the descending order of its harmonic closeness centrality.
5) PageRank repair strategy (PRRS). The failed node in the IMECN is sorted in the descending order of its PageRank.
6) Eigenvector centrality repair strategy (ECRS). The failed node in the IMECN is sorted in the descending order of its eigenvector centrality.
7) Subgraph centrality repair strategy (SCRS). The failed node in the IMECN is sorted in the descending order of its subgraph centrality.

Additionally, on the basis of the interdependent measures, the corresponding repair strategies are defined as follows:

1) Interdependent degree repair strategy (IDRS). The failed node in the IMECN is sorted in the descending order of its interdependent degree.
2) Interdependent betweenness centrality repair strategy (IBCRS). The failed node in the IMECN is sorted in the descending order of its interdependent betweenness centrality.
3) Interdependent harmonic closeness centrality repair strategy (IHCCRS). The failed node in the IMECN is sorted in the descending order of its interdependent harmonic closeness centrality.
4) Interdependent PageRank repair strategy (IPRRS). The failed node in the IMECN is sorted in the descending order of its interdependent PageRank.
5) Interdependent eigenvector centrality repair strategy (IECRS). The failed node in the IMECN is sorted in

the descending order of its interdependent eigenvector centrality.

6) Interdependent subgraph centrality repair strategy (ISCRS). The failed node in the IMECN is sorted in the descending order of its interdependent subgraph centrality.

According to the orders obtained by these repair strategies, the failed node is repaired one by one. Note that if the measures of some nodes are the same, they will be randomly recovered.

D. QUANTIFICATION OF ROBUSTNESS AND RESILIENCE

To quantify the impact of cascading failures by attacks, we use the relative size of active nodes $R(t)$ to assess the robustness of IMECN at simulation step t, which is defined as follows:

$$R(t) = (\frac{n_m(t)}{N_m} + \frac{n_e(t)}{N_e} + \frac{n_c(t)}{N_c})/3 \tag{13}$$

where $n_m(t)$, $n_e(t)$, and $n_c(t)$ are the numbers of remaining functional nodes belonging to the active components in machine, electricity, and communication networks at simulation step t, respectively. N_m, N_e, and N_c are the numbers of nodes in these subnetworks, respectively. It is clear that the larger $R(t)$, the stronger the robustness of IMECN against cascading failures.

Although some studies on the resilience have been conducted, their focus is to assess the ability to resist the perturbations, which is similar to the evaluation of the robustness. In this article, the resilience of IMECN is defined as the ability to recover the performance of IMECN to a certain level after extreme perturbations. In view of the framework [37] and the relative size of active nodes $R(t)$, we utilize the recovery ability RA to quantify the resilience, which is expressed as,

$$RA = \frac{2\int_{t_s}^{t_f}(R(t) - R(t_s))dt}{[1 - R(t_s)][N_m + N_e + N_c - n_m(t_s) - n_e(t_s) - n_c(t_s)]} \tag{14}$$

where t_s represents the time when the attacks stop and the repair processes start, and t_f represents the time when the repair of all broken nodes finishes. That is to say, IMECN is in the disruptive process by attacking the active node one by one in the range of $t \leq t_s$, while the one is in the recovery process by repairing the failed node one by one in the range of $t_s < t \leq t_f$. Note that theoretically, there exists an optimal repair strategy that can change a failed node into an active node at each simulation step in the case of meeting the conditions of the active component, therefore $R(t)$ linearly restores and $RA = 1$ when $N_m = N_e = N_c$. On the contrary, there also exists a worst repair strategy, under which the active component occurs until the last failed node is repaired, so $RA = 0$. In general, the recovery of $R(t)$ is slow at the start of the recovery process since the repaired node hardly forms an active component, while the robustness recovers quickly at the end of the recovery process. Thus, $0 < RA < 1$. Obviously, the larger RA, the higher the resilience of IMECN.

Additionally, it is worth emphasizing a specific condition that during the recovery process, the component may not satisfy the demand for the operation when most of the nodes malfunction, and thus the value of $R(t)$ keeps unchanged after a few nodes are repaired. To this end, we also define the critical number of repaired nodes r_c, above which the value of $R(t)$ increases from 0 to a certain value but below which no active component occurs. Apparently, for the smaller value of r_c, the paralyzed IMECN is able to faster return to the partial function.

These three indexes emphasize different aspects of the resilience. $R(t)$ reflects the change of the performance during the recovery process in IMECN, while RA indicates the resilience level during the whole recovery process. In order to enable the collapsing IMECN to have the partial function again, r_c focuses on the minimal cost in the worst-case scenario.

III. RESULTS

As a typical mechatronic system, a high-speed train is composed of a traction system, a braking system, a train control system, and so on, where a lot of machine, electricity, and communication components (e.g., a traction motor, a gear box, a sensor, etc) operate together. Consequently, we take the high-speed train as an example to perform a case study. The topology of the interdependent machine-electricity-communication network, including MN with 144 nodes and 180 edges, EN with 75 nodes and 125 edges, and CN with 62 nodes and 71 edges, respectively, is obtained by CRHX high-speed train in China. Additionally, there are 55, 38, and 38 interdependency links among MN-EN, MN-CN, and EN-CN, respectively.

The malfunction of equipment randomly occurs in most cases, hence we quantify the robustness of IMECN by randomly removing a node and all its edges at each simulation step when $t \leq t_s$. In order to have a better statistic, all simulation processes in this article are repeated 1000 times. According to the cascading failure model, we first carry out the simulations on the robustness at $\delta = 0$, $\delta = 0.1$, and $\delta = 0.6$. It is worth mentioning that when the component has two kinds of interdependent links from different subnetworks, $\delta = 0$ corresponds to the case that the component is active no matter what its size is, while $\delta = 0.6$ corresponds to the case that it having the largest size is active.

As shown in Fig.2(a), it is clear that the smaller δ, the larger the mean value of $R(t)$ because the node belonging to the component with the small size can continue to operate for the smaller value of δ. This indicates that the component with the small size is closely correlated with the robustness. Similarly, the minimum value of $R(t)$ also decreases with the increase of δ. On the contrary, there is a slight difference among the maximum values of $R(t)$ for different δ. The main reason is that the value of $R(t)$ can be maximized only if the low degree nodes are attacked preferentially.

