Research Article

Online Decision-Making of Parallel Restoration Strategy for Power Systems Based on Susceptible-Infected-Recovered Model

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Parallel restoration following blackouts can reduce economic and social losses. This paper aims to develop a parallel restoration method coordinating the partitioning scheme of the blackout system and restoration strategies of subsystems. The susceptible-infected-recovered model, i.e., a virus propagation model of complex networks, is used to decide the parallel restoration strategies online. Firstly, various types of viruses are used to represent different subsystems. The probability vector of virus infection is obtained according to the importance level of each bus. Secondly, an immunization strategy is developed based on the faulted buses in the blackout situation. According to the infection rate and the immunization strategy, the virus propagation direction will be changed based on real-time system conditions. The startup characteristics of units and the charging reactive power of restoration paths are considered as constraints to embed in the virus propagation process. Finally, the partitioning scheme and the restorative actions for subsystems are determined based on the infected results of viruses. The effectiveness of the proposed method is validated by case studies on the IEEE 39-bus and the IEEE 118-bus test systems.

1. Introduction

In the past few decades, there have been several major blackouts around the world [1, 2]. For instance, in 2019, blackouts occurred in Venezuela, Argentina, and the UK. Reasonable and effective restoration strategies should be developed to restore the blackout systems after power outages. Most utilities and system operators have made parallel restoration plans for blackouts, reducing the outage time and the economic loss effectively [3–6]. The parallel restoration tasks are to partition the blackout system and restore the generated subsystems in parallel.

Generally, partitioning principles for parallel restoration are shown in [7–9]. Utilities and system operators usually determine partitioning strategies based on geographic information and expert experience [5]. Nevertheless, they lack theoretical support. Reference [10] proposed the ordered binary decision graph (OBDD) algorithm to generate restoration subsystems. Reference [11] proposed a cut-set matrix-based partitioning method for parallel restoration. These recursive bisection-based methods create two new subsystems in one iteration. Thus, it needs to execute the procedure multiple times to get multiple subsystems. Since the power system has the characteristic of complex networks [12], algorithms in the theory of complex networks, e.g., the Girven Newman (GN) algorithm [13], and the spectral clustering method [14], are used to generate multiple subsystems with low complexity. These methods provide suitable partitioning strategies for large power systems. However, the interaction between partitioning the blackout system and restoring partitioned subsystems is complex. An effective partitioning scheme, which can facilitate the subsequent restoration, should be developed.

The second fundamental problem of parallel restoration is to develop restoration strategies of subsystems. In a subsystem, the blackstart (BS) unit is restarted to restore the
non–blackstart (NBS) units sequentially. The problem of the unit startup sequence is usually formulated as an optimization model. Various methods, e.g., mixed-integer linear programming [15] and genetic algorithm [16], are used to solve it. Based on predesigned partitioning plans, the unit startup sequence of each subsystem can be determined by these methods. Some researchers have studied the coordination of the partitioning and the subsystem restoration in parallel restoration. Reference [17] proposed a bi-level programming-based sectionalizing method considering the restoration of generators and critical loads. Based on the benders decomposition, reference [18] decomposed the problem of parallel restoration. The master problem is about the unit startup sequence, and the subproblem is about the partitioning scheme. Reference [19] formulated the unit startup sequence and the system partitioning as a single-objective optimization model. However, vast unrestored buses without connecting generators or loads in the existing methods were not classified into any subsystems. Thus, the boundaries of subsystems are not clear. It increases the difficulty of executing restoration strategies.

Most of the existing approaches for parallel restoration are based on the scenarios before blackouts. The results of partitioning and restoration are obtained based on offline data, in which all devices are assumed to be available for service restoration. The impact of faulted devices on the subsequent restoration strategy is not considered, so the results based on offline data cannot meet the actual situation. Furthermore, during the restoration process, buses of the system may be destroyed by extreme events or mal-operations. Since faulted buses cannot be forecasted, the offline restoration plans were not suitable for online applications. Restoration strategies according to the blackout system condition changing in real-time should be adjusted.

This paper proposes a susceptible-infected-recovered (SIR) model-based method to determine parallel restoration strategies, including the partitioning strategy of the whole system and the restoration strategies of different generated subsystems. Since the SIR model in complex networks has the characteristics of low computational complexity, high computational accuracy, and great classification ability [20], it is suitable for online decision-making of parallel restoration. Multiple subsystems are obtained considering the BS ability, the generation-load balance of subsystems, and the actual blackout situation. The methodology proposed here also provides the restoration schemes of different subsystems that satisfy constraints on unit startup, power flow, etc. The information representing the blackout system’s real-time state is used to formulate and adjust the parallel restoration strategy. Hence, the proposed method adapts various blackout conditions.

The major contributions of this paper are given as follows.

1. An optimization model for the parallel restoration of power systems based on the SIR model is developed, integrating the partitioning and restoration models. This optimization model considers the partitioning problem and the restoration problem simultaneously.

2. A scalable, efficient, and accurate SIR model-based parallel restoration algorithm with low computational complexity is proposed. All buses are divided into subsystems so that the boundaries of subsystems are specific.

3. The impact of faulted buses on the determination of restoration strategies is considered. The faulted buses are used to formulate the immunization vector of the SIR model, which helps to adjust the subsequent parallel restoration strategy based on the real-time system.