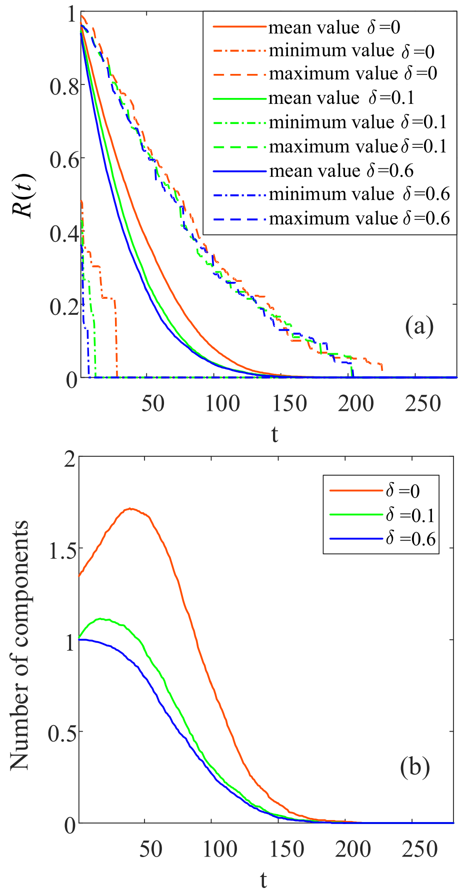

FIGURE 2. **The relative size of active nodes $R(t)$ is shown as a function of the simulation step t in the cases of $\delta = 0$, $\delta = 0.1$, and $\delta = 0.6$ (a). The number of components is shown as a function of the simulation step t in the cases of $\delta = 0$, $\delta = 0.1$, and $\delta = 0.6$ (b).**

During this process, the network does not split into several clusters and there exists only one component in a subnetwork usually, therefore the maximum values of $R(t)$ are similar for different values of δ. Owing to the importance of the small size component, we also provide an analysis of the number of components. Fig.2(b) illustrates that there is a negative correlation between δ and the number of components for a given simulation step. Moreover, because of the existence of the small size component, the number of components increases first and then decreases for the range of $\delta < 0.6$ as the simulation step increases. When the values of t at $\delta = 0$ and $\delta = 0.1$ increase to near 40 and 17, respectively, the number of components reaches a maximum. These results show that δ is closely related to the robustness, and the small value of δ makes IMECN more robust against cascading failures.

Since the attack has a serious impact on the robustness of IMECN, our aim is to adopt a reasonable order to effectively repair failed nodes in the remaining part, where the resilience is reflected by the recovery of $R(t)$, r_c, and RA. Taking into account that cascading failures may not lead to the failures of all nodes, we start to repair the broken nodes when the proportion of total failed nodes rises to a given value p_{fail} at simulation step t_s. Based on the repair strategies concerning the single measures, simulation results are presented under different values of δ and p_{fail} in Fig.3.

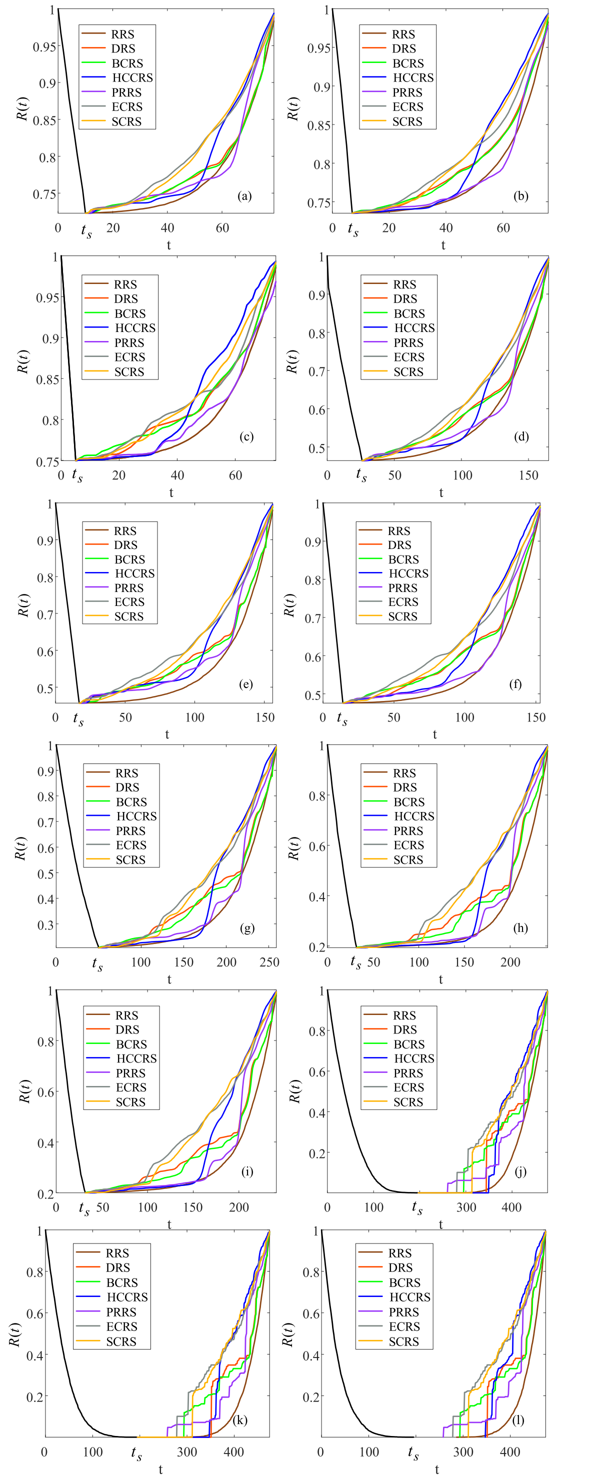

FIGURE 3. **Comparison of $R(t)$ under repair strategies concerning the single measures in the cases of (a) $\delta = 0$, (b) $\delta = 0.1$, and (c) $\delta = 0.6$ when $p_{fail} = 25\%$. That under repair strategies concerning the single measures in the cases of (d) $\delta = 0$, (e) $\delta = 0.1$, and (f) $\delta = 0.6$ when $p_{fail} = 50\%$. That under repair strategies concerning the single measures in the cases of (g) $\delta = 0$, (h) $\delta = 0.1$, and (i) $\delta = 0.6$ when $p_{fail} = 75\%$. That under repair strategies concerning the single measures in the cases of (j) $\delta = 0$, (k) $\delta = 0.1$, and (l) $\delta = 0.6$ when $p_{fail} = 100\%$.**