The remainder of this paper is organized as follows. An online decision support system for parallel power system restoration is presented in Section 2. The proposed parallel restoration model is introduced in Section 3. Section 4 provides the parallel restoration method based on the SIR model. Section 5 presents the simulation results, followed by conclusions.

2. Framework of Online Decision Support System

The online decision process of parallel power system restoration includes partitioning and subsystem restoration, shown in Figure 1. It is worth mentioning that the real-time data should guarantee the online decision. Therefore, it is assumed that the communication system and the monitoring devices are available after blackouts. Based on the information technology, the framework of parallel
restoration is constructed. First, system data are acquired online by the energy management system (EMS). Dispatchers can be aware of the current condition of the blackout system. Then, based on the blackout information, the partitioning scheme is generated by using the SIR-based method. The unrestored unit startup sequence and the corresponding restoration paths in each subsystem are also obtained. Finally, dispatchers carry out the partitioning scheme and the restoration actions via the EMS. During the restoration process, if the next restored bus cannot be repaired quickly, the procedure will recognize the state and adjust the partitioning scheme and subsequent restoration strategies.

An effective online decision-making strategy depends on a complete communication system. With the development of communication technologies and energy storage systems, the communication system can usually keep operation after blackouts. Thus, the communication system is assumed to work in this paper.

3. Parallel Restoration Model

3.1. Objective. The ultimate goal of power system restoration is to restore all the outage loads as quickly and safely as possible. Therefore, the optimal objective of the proposed restoration model is to generate more active power in the shortest time. During power system restoration, the charging reactive power of restored paths should be as little as possible to prevent overvoltage. Thus, this paper defines a multi-objective function, including the total time of restoring units, the total active power from NBS units in a specified period, and the total charging reactive power of restored paths.

\[
\begin{align*}
F_1 &= \min \left\{ F_1, F_2, F_3 \right\}, \\
F_1 &= \sum_{m=1}^{N_S} \left( \sum_{l=1}^{N_{G_m}} T_l + T_{\text{start}_m} \right), \\
F_2 &= -\sum_{m=1}^{N_S} P_{G_m}^m (T), \\
F_3 &= \sum_{m=1}^{N_S} \sum_{i=1}^{N_{G_m}} Q_t,
\end{align*}
\]

where \(T_l\) is the charging time of line \(l\) in the restoration path; \(T_{\text{start}_m}\) is the cranking time of unit \(m\); \(P_{G_m}^m\) is the output active power of unit \(m\) at \(t\)-th step; \(Q_t\) is the charging reactive power of line \(l\) in the restoration path; \(N_{G_m}\) is the number of restored units at \(t\)-th step; \(N_{G_m}\) is the number of transmission lines to restore unit \(m\) at \(t\)-th step; \(T\) is the specified restoration period. This paper defines \(T\) as the time when the last unit is connected to the grid.

3.2. Constraints

3.2.1. The Number of Subsystems. Each subsystem must contain a BS unit at least, i.e.,

\[
H \leq M,
\]

where \(H\) is the number of subsystems and \(M\) is the number of BS units. Maximizing the number of subsystems helps accelerate the parallel restoration. Thus, it assumed that each subsystem exists only one BS unit in this paper. The maximum number of subsystems is achieved and equals to the number of BS units.

3.2.2. The Balance of Active Power. There should be sufficient loads in each subsystem to ensure the stable operation of units [21].

\[
\sum_{m=1}^{N_S} \alpha_m C_{G_m} - \sum_{s=1}^{N_{P_b}} P_{L_s} \leq 0,
\]

where \(C_{G_m}\) is the maximum output active power of unit \(m\). \(P_{L_s}\) is the active load of bus \(s\). \(N_{P_b}\) is the total number of restored units. \(N_{P_b}\) is the total number of restored buses. \(\alpha_m\) is the minimum technical output coefficient of the unit \(m\). Generally, \(\alpha_m\) of thermal power units varies from 25% to 35%, whereas that of hydropower units is 0 [18].

3.2.3. The Size of Subsystems. It takes an extended time to restore oversize subsystems. Generating oversize subsystems delay the restoration process [18]. Thus, this paper limits the maximum size of each subsystem.

\[
\max_{1 \leq i \leq M} D_{BS,i} \leq L_{\text{max}},
\]

where \(D_{BS,i}\) is the shortest connection from the BS unit to bus \(i\) in each subsystem; \(L_{\text{max}}\) is the maximum size of subsystems, which can be adjusted by dispatchers according to the actual system.

3.2.4. The Observability. The definition of observability constraint is as follows [22]. The observability constraint ensures that each bus is observable either by at least one of its neighboring buses or by itself.

\[
\sum_{j \in V_i} z_{ij} r_j + r_i \geq 1,
\]

where \(V_i\) is set of the number of buses adjacent to bus \(i\). \(z_{ij}\) is a binary decision variable and represents the relationship between bus \(i\) and bus \(j\). If bus \(i\) and \(j\) are the adjacent buses and both are in the same subsystem, \(z_{ij}\) equals 1; otherwise, \(z_{ij}\) equals 0. Variable \(r_i\) indicates whether PMU exists at bus \(i\). It can be calculated by multiple methods. If the observability constraint is not satisfied, some buses in the partitioning result are not observable. New partitioning schemes should be generated. \(z_{ij}\) is updated based on the new scheme for examining this constraint.
3.2.5. The Startup Time of Units. After blackouts, the generator has two states: hot-start and cold-start and there are two constraints of start time including $T_{1m}^r$ and $T_{1m}^c$. The NBS unit should be restarted within a maximum critical time; otherwise, it has to be restarted after a time delay.