From Figs.3(a)-(c), it can be found that during the recovery process at $p_{fail} = 25\%$ for different δ, the robustness exhibits a slow recovery process with the increase of δ under repair strategies except for ECRS and SCRS. Moreover, the curves of ECRS and SCRS are higher than the ones of other repair strategies on the whole, indicating that according to the eigenvector centrality and the subgraph centrality to restore the failed nodes, IMECN is more resilient in the case of a small number of failed nodes. This is due to the fact that the node with the high eigenvector centrality either connects with the hub node or has the high degree, which means that repairing this node enables it to reconnect with the large size component in consideration of its degree and the importance of its adjacent node. In terms of the subgraph centrality, it reflects the information on the local and whole network. Therefore, restoring the node with the high subgraph centrality can make IMECN more resilient. Besides, when t is large, the value of $R(t)$ obtained by HCCRS is larger than others for $\delta = 0.6$ while there is little difference among repair strategies for $\delta = 0$ and $\delta = 0.1$, which implies that δ affects the recovery of $R(t)$ when $p_{fail} = 25\%$.

In Figs.3(d)-(l), during the early period of the recovery (i.e., the small value of t), it can be seen that as the values of p_{fail} increase to 50%, 75% and 100%, respectively, there is a common ground that ECRS and SCRS still yield better performance regardless of δ. In the latter period of the recovery (i.e., the large value of t), the values of $R(t)$ obtained by HCCRS, ECRS, and SCRS are high in the cases of $p_{fail} = 50\%$, $p_{fail} = 75\%$, and $p_{fail} = 100\%$. Therefore, it is efficient to restore a lot of broken nodes by HCCRS, ECRS and SCRS. When t increases to a large enough value (i.e., the recovery of almost all failed nodes), the results of different repair strategies are similar. For all repair strategies, IMECN with RRS shows a low resilience, while PRRS is an ineffective repair strategy in most cases in terms of repair strategies regarding the single measure. In addition, the change of δ has little impact on $R(t)$ during the recovery processes under different repair strategies when $p_{fail} = 50\%$, $p_{fail} = 75\%$ and $p_{fail} = 100\%$.

Although the results of $R(t)$ at $p_{fail} = 50\%$ and $p_{fail} = 75\%$ are similar to the ones at $p_{fail} = 100\%$, it is worth emphasizing a specific detail that the value of $R(t)$ keeps unchanged after a few broken nodes are restored at $t > t_s$ in the case of $p_{fail} = 100\%$. This is because even though several failed nodes are repaired when all nodes malfunction, no active components occur in three subnetworks. Thus, it is meaningful to investigate how many failed nodes need to be repaired so that IMECN no longer collapses. The values of r_c under different repair strategies are shown in Fig.4.

In Fig.4, it is evident that for different values of δ, the values of r_c under RRS are larger than others. Interestingly, although the value of $R(t)$ under PRRS slowly increases, the value of r_c under the one is the smallest, i.e., $r_c = 63$, which implies that IMECN starts to have the partial function after we give priority to restoring at least 63 nodes with the high PageRank. The second-best repair strategy is ECRS in

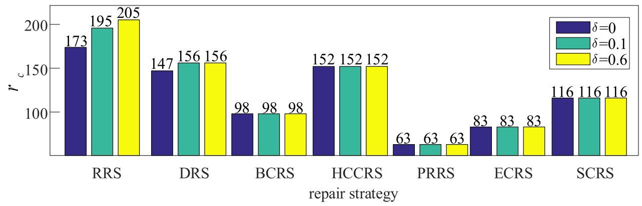

FIGURE 4. Comparison of r_c under repair strategies concerning the single measures when $p_{fail} = 100\%$.

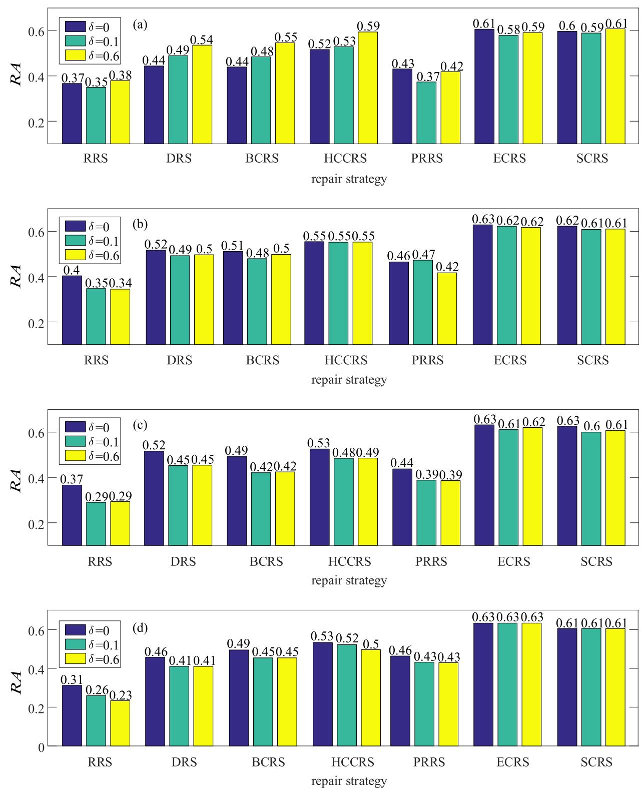

FIGURE 5. Comparison of RA under repair strategies concerning the single measures in the cases of (a) $p_{fail} = 25\%$, (b) $p_{fail} = 50\%$, (c) $p_{fail} = 75\%$, and (d) $p_{fail} = 100\%$.

terms of r_c. Additionally, when the simulation step t increases from t_s to a certain value, there may exist a component in every subnetwork usually. If these three components have two kinds of interdependent links, they must be functional according to the assumption about the active component no matter what δ is. This is because a single component in every subnetwork is the giant component regardless of δ. Consequently, it can be found that varying the value of δ has little effect on r_c for different repair strategies. Especially for BCRS, HCCRS, PRRS, ECRS and SCRS, the values of r_c under them are the same for different δ.