$$0 < T_{1m}^r < T_{1m}^c,$$  \hspace{0.5cm} (7)

$$T_{1m}^c > T_{1m}^r,$$  \hspace{0.5cm} (8)

where $T_{1m}^r$ is the startup time of unit $m$ at $t$-th step. $T_{1m}^c$ is the maximum hot-start time of unit $m$ and $T_{1m}^c$ is the minimum cold-start time of unit $m$. The temperature of outage units reduces following blackouts. If $T_{1m}^c$ is shorter than $T_{1m}^c$, the temperature of unit $m$ is still in the temperature internal of hot-start. Unit $m$ can be restarted quickly. If $T_{1m}^r$ is longer than $T_{1m}^c$, the temperature of unit $m$ is out of the temperature internal of hot-start. It must take plenty of time to reduce the temperature of the unit for cold-start. If $T_{1m}^c$ is longer than $T_{1m}^c$, unit $m$ is suitable for cold-start. Thus, the value of $T_{1m}^c$ is larger than $T_{1m}^c$. Formulas (7) and (8) cannot be combined. During the restoration process, units need to be restarted as soon as possible; otherwise, they will be delayed to restart.

3.2.6. The Cranking Power of Units. Power systems need to provide enough cranking power to restart the unrestored NBS units. Thus, the following constraint should be checked during the restoration process.

$$\sum_{m=1}^{N_u} \left[ P_{1m}^c - P_{1m}^{start} \right] > 0,$$  \hspace{0.5cm} (9)

where $P_{1m}^{start}$ is the power required to restart unit $m$.

3.2.7. The Overvoltage. Overvoltage has to be considered when restoration paths are energized [23].

$$\sum_{k=1}^{N_b} Q_{1k} - \sum_{k=1}^{N_b} Q_{1k}^p = \sum_{m=1}^{N_u} Q_{1m},$$  \hspace{0.5cm} (10)

where $Q_{1k}^p$ is the reactive load of bus $k$ at $t$-th step. $Q_{1m}$ is the reactive power absorbing capability of the restored unit $m$. $N_u$ is the number of restored transmission lines at $t$-th step. $N_b$ is the number of restored buses at $t$-th step.

3.2.8. The Power Flow

$$\begin{align*}
P_{0m} = P_{0m}^{Gm}, & \quad m = 1, 2, \ldots, N_u, \\
U_{k} \leq U_{k}^\text{max}, & \quad k = 1, 2, \ldots, N_b, \\
P_{b} \leq P_{b}^\text{max}, & \quad b = 1, 2, \ldots, N_b,
\end{align*}$$  \hspace{0.5cm} (11)

where $P_{0m}^{Gm}$ and $P_{0m}^{Gm}$ denote the maximum and minimum active power output of unit $m$; $U_{k}$ is the voltage magnitudes of bus $k$. $U_{k}^\text{max}$ and $U_{k}^\text{min}$ denote the maximum and minimum voltage magnitudes of bus $k$, respectively.

$P_{b}$ and $P_{b}^\text{max}$ are the power and the maximum acceptable value of transmission line $b$, respectively.

Constraints (2)–(6) are related to the partitioning schemes, whereas constraints (7)–(11) are used for developing the restoration strategies of subsystems. $H, T_{0}^m, P_{0m}, N_{G}^m, N_{G}^m, N_{b}^m, N_{b}^m, Q_{E_b},$ and $z_{ij}$ are decision variables. $T_{m}, M, a_{m}, I_{max}, T_{1m}^r, T_{1m}^c, P_{Gm}^{Gm}, P_{Gm}^{Gm}, U_{k}^\text{max}, U_{k}^\text{min}, U_{b}, P_{b}, P_{b}^\text{max}, D_{BS}, n_{P}^{start}, T_{1m}^c, Q_{0}, T_{b}, Q_{Gm}, r_n, V_{b}, C_{Gm}, P_{L_b}, N_{G}^m,$ and $N_{b}$ are parameters.

4. The Proposed Parallel Restoration Method

This section presents the partitioning strategy and the subsystem restoration strategies for parallel restoration based on the SIR model. First, the graph representation of a power system in a blackout and the basic introduction of the SIR model are described. Then, the parallel power system restoration method based on the SIR model is proposed. Besides, the flowchart of the proposed strategy is shown in the last subsection.

4.1. Graph Representation and SIR Model

4.1.1. Graph Representation of a Power System. A power grid is abstracted as an undirected graph based on the rules in [24]. In the power graph, this paper uses two indexes to evaluate the importance of nodes, $k_i$ and $c_i$, respectively. $k_i$ is the closeness centrality of node $i$, which is usually calculated by the node contraction method [25]. $k_i$ evaluates the importance of node $i$ by summarizing all the distances between node $i$ and other nodes. For a connected network, $k_i$ is defined as inverse of the mean shortest distances from node $i$ to all other nodes.

$$k_i = \frac{1}{n_i \sum_{p,q} d_{min,p,q}^i / (n_i (n_i - 1)/2)},$$  \hspace{0.5cm} (12)

where $n_i$ is the total number of nodes in the network after node $i$ is contracted. $d_{min,p,q}^i$ is the number of branches in the shortest connection path between nodes $p$ and $q$ after the node contraction. $V_i$ is a set of all nodes in the network. The closeness centrality reflects the importance of a node in the network. The larger the closeness centrality is, the more significant the corresponding node is.

The other index reflecting the physical characteristics is the node capacity $c_i$. It represents the carrying capacity of a node. The larger the node capacity is, the more important the node is.

$$c_i = \frac{C_i}{C_0},$$  \hspace{0.5cm} (13)

$$C_i = \sum_{ij} C_{ij},$$  \hspace{0.5cm} (14)

where $C_{ij}$ is the rated capacity of edge $i-j$ and $C_i$ is the sum of the rated capacity of all edges connecting node $i$. $C_0$ is the based capacity. Generally, the node with the largest capacity
in the network is selected as the based capacity. The value of $c_i$ can reflect the importance of node $i$.

4.1.2. The SIR Model of Viruses Propagation. For the SIR model, there are three states on nodes in a network: susceptible-state (S-state), infected-state (I-state), and recovered-state (R-state) [26]. During the virus propagation process, S-state nodes are healthy but can be infected by the virus. The nodes that have been infected by the virus are in I-state. They can infect adjacent S-state nodes with probability $\alpha$. The infected nodes are recovered from the I-state to R-state with probability $\delta$. What is more, viruses cannot infect the R-state nodes again. The SIR model can describe the transmission dynamics of various viruses in complex networks. Nodes host the individuals who can propagate viruses, and edges constitute virus’ propagate paths in a network [26]. The number of nodes in different states of a power system should be accommodated at the $t$-th virus propagation.

$$S(t) + I(t) + R(t) = V,$$  \hspace{1cm} (15)

where $S(t)$, $I(t)$, and $R(t)$ represent the number of S-state, I-state, and R-state nodes, respectively. $V$ is the total number of nodes in the network.

(i) No immunization nodes

A classical virus propagation process of the SIR model is shown in Figure 2. This paper defines two subsets of nodes with two types of virus information, i.e., a type virus information in node 1 and $b$ type virus information in node 10. Hence, nodes 1 and 10 are the I-state nodes. The other nodes in the network are in S-state. They can change their states during the virus propagation process. The infected nodes can be obtained until the virus propagation stops. Nodes 1, 2, 3, 4, and 5 infected by $a$ type virus are divided into subnetwork 1. Nodes 6, 7, 8, 9, and 10 infected by $b$ type virus are in subnetwork 2. Thus, the SIR model can be used to partition networks. Since viruses propagate following specific rules, modeling significant restoration constraints as the propagation rules can generate subsystem restoration strategies during the virus propagation process.

(ii) With immunization nodes

The nodes, which viruses cannot infect, are defined as the immunization nodes [27]. The edges connecting to the immunized nodes are removed from the network, and the number of possible paths for virus propagation is reduced. Thus, the virus propagation process can be changed by adopting immunization strategies. For example, nodes 5 and 6 are set as the immunization nodes, as shown in Figure 3. During the virus propagation process, edges 3–5, 4–5, 5–6, 6–7, and 6–8 are removed from the network. Nodes 5 and 6 are not infected by any viruses. Thus, the process of virus propagation differs from the process in Figure 2.

4.2. Parallel Restoration Method Based on SIR Model. In this paper, the SIR model is applied to the parallel restoration of power system. The buses of power system are abstracted as the nodes of a graph. During the virus propagation process for determining the partitioning scheme, buses infected by the same virus become the I-state buses and are divided into the same subsystem. It means that the partitioning scheme is based on the I-state buses. R-state buses represent the buses recovered from I-state buses. Since the R-state buses cannot be re-infected by any virus, they are used for representing the restored portion in this paper. The BS unit generates the cranking power to restart NBS units via restoration paths in a subsystem. A restoration path consists of transmission lines or transformers restored from the outage state. If a transmission line or a transformer in a subsystem is restored, the I-state buses at both ends of the corresponding line or transformer change to R-state buses. Thus, the restoration path depends on the buses whose state changes from I-state to R-state in each decision-making step.

The propagation process of the virus simulates the partition and restoration process of the power system. The proposed parallel restoration method based on the SIR model includes three parts: initialization, refinement, and decision-making.
4.2.1. Initialization Model

(1) Initialization Based on Characteristics of Power Systems.

(i) Initial Infection Matrix

Viruses propagate among buses. S-state can be infected by various types of viruses. Since a type of virus indicates a subsystem, the buses infected by the same type of viruses are in the same subsystem. For an n-bus power system, an infection matrix \( F_t \) is proposed to determine the partitioning scheme in \( t \)-th step of virus propagation,

\[
F_t = [f_{i,h}]_{nxH} = \begin{cases} 
1, & \text{bus } i \text{ in subsystem } h, \\
0, & \text{bus } i \text{ not in subsystem } h.
\end{cases}
\]

where \( i = 1, 2, \ldots, n; h = 1, 2, \ldots, H \). If bus \( i \) is infected by virus \( h \) to become I-state bus in \( t \)-th step, \( f_{i,h} \) equals 1 and bus \( i \) is divided into subsystem \( h \); otherwise, bus \( i \) does not belong to subsystem \( h \) and \( f_{i,h} \) equals 0.