What can be clearly seen in Fig.5(a) is a great impact of δ on RA in the case of $p_{fail} = 25\%$. However, in Fig.5(d), when p_{fail} increases to 100%, the values of RA are similar to each other for different δ under any repair strategy. Especially for ECRS, the values of RA equal 0.63 for the arbitrary value of δ. These results imply that increasing the number of failed nodes weakens the impact of δ on RA. Moreover, Fig.5 reveals that the values of RA obtained by ECRS and SCRS are much higher than the ones obtained by other repair strategies no matter what δ and p_{fail} are. This finding suggests that for enhancing the resilience, it is more efficient to repair failed nodes by their eigenvector centralities in the matter of repair strategies concerning single measures, which also agrees with the analysis of Fig.3.

In the above section, the repair strategies concerning the single measures have been discussed in detail. It can be concluded that, in terms of the recovery of $R(t)$ and RA, ECRS and SCRS are effective repair strategies for different p_{fail} and δ, while PRRS makes r_c small. Additionally, δ has an impact on $R(t)$ and RA in the case of a small number of failed nodes. In order to study the resilience of IMECN under the repair strategies concerning the interdependent measures, we complete the comparison of $R(t)$, r_c, and RA among these repair strategies for different values of δ and p_{fail}.

As shown in Figs.6(a)-(i), it is apparent that the repair strategies with the interdependent measures except for IHCCRS yield better performance, indicating that compared with single measures, interdependent measures can clearly identify the important node that needs to be repaired with a higher priority. In particular, under IPRRS, IECRS, and ISCRS, the corresponding values of $R(t)$ exhibit a nearly linear increase with the increase of t for different values of δ and p_{fail}, which indicates that IMECN possesses the higher resilience to restore the failed node with high interdependent PageRank, interdependent eigvector centrality, or interdependent subgraph centrality. Moreover, we observe that the curve of IDRS is similar to the one of IBCRS regardless of δ and p_{fail}. The values of $R(t)$ obtained by these two repair strategies significantly increase in the range of small t, but the curves show a slow rise near the end of the recovery process. Additionally, a remarkable phenomenon is that the recovery speed of the robustness in IMECN under IHCCRS becomes slow as δ increases from 0 to 0.6 when p_{fail} is small (e.g., $p_{fail} = 25\%$ and $p_{fail} = 50\%$). However, the curve of IHCCRS is insensitive to the change of δ when $p_{fail} = 75\%$ and $p_{fail} = 100\%$. The above result suggests that in the case of using the interdependent measure to restore failed nodes, δ has a great impact on the resilience for the small p_{fail}, which is similar to the case of using the single measure. In Fig.6(j)-(l), it is worth noting that the collapsed IMECN under most of repair strategies starts to possess functions once the recovery process begins. To this end, we also pay attention to the critical number of repaired nodes r_c under repair strategies with the interdependent measures, whose results are presented in Fig.7.

Fig.7 demonstrates that the values of r_c obtained by IDRS, IBCRS, IPRRS, IECRS and ISCRS are significantly smaller than the ones obtained by IHCCRS. In particular, $r_c = 13$ under IPRRS indicates that after 13 broken nodes with the high interdependent PageRank are restored at least, IMECN restores its partial function, which is much fewer than 63 repaired nodes under PRRS (see Fig.4). This is because, considering that the functional component needs the

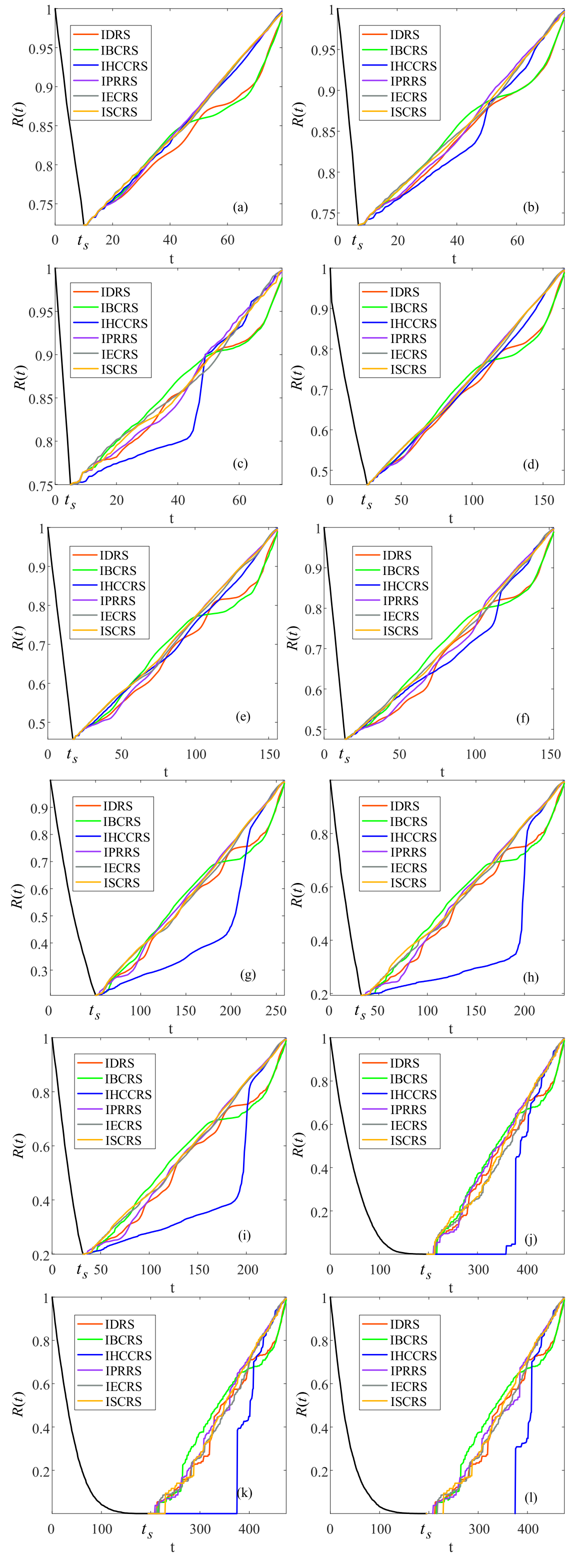

FIGURE 6. Comparison of $R(t)$ under repair strategies concerning the interdependent measures in the cases of (a) $\delta = 0$, (b) $\delta = 0.1$, and (c) $\delta = 0.6$ when $p_{fail} = 25\%$. That under repair strategies concerning the interdependent measures in the cases of (d) $\delta = 0$, (e) $\delta = 0.1$, and (f) $\delta = 0.6$ when $p_{fail} = 50\%$. That under repair strategies concerning the interdependent measures in the cases of (g) $\delta = 0$, (h) $\delta = 0.1$, and (i) $\delta = 0.6$ when $p_{fail} = 75\%$. That under repair strategies concerning the interdependent measures in the cases of (j) $\delta = 0$, (k) $\delta = 0.1$, and (l) $\delta = 0.6$ when $p_{fail} = 100\%$.