The number of subsystems depends on the number of BS units. In each subsystem, the BS unit provides the cranking power for starting NBS units. Thus, in the initial stage, BS unit buses should be infected by different types of viruses, while other buses of the system are the S-state buses. The initial infection matrix \( F_0 \) can be determined based on the location and the number of BS units, i.e.,

\[
F_0 = [f_{i,h}]_{nxH} = \begin{cases} 
1, & \text{bus } i \text{ is BS unit,} \\
0, & \text{otherwise.}
\end{cases}
\]

(ii) Initial infection probability

The probability vector of virus infection \( W \) denotes the probability that the infected buses infect the neighboring buses through the connecting transmission lines or transformers. For two connecting buses, if their relationship is strong, the probability of virus infection is large. The virus can propagate from a bus to another bus quickly. Considering the topological and physical characteristics of power networks, \( k_i \) and \( c_i \) are used to construct \( W \), i.e.,

\[
W = [w_i] = \omega_1[k_i] + \omega_2[c_i],
\]

where \( \omega_1 \) and \( \omega_2 \) can be obtained by the entropy weight method [28].

4.2.2. Refinement Model

(1) Refinement Based on Current Condition of System. Since some buses are damaged during the blackout and cannot be repaired or replaced quickly, they are not used for service restoration. Offline restoration strategies based on the hypothetical blackout scenarios cannot be applied successfully. Dispatchers should make an online decision on adjusting restoration strategies, considering the real-time state of the blackout system. This paper uses the immunization strategy to refine the \( W \). The faulted buses are immunized and cannot be infected by viruses. Therefore, the refined probability vector of virus infection \( \tilde{W} \) is

\[
\tilde{W} = [\tilde{w}_i] = \begin{cases} 
1 - c, & \text{faulted bus } i, \\
0, & \text{normal bus } i.
\end{cases}
\]

where \( c (0 < c \leq 1) \) is the immunization probability of faulted buses.

(2) Solving Parallel Restoration Problem by SIR Model. \( Y_i \) represents the possibility of bus \( i \) being infected by viruses of other buses. In the \( t \)-th propagation, if S-state bus \( i \)'s neighboring buses are infected by \( Z \) types of viruses, \( Y_{i,t} \) can be calculated:

\[
Y_{i,t} = \max_{z \in Z} \left[ 1 - (1 - \tilde{W})^{\lambda^{(i)}_z} \right],
\]

where \( \lambda^{(i)}_z \) is the number of I-state neighboring buses which were infected by \( z \) type of virus.

To infect all buses in the network with the viruses, the propagation threshold \( \lambda_c \) should be set.

\[
\lambda_c = \min_{i \in \mathbb{N}} \{ \tilde{w}_i \},
\]

\[
\tilde{f}_{i,t} = \begin{cases} 
1, & Y_{i,t} > \lambda_c, \\
0, & Y_{i,t} < \lambda_c.
\end{cases}
\]

I-state bus \( i \) can recover to R-state with probability \( \delta \). According to the recovery matrix \( R \), the R-state buses can be obtained.

\[
R_i = [R_{i,t}] = \begin{cases} 
1, & (1 - \delta) < Y_{i,t}, \\
0, & (1 - \delta) \geq Y_{i,t},
\end{cases}
\]

where \( \delta (0 < \delta \leq 1) \) is the probability of the I-state bus transfer to the R-state bus.

If the process of virus propagation ends, the parallel restoration strategy is output. The various sets of I-state buses construct different subsystems of the blackout system. The order in which buses change from the I-state to the R-state represents the restoration strategy of each subsystem. With viruses propagating among buses, partitioning constraints (2)–(6) and restoration constraints (7)–(11) are checked except for the requirements of the SIR model.

4.2.3. Solving Model

(1) The Process of Parallel Restoration by SIR Model. This paper proposes the parallel restoration method based on the SIR model, including the partitioning scheme and the restoration strategy. The idea of step-by-step decision-making is used to solve the problem of partitioning and restoration.
Set the initial parameters of the system, and set Flag1 = 0, Flag2 = 0

Build the initial infection matrix $F_0$ and the probability vector of virus infection $W$

The state of the grid has changed? No

Get the refined probability vector $\overline{W}$ of buses through immunization strategy

Calculate the node propagation rate $Y_i$ and the propagation threshold $\lambda_c$

Update the infected matrix $F$

Are constraints (2)-(6) satisfied for subsystem $h$? No

The new units were infected? No

All buses have been infected? No

Use the entropy method to solve, and sort the infected units from best to worst $G_{\text{inf}}(m = 1, 2, \ldots, N_{tG})$

The target unit number is defined as $G_m (m = 1)$

$m \leq N_{tG}$? Yes

Attain the restoration path of the target unit $G_m$

Satisfy the constraints (7)-(11)? No

Update the recovery matrix $R$

All units have been restored? No

Flag1 = 1

Flag2 = 1

Flag2 == 1? No

Flag1 == 1? No

Yes

Yes

Output restoration and infection results

End

FIGURE 4: The flow chart of the proposed parallel restoration method.
Each decision-making step is to execute the complete process from S-state to I-state to R-state.

As shown in Figure 4, firstly, the virus starts from the BS unit-buses and spreads to other buses. Some S-state buses are infected by viruses and become I-state buses gradually. Since the partitioning scheme depends on the I-state buses, it is updated with the buses’ state changing from S-state to I-state. Secondly, when the new units are infected, the startup sequence of the infected units is determined based on the calculation results of the objective function in (24). The optimal unit should be selected to be restored, and the other units are involved in the next decision-making step. The I-state buses related to the selected unit and the restoration path are changed to R-state buses. Since the restoration scheme depends on the R-state buses, it is updated with the buses’ state changing from I-state to R-state.