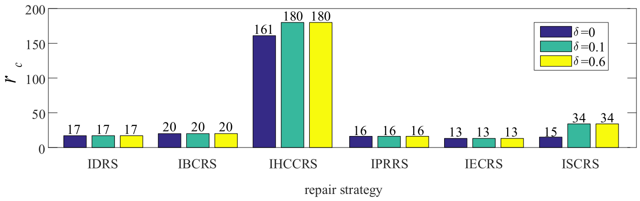

FIGURE 7. Comparison of r_c under repair strategies concerning the interdependent measures when p_{fail} = 100%.

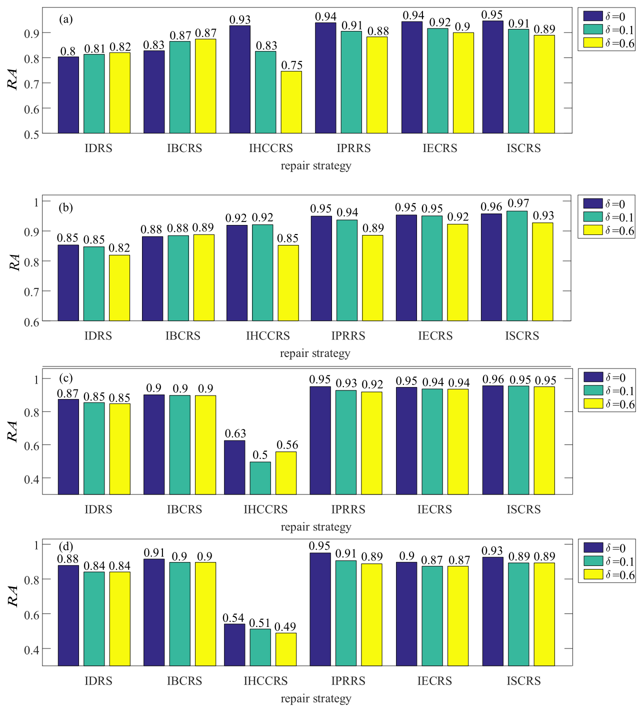

FIGURE 8. Comparison of ***RA*** under repair strategies concerning the interdependent measures in the cases of (a) p_{fail} = 25%, (b) p_{fail} = 50%, (c) p_{fail} = 75%, and (d) p_{fail} = 100%.

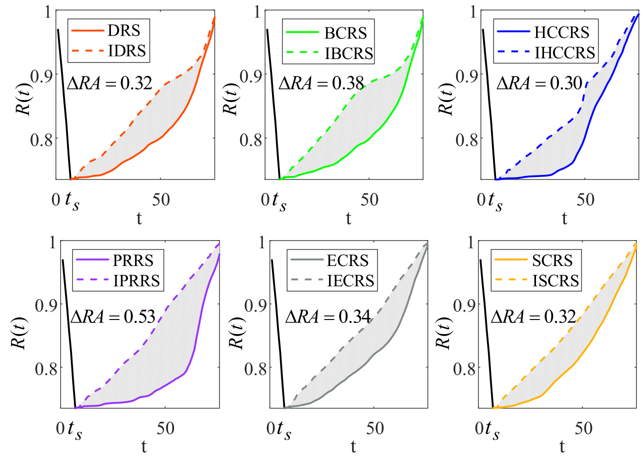

FIGURE 9. Comparison between repair strategies with the single measures and the ones with the interdependent measures in the case of $\delta = 0.1$ and p_{fail} = 25%.

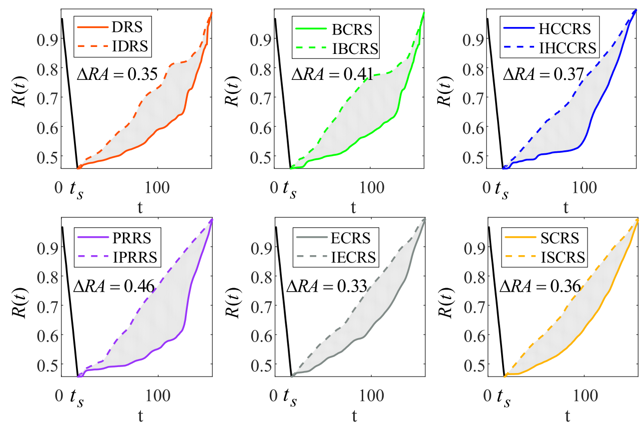

FIGURE 10. Comparison between repair strategies with the single measures and the ones with the interdependent measures in the case of $\delta = 0.1$ and p_{fail} = 50%.

interdependency link, the repair strategies with regard to the interdependent measures give priority to the repair of the failed node with one or two interdependency links. Under this condition, the functional component occurs more quickly after a few failed nodes are restored. Additionally, we find no significant difference of r_c under these repair strategies for different δ.

As we can see in Fig.8, under repair strategies with the interdependent measures, especially for IHCCRS, there exists a great difference in the values of *RA* at different δ when $p_{fail} = 25\%$ and $p_{fail} = 50\%$ while the values of *RA* slightly change by varying the value of δ when $p_{fail} = 75\%$ and $p_{fail} = 100\%$. The phenomenon shows that δ has an effect on the resilience under repair strategies with interdependent measures for a small number of failed nodes, which is similar to the case of repair strategies with single measures (see Fig.5). In addition, it can be found that the values of *RA* obtained by IPRRS, IECRS, and ISCRS are large no matter what δ and p_{fail} are. This can be interpreted that the interdependent PageRank, interdependent eigvector centrality, and the interdependent subgraph centrality proposed in this article can reflect the importance of its adjacent node and dependent node so restoring the node with these high interdependent measures tends to form the functional components with the interdependency link in three subnetworks. Besides, we can see that in terms of IHHCRS, the recovery of $R(t)$ is slow in Fig.8 (c) and $R(t)$ almost keeps unchanged at the start of the recovery process in Fig.8 (d), therefore the values of *RA* obtained by repair strategies with interdependent measures except for IHHCRS are high at $p_{fail} = 75\%$ and $p_{fail} = 100\%$.

The above simulation results indicate that the resilience of IMECN under IECRS and ISCRS is strong on the whole in the matter of $R(t)$ and *RA*, while IMECN under IHCCRS has small r_c. Furthermore, δ has a negative effect on the resilience for small p_{fail}. In order to carefully compare two kinds of repair strategies with the single and interdependent measures, $R(t)$, r_c, and ΔRA are shown under these repair strategies, where ΔRA equals the value of *RA* obtained by a repair strategy with an interdependent measure minus the one obtained by a repair strategy with its corresponding single measure.

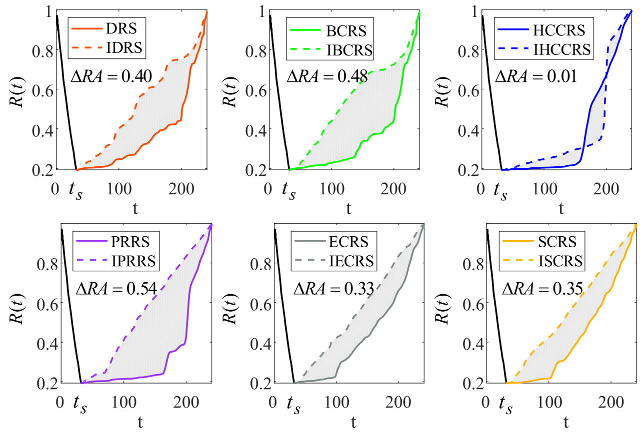

FIGURE 11. Comparison between repair strategies with the single measures and the ones with the interdependent measures in the case of $\delta = 0.1$ and $p_{fail} = 75\%$.

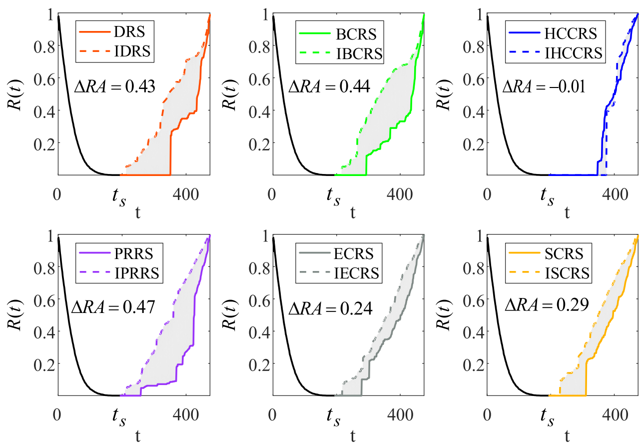

FIGURE 12. Comparison between repair strategies with the single measures and the ones with the interdependent measures in the case of $\delta = 0.1$ and $p_{fail} = 100\%$.

From Figs.9-12, we can observe the differences of $R(t)$ and r_c among repair strategies concerning single measures and interdependent measures and the gray area represents the difference of RA. Because the interdependent measure gives consideration to the role of the dependent node, their repair strategies yield better performance in most instances. An obvious phenomenon is that in contrast to the repair strategies concerning the single measures, the ones concerning the interdependent measures result in the higher value of $R(t)$ regardless of p_{fail} during the recovery process except for the case concerning the harmonic closeness centrality at $p_{fail} = 75\%$ and $p_{fail} = 100\%$, which indicates that the recovery of the robustness is quicker according to repair strategies with interdependent measures. In Fig.12, it is apparent that the small values of r_c under IDRS, IBCRS, IPRRS, IECRS and ISCRS indicate that IMECN no longer paralyses and has the partial function by restoring a few broken nodes selected by their interdependent measures. In addition, $\Delta RA > 0$ in most cases illustrates that the repair strategies with the interdependent measures can make IMECN more resilient compared with the ones with the single measures. On the basis of these discussions, it is found that the repair strategies concerning the interdependent measures proposed in this article significantly enhance the resilience of IMECN.

IV. CONCLUSION

The resilience of interdependent networks has drawn increasing attention. In this study, we propose a cascading failure model for the interdependent machine-electricity-communication network (IMECN), in which the non-giant component is also active when its size proportion is not smaller than the proportion threshold δ and it has two kinds of interdependency links. In order to restore the performance of IMECN subjected to attacks, by defining the interdependent measure, we obtain the repair strategies concerning the single and interdependent measures. Then, the simulations on the impact of δ on the robustness and the resilience are carried out. In addition, in the light of the quantification of the resilience by the values of $R(t)$, r_c, and RA, we vary δ and the proportion p_{fail} of failed nodes to compare repair strategies. Based on these experiments, the advantages of the repair strategies with the interdependent measures are analyzed.

The simulation results illustrate that there is a negative correlation between δ and the robustness in IMECN. In addition, the impact of δ on the resilience is more significant in the range of small p_{fail} under repair strategies with single and interdependent measures. In terms of repair strategies concerning the single measures, the recovery of $R(t)$ is quick and the recovery ability RA is strong under ECRS and SCRS no matter what δ and p_{fail} are, while the critical number of repaired nodes r_c under PRRS is small for the recovery of the partial function in IMECN. In terms of $R(t)$ and RA among the repair strategies concerning the interdependent measures, IPRRS, IECRS, and ISCRS outperform other repair strategies regardless of δ and p_{fail}. Except for IHCCRS, repair strategies concerning the interdependent measures give rise to the small critical number of repaired nodes. Furthermore, we find that IMECN under repair strategies with interdependent measures has the strong resilience in contrast to the one under repair strategies with single measures. In the future work, we intend to optimize the resilience of IMECN based on heuristic algorithms, and compare the advantages and disadvantages between the optimized strategy and the repair strategy proposed in this article. In addition, by considering the physical properties of different kinds of equipment, we will also attempt to develop a framework of the failure propagation for the interdependent mechatronic system, which can more fully capture the behavior of the cascading failures. To sum up, our work may contribute to effectively recovering the performance in the real-life mechatronic system after disturbance events.