In conclusion, this paper adopts the strategy of infecting each bus with different viruses and achieves the maximum number of subsystems. In each decision-making step, the partitioning scheme and the restoration strategy are updated based on the different states of the buses. They are obtained simultaneously when the proposed method converges.

(2) Model Solving Based on Multistep Decision-Making. This paper uses the greedy algorithm to decompose the unit startup problem into a multistep decision-making problem. The total restoration time consists of the restoration time of each unit. In each decision-making step, the units with the shortest restoration time should be restored so that the total time of restoring all units is as short as possible. The units with the highest climbing rate are also restored so that they can generate as much active power as possible in a specified restoration period. The total charging reactive power of restoration paths can be decomposed into the charging reactive power of each unit’s restoration path. Therefore, the multi-objective function (1) is converted into function (24), including the restoration time of each unit \( f_1 \), the climbing rate of each unit \( f_2 \), and the charging reactive power of each unit’s restoration path \( f_3 \).

\[
\begin{align*}
\min & \quad f_1, f_2, f_3 \\
 f_1 &= \sum_{i=1}^{N_{bs}} T_i + T_{\text{startm}} \\
 f_2 &= \frac{C_{Gm}}{T_m} \\
 f_3 &= \sum_{i=1}^{N_{bs}} Q_i,
\end{align*}
\]

(24)

where \( T_m \) is the time when units ramp to the maximum power output.

The entropy weight method is used for transforming the multiobjective function (24) into a single objective function, i.e., \( \Omega = \gamma_1 f_1 + \gamma_2 f_2 + \gamma_3 f_3 \). \( \gamma_1, \gamma_2, \gamma_3 \) are solved by the entropy weight method. The unit with maximum \( \Omega \) value is selected for restarting in each decision step.

For accelerating the restoration process, as many lines as possible are considered to be restored. Reference [29] proposed an extended blackstart scheme using a single BS unit to restart multiple units simultaneously. Based on [29], this paper proposed a restoration mode of expansion path. For each step to restart an NBS unit, the unit with the first priority and the corresponding restoration path are restored. If the restoring system has abundant capacity for absorbing reactive power, the second priority unit’s restoration path, which is defined as the expansion path, is considered simultaneously. The expansion path that satisfied the restoration constraint in (7)–(11) is selected to be restored.

(3) The Framework of Parallel Restoration. The constraints in the manuscript include the partitioning constraints in (2)–(6), i.e., the number of subsystems, the balance of active power, the size of subsystems, the observability, and the restoration constraints in (7)–(11), i.e., the startup time of units, the cranking power of units, the overvoltage, and the power flow.

As shown in Figure 4, when a new unit is infected by virus, a new partitioning result is obtained and checked by the partitioning constraints in (2)–(6). Then, the startup sequence of the infected units is determined based on the calculation results of the objective function. The unit with the first priority and the corresponding restoration path are selected. A new restoration system including the selected unit and restoration path is formed. If the restoration constraints in (7)–(11) are not satisfied, the unit with the second priority is considered.

The proposed method sets two flags. Flag1 represents the restoration of generation units, whereas Flag2 denotes the partitioning scheme.

Step 1. The initial parameters of the system are input. Flag1 and Flag2 are set as 0.

Step 2. According to the number of buses and BS unit-buses, \( F \) is constructed. Based on the location of BS units, the initial infection matrix \( F_0 \) is determined. Considering the topological and physical characteristics of power networks, the initial infection probability of each bus is calculated and \( W \) is obtained.

Step 3. Based on the blackout scenario, an immunization strategy is online developed. \( W \) is improved to \( \overline{W} \).

Step 4. \( Y_{i,t} \) in the \( t \)-th propagation process is calculated according to bus \( i \)’s infection probability and its neighboring buses’ infection states.

Step 5. According to the relationship between \( Y_{i, t} \) and \( \lambda_i \), the infected matrix \( F \) is updated.

Step 6. Partitioning constraints (2)–(6) are integrated into the virus propagation process. Check whether the 1-state
buses satisfy the constraints. If so, the procedure goes into Step 7. Otherwise, the procedure returns to Step 5.

**Step 7.** Check whether a new unit bus is infected. If so, the procedure goes into Step 10. Otherwise, the procedure goes into Step 8.

**Step 8.** Check whether all buses have been infected. If so, Flag2 is set as 1. The procedure goes into Step 9. Otherwise, the procedure returns to Step 5.

**Step 9.** Check whether Flag1 equals 1. If so, the procedure goes into Step 15. Otherwise, the procedure goes into Step 10.

**Step 10.** The restoration order of the infected unit-buses is sorted from large to small according to the value of the single objective function. The target unit number is defined as $G_m (m = 1)$.

**Step 11.** Check whether $m \leq N_{G'}$. If so, the procedure goes into Step 12. Otherwise, the procedure goes into Step 13.

**Step 12.** The restoration path of the target unit is attained by using Dijkstra’s algorithm. Check whether the constraints (7)–(11) are satisfied. If so, the restoration path of the target unit is restored, and the recovery matrix $R$ is updated. Otherwise, set $m = m + 1$. The procedure returns to Step 11.

**Step 13.** Check whether all units have been restored. If so, Flag1 is set as 1. The procedure goes into Step 14. Otherwise, the procedure returns to Step 5.