REFERENCES

[1] S. V. Buldyrev, R. Parshani, G. Paul, H. E. Stanley, and S. Havlin, "Catastrophic cascade of failures in interdependent networks," *Nature*, vol. 464, no. 7291, p. 1025, 2010.

[2] J. Gao, S. V. Buldyrev, S. Havlin, and H. E. Stanley, "Robustness of a network of networks," *Phys. Rev. Lett.*, vol. 107, no. 19, p. 195701, 2011.

[3] S. Havlin, H. E. Stanley, A. Bashan, J. Gao, and D. Y. Kenett, "Percolation of interdependent network of networks," *Chaos, Solitons Fractals*, vol. 72, pp. 4–19, Mar. 2015.
[4] R. Parshani, S. V. Buldyrev, and S. Havlin, "Interdependent networks: Reducing the coupling strength leads to a change from a first to second order percolation transition," *Phys. Rev. Lett.*, vol. 105, no. 4, p. 48701, Jul. 2010.
[5] J. Wang, Y. Li, and Q. Zheng, "Cascading load model in interdependent networks with coupled strength," *Phys. A, Stat. Mech. Appl.*, vol. 430, pp. 242–253, Jul. 2015.
[6] R.-Q. Li, S.-W. Sun, Y.-L. Ma, L. Wang, and C.-Y. Xia, "Effect of clustering on attack vulnerability of interdependent scale-free networks," *Chaos, Solitons Fractals*, vol. 80, pp. 109–116, Nov. 2015.
[7] S. Shao, X. Huang, H. E. Stanley, and S. Havlin, "Robustness of a partially interdependent network formed of clustered networks," *Phys. Rev. E, Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top.*, vol. 89, no. 3, p. 32812, Mar. 2014.
[8] Z. Chen, W.-B. Du, X.-B. Cao, and X.-L. Zhou, "Cascading failure of interdependent networks with different coupling preference under targeted attack," *Chaos, Solitons Fractals*, vol. 80, pp. 7–12, Nov. 2015.
[9] M. Tian, X. Wang, Z. Dong, G. Zhu, J. Long, D. Dai, and Q. Zhang, "Cascading failures of interdependent modular scale-free networks with different coupling preferences," *EPL (Europhys. Lett.)*, vol. 111, no. 1, p. 18007, Jul. 2015.
[10] Y. Hao, L. Jia, and Y. Wang, "Cascading failures in interdependent scale-free networks of different coupling preferences with the harmonic closeness," *EPL (Europhys. Lett.)*, vol. 127, no. 3, p. 38003, Sep. 2019.
[11] L. Zhou, X. Qi, and L. Liu, "The robustness of interdependent networks with traffic loads and dependency groups," *IEEE Access*, vol. 8, pp. 98449–98459, May 2020.
[12] X. Huang, J. Gao, S. V. Buldyrev, S. Havlin, and H. E. Stanley, "Robustness of interdependent networks under targeted attack," *Phys. Rev. E, Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top.*, vol. 83, no. 6, p. 65101, Jun. 2011.
[13] G. Dong, J. Gao, R. Du, L. Tian, H. E. Stanley, and S. Havlin, "Robustness of network of networks under targeted attack," *Phys. Rev. E, Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top.*, vol. 87, no. 5, p. 52804, May 2013.
[14] Y. Hao, L. Jia, and Y. Wang, "Edge attack strategies in interdependent scale-free networks," *Phys. A, Stat. Mech. Appl.*, vol. 540, Feb. 2020, Art. no. 122759.
[15] X. Gao, M. Peng, C. K. Tse, and H. Zhang, "A stochastic model of cascading failure dynamics in cyber-physical power systems," *IEEE Syst. J.*, vol. 14, no. 3, pp. 4626–4637, Sep. 2020.
[16] Y. Zhang and O. Yagan, "Robustness of interdependent cyber-physical systems against cascading failures," *IEEE Trans. Autom. Control*, vol. 65, no. 2, pp. 711–726, Feb. 2020.
[17] Z. Huang, C. Wang, M. Stojmenovic, and A. Nayak, "Characterization of cascading failures in interdependent cyber-physical systems," *IEEE Trans. Comput.*, vol. 64, no. 8, pp. 2158–2168, Aug. 2015.
[18] Y. Chen, Y. Li, W. Li, X. Wu, Y. Cai, Y. Cao, and C. Rehtanz, "Cascading failure analysis of cyber physical power system with multiple interdependency and control threshold," *IEEE Access*, vol. 6, pp. 39353–39362, Jul. 2018.
[19] D. T. Nguyen, Y. Shen, and M. T. Thai, "Detecting critical nodes in interdependent power networks for vulnerability assessment," *IEEE Trans. Smart Grid*, vol. 4, no. 1, pp. 151–159, Mar. 2013.
[20] B. Moussa, P. Akaber, M. Debbabi, and C. Assi, "Critical links identification for selective outages in interdependent power-communication networks," *IEEE Trans. Ind. Informat.*, vol. 14, no. 2, pp. 472–483, Feb. 2018.
[21] W. Wei, S. Mei, L. Wu, J. Wang, and Y. Fang, "Robust operation of distribution networks coupled with urban transportation infrastructures," *IEEE Trans. Power Syst.*, vol. 32, no. 3, pp. 2118–2130, May 2017.
[22] A. M. Farid, "A hybrid dynamic system model for multimodal transportation electrification," *IEEE Trans. Control Syst. Technol.*, vol. 25, no. 3, pp. 940–951, May 2017.
[23] Q. Zou and S. Chen, "Enhancing resilience of interdependent traffic-electric power system," *Rel. Eng. Syst. Saf.*, vol. 191, Nov. 2019, Art. no. 106557.
[24] C. Heracleous, P. Kolios, C. G. Panayiotou, G. Ellinas, and M. M. Polycarpou, "Hybrid systems modeling for critical infrastructures interdependency analysis," *Rel. Eng. Syst. Saf.*, vol. 165, pp. 89–101, Sep. 2017.
[25] B. Wu, A. Tang, and J. Wu, "Modeling cascading failures in interdependent infrastructures under terrorist attacks," *Rel. Eng. Syst. Saf.*, vol. 147, pp. 1–8, Mar. 2016.
[26] B. Wang, S. Wan, X. Zhang, and K.-K.-R. Choo, "A novel index for assessing the robustness of integrated electrical network and a natural gas network," *IEEE Access*, vol. 6, pp. 40400–40410, Jul. 2018.