**Step 14.** Check whether Flag2 equals 1. If so, the procedure goes into Step 15. Otherwise, the procedure returns to Step 5.

**Step 15.** The buses with the same type of viruses are divided into the same subsystem. The restoration schemes of subsystems are obtained. Finally, the parallel restoration strategy is generated.

### 5. Case Studies

Case studies on the IEEE 39-bus and IEEE 118-bus test systems are used to verify the effectiveness of the proposed method. The proposed method has been simulated in MATLAB R2018b.

#### 5.1. IEEE 39-Bus Test System

In this case, there are two BS units located at buses 30 and 36. Hence, this system can be partitioned into two subsystems. Two types of viruses representing two subsystems infect buses 30 and 36, respectively, in the initial period. The optimal PMU locations refer to [21]. The maximum size of subsystems is set as $L_{max} = 8$ [30]. By applying the entropy weight method, $\omega_1$ is 0.6748 and $\omega_2$ is 0.3252. The detailed data of this system are shown in [18]. Two scenarios are considered in this case. In scenario 1, all buses of this system are available for service restoration following a blackout. This scenario is used for verifying the validity of the proposed method. In scenario 2, bus 5 destroyed by disasters cannot be repaired or replaced for service restoration quickly. Scenario 2 illustrates the impact of faulted buses on the parallel restoration strategy.

#### 5.1.1. Scenario 1: All Buses Are Available for Restoration

It is assumed that every bus of the system is available for service restoration after a blackout. The partitioning scheme of the system and the unit startup sequence of each subsystem are shown in Figure 5.

The tie lines between two subsystems are edges 14–15, 17–18, and 17–27. The virus propagation process is shown in Table 1. Each subsystem is formed by the same type of virus.
Table 2 shows the information of the generated subsystems. For each subsystem, there is a BS unit for providing the cranking power. The generation capacity is sufficient for picking up loads. The maximum size of subsystems is 7. Buses in each subsystem are observable. Thus, this partitioning strategy is satisfied with the partitioning constraints (2)–(6). All subsystems in the partitioning strategy are reasonable.

The unit startup sequences and the corresponding restoration paths in each subsystem are shown in Table 3. The unit startup sequence of subsystem 1 is $G_{37}$, and that of subsystem 2 is $G_{35}$. The system reactive power constraint is used to evaluate the restoration paths in the virus propagation process. Meanwhile, for accelerating the restoration process, as many lines as possible are restored. Considering the demand of the target unit, if the system has abundant capacity for absorbing reactive power, the path of the next unit can be restored simultaneously. So, the restoration of expansion paths that satisfy the constraints is also obtained. For example, through restoration path $37–2–25–37; 2–3–4; 15 25$, the target unit, i.e., $G_{37}$, is restarted at 15 min. At the same time, the next unit’s restoration path $2–3–4; 15 25$ is also restored because the system can absorb the charging reactive power of path $2–3–4$. The output power of the system is 25 MW at 15 min. The last unit, i.e., $G_{38}$ in subsystem 1, is restarted at 117 min and $G_{34}$ in subsystem 2 at 66 min.

In order to prove the effectiveness of the proposed method, Table 4 compares the proposed method and other methods in [13, 16, 18]. Strategy 1 is obtained by the proposed method. Strategy 2 is generated by the methods in [13, 16]. Firstly, the Girven Newman (GN) algorithm proposed in [13] was used to obtain the system partitioning schemes. Then, the genetic algorithm in [16] was used to optimize the startup sequence of units. Strategy 3 is the restoration strategy of [18], which used the Benders decomposition to obtain the startup sequence of units and the partitioning scheme of the blackout system.

Since power systems have the characteristics of small-world networks, the modularity, namely $Q$, can be used to evaluate the subsystem’s rationality [13]. The $Q$ value of strategy 1, i.e., 0.4477, is the largest of the three strategies. It indicates that the strategy developed by this method has good partitioning characteristics.

In this case, the restoration time of the proposed strategy is 153 min, which is less than that of the methods in strategies 2 and 3. The total output power of NBS units is 621.574 MW. It indicates that the proposed parallel restoration strategy helps to accelerate the restoration process after blackouts. Since the last unit connected to the grid in
strategy 2 needs 3.387 h, the total outputs of strategies 1 and 3 at 3.387 h are calculated, i.e., 1200.773 MW and 1058.09 MW, respectively. The total output of the proposed strategy is larger than that of strategies 2 and 3, meaning that abundant power is generated for restoring the blackout system. The startup sequences of NBS units in different methods are in Table 4. The maximum size of subsystems obtained in this paper is the same as that of strategy 2 and smaller than that of strategy 3. Overall, the proposed method has a good performance of parallel restoration.

5.1.2. Scenario 2: Some Faulted Buses Are Not Available for Service Restoration. It is assumed that bus 5 is damaged by disasters and cannot be repaired or replaced quickly. The immunization strategy is used to make an online decision to refine the virus infection probability matrix through setting the immunization probability $c$ of the faulted bus. The immunization probability of bus 5 is set as 1. Thus, all the transmission lines which connect the bus 5 cannot be restored.

Based on the system condition, the proposed method quickly forms a new restoration scheme online, as shown in Figure 6 and Table 5. The $Q$ value of this scenario is 0.4602, which is larger than that of scenario 1. It indicates that the strategy developed by this method has good partitioning characteristics. The maximum size of subsystems is 8, which satisfied the subsystem size constraint.