[27] A. Marzuoli, E. Boidot, E. Feron, P. B. C. van Erp, A. Ucko, A. Bayen, and M. Hansen, "Multimodal impact analysis of an airside catastrophic event: A case study of the Asiana crash," *IEEE Trans. Intell. Transp. Syst.*, vol. 17, no. 2, pp. 587–604, Feb. 2016.
[28] L. M. Shekhtman, M. M. Danziger, and S. Havlin, "Recent advances on failure and recovery in networks of networks," *Chaos, Solitons Fractals*, vol. 90, pp. 28–36, Sep. 2016.
[29] A. Majdandzic, B. Podobnik, S. V. Buldyrev, D. Y. Kenett, S. Havlin, and H. E. Stanley, "Spontaneous recovery in dynamical networks," *Nature Phys.*, vol. 10, no. 1, pp. 34–38, Jan. 2014.
[30] M. Gong, L. Ma, Q. Cai, and L. Jiao, "Enhancing robustness of coupled networks under targeted recoveries," *Sci. Rep.*, vol. 5, no. 1, p. 8439, Feb. 2015.
[31] Y. Shang, "Localized recovery of complex networks against failure," *Sci. Rep.*, vol. 6, no. 1, p. 30521, Jul. 2016.
[32] M. Gong, Y. Wang, S. Wang, and W. Liu, "Enhancing robustness of interdependent network under recovery based on a two-layer-protection strategy," *Sci. Rep.*, vol. 7, no. 1, p. 12753, Oct. 2017.
[33] M. A. Di Muro, C. E. La Rocca, H. E. Stanley, S. Havlin, and L. A. Braunstein, "Recovery of interdependent networks," *Sci. Rep.*, vol. 6, no. 1, p. 22834, Mar. 2016.
[34] J. Gao, B. Barzel, and A. L. Barabasi, "Universal resilience patterns in complex networks," *Nature*, vol. 530, no. 7590, p. 307, Feb. 2016.
[35] U. Bhatia, D. Kumar, E. Kodra, and A. R. Ganguly, "Network science based quantification of resilience demonstrated on the Indian railways network," *PLoS ONE*, vol. 10, no. 11, Nov. 2015, Art. no. e0141890.
[36] K. L. Clark, U. Bhatia, E. A. Kodra, and A. R. Ganguly, "Resilience of the U.S. National airspace system airport network," *IEEE Trans. Intell. Transp. Syst.*, vol. 19, no. 12, pp. 3785–3794, Dec. 2018.
[37] M. Bruneau, S. E. Chang, R. T. Eguchi, G. C. Lee, T. D. O'Rourke, A. M. Reinhorn, M. Shinozuka, K. Tierney, W. A. Wallace, and D. von Winterfeldt, "A framework to quantitatively assess and enhance the seismic resilience of communities," *Earthq. Spectra*, vol. 19, no. 4, pp. 733–752, Nov. 2003.
[38] M. Ouyang, L. Dueñas-Osorio, and X. Min, "A three-stage resilience analysis framework for urban infrastructure systems," *Struct. Saf.*, vols. 36–37, pp. 23–31, May 2012.
[39] Y. Gu, X. Fu, Z. Liu, X. Xu, and A. Chen, "Performance of transportation network under perturbations: Reliability, vulnerability, and resilience," *Transp. Res. E, Logistics Transp. Rev.*, vol. 133, Jan. 2020, Art. no. 101809.
[40] W. Zhang and N. Wang, "Resilience-based risk mitigation for road networks," *Struct. Saf.*, vol. 62, pp. 57–65, Sep. 2016.
[41] H. Fotouhi, S. Moryadee, and E. Miller-Hooks, "Quantifying the resilience of an urban traffic-electric power coupled system," *Rel. Eng. Syst. Saf.*, vol. 163, pp. 79–94, Jul. 2017.
[42] M. Ouyang and Z. Wang, "Resilience assessment of interdependent infrastructure systems: With a focus on joint restoration modeling and analysis," *Rel. Eng. Syst. Saf.*, vol. 141, pp. 74–82, Sep. 2015.
[43] R. Francis and B. Bekera, "A metric and frameworks for resilience analysis of engineered and infrastructure systems," *Rel. Eng. Syst. Saf.*, vol. 121, pp. 90–103, Jan. 2014.
[44] C. Nan and G. Sansavini, "A quantitative method for assessing resilience of interdependent infrastructures," *Rel. Eng. Syst. Saf.*, vol. 157, pp. 35–53, Jan. 2017.
[45] Y. Almoghathawi, K. Barker, and L. A. Albert, "Resilience-driven restoration model for interdependent infrastructure networks," *Rel. Eng. Syst. Saf.*, vol. 185, pp. 12–23, May 2019.
[46] M. Ouyang and Y. Fang, "A mathematical framework to optimize critical infrastructure resilience against intentional attacks," *Comput.-Aided Civil Infrastruct. Eng.*, vol. 32, no. 11, pp. 909–929, Nov. 2017.
[47] M. Ouyang, "Review on modeling and simulation of interdependent critical infrastructure systems," *Rel. Eng. Syst. Saf.*, vol. 121, pp. 43–60, Jan. 2014.

YUCHENG HAO is currently pursuing the Ph.D. degree with the School of Traffic and Transportation, Beijing Jiaotong University, Beijing, China. His research interests include complex network analysis, complex system analysis, railway systems reliability and safety, and safety technology and engineering.

LIMIN JIA received the Ph.D. degree from the China Academy of Railway Sciences, Beijing, in 1991. He is currently with the State Key Laboratory of Rail Traffic Control and Safety, Beijing Jiaotong University. His current research interests include safety science and engineering, control science and engineering, transportation engineering, safety technology and engineering, and system science.

YANHUI WANG received the Ph.D. degree from the University of Science and Technology Beijing, Beijing, China, in 2003. He is currently with the State Key Laboratory of Rail Traffic Control and Safety, Beijing Jiaotong University. His current research interests include rail transit operation reliability and safety, intelligent transportation systems, urban rail transit network operation management, and traffic model.

ZHICHAO HE is currently pursuing the Ph.D. degree with the School of Traffic and Transportation, Beijing Jiaotong University, Beijing, China. His research interests include rail transit operation reliability and safety, intelligent transportation systems, and urban rail transit network operation management.