### Table 5: The parallel restoration result of the IEEE 39-bus system in scenario 2.

<table>
<thead>
<tr>
<th>Sub</th>
<th>Unit startup sequence</th>
<th>Restoration path</th>
<th>Expansion path</th>
<th>Cranking time (min)</th>
<th>Power output (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>37</td>
<td>30–2–25–37;</td>
<td>2–3–4;</td>
<td>15</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>39, 38</td>
<td>2–1–39, 26–29–38;</td>
<td></td>
<td>122, 127</td>
<td>428.91</td>
</tr>
<tr>
<td>2</td>
<td>35</td>
<td>36–23–22–35;</td>
<td>23–24, 24–16;</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>33, 34</td>
<td>16–19–33, 19–20–34;</td>
<td></td>
<td>61, 66</td>
<td>149.03</td>
</tr>
</tbody>
</table>

**Figure 7:** The parallel restoration strategy of the IEEE 118-bus system.
The startup sequences of G31 and G32 are different from scenario 1. The paths connecting to bus 5 remove from the network, so the number of possible paths for virus propagation is reduced. With the loss of these paths, alternative restoration paths, i.e., 4–14–13–10–32 and 11–6–31, are computed by the SIR model, respectively. The last unit, i.e., G38 in subsystem 1, is restarted at 127 min. The restoration time of the proposed strategy is 163 min. The total output power of NBS units is 670.792 MW. In response to critical contingencies, the proposed restoration strategies can be provided within 0.08 s. As a result, the restoration process is robust and adaptive to system contingencies.

5.2. IEEE 118-Bus Test System. To illustrate the applicability of the proposed method in a large-scale power system, this paper uses the IEEE 118-bus test system. The optimal PMU locations for this test system are shown in [21]. By applying the entropy weight method, \( \omega_1 = 0.65 \) and \( \omega_2 = 0.35 \). The BS units are located at buses 25, 66, and 100. Thus, three types of viruses representing three subsystems infect buses 23, 66, and 100, respectively, in the initial period. In this case, the data refer to IEEE 118 bus test system. The rated capacity of each unit is calculated according to the maximum output capacity. Every bus of the system is available for restoration. During the parallel restoration process, as the NBS units continue to be infected and recovered, the partitioning scheme of this system and the unit startup sequence of each generating subsystem are obtained, shown in Figure 7.

The boundary lines among the three subsystems are edges 15–33, 15–19, 18–19, 19–20, 30–38, 24–70, 71–72, 68–81, 69–77, 75–77, and 76–118. In Table 6, each subsystem satisfies the constraint of power balance. All buses in each subsystem are observable. \( D_{BS, 1}, D_{BS, 2}, \) and \( D_{BS, 3} \) are all equal to 6. The size of each subsystem is balanced. The Q value of the proposed strategy is 0.6279. It indicates that the strategy developed by this method has good partitioning characteristics.

The startup sequence of units and the corresponding restoration paths in each subsystem are in Tables 7–9. The unit startup sequence of subsystem 1 is (G26, G27) \( \rightarrow \) G32 \( \rightarrow \) G31 \( \rightarrow \) (G10, G12, G8) \( \rightarrow \) (G113, G18, G15) \( \rightarrow \) G6 \( \rightarrow \) G4 \( \rightarrow \) G1 \( \rightarrow \) G24 \( \rightarrow \) G72, that of subsystem 2 is G99 \( \rightarrow \) (G89, G80) \( \rightarrow \) G103 \( \rightarrow \) (G111, G92, G110) \( \rightarrow \) G91 \( \rightarrow \) G90 \( \rightarrow \) (G104, G105) \( \rightarrow \) (G107, G112) \( \rightarrow \) (G85, G77) \( \rightarrow \) (G87, G76), and that of subsystem 3 is

### Table 6: Each subsystem of the IEEE 118-bus system.

<table>
<thead>
<tr>
<th>Sub.</th>
<th>BS unit</th>
<th>( P_i ) (MW)</th>
<th>( P_{G_{in}} ) (MW)</th>
<th>Observable</th>
<th>( D_{BS,i} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25</td>
<td>943</td>
<td>2676</td>
<td>Yes</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>66</td>
<td>1935</td>
<td>4074.2</td>
<td>Yes</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>1364</td>
<td>3216</td>
<td>Yes</td>
<td>6</td>
</tr>
</tbody>
</table>

### Table 7: The parallel restoration result of the IEEE 118-bus system (Subsystem 1).

<table>
<thead>
<tr>
<th>Sub.</th>
<th>Unit startup sequence</th>
<th>Restoration path</th>
<th>Expansion path</th>
<th>Cranking time (min)</th>
<th>Power output (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>27–32</td>
<td></td>
<td>23.86</td>
<td>35.63</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>32–31</td>
<td></td>
<td>28.86</td>
<td>43.10</td>
<td></td>
</tr>
<tr>
<td>10,12,8</td>
<td>26–30–8–9–10</td>
<td>30–17–16–12</td>
<td>48.86,48.86,48.86</td>
<td>89.93</td>
<td></td>
</tr>
<tr>
<td>113,18,15</td>
<td>17–113</td>
<td>17–18,17–15</td>
<td>53.86,53.86,53.86</td>
<td>112.29</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>6</td>
<td>12–7–6</td>
<td>63.86</td>
<td>162.27</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>6–5–4</td>
<td>5–3</td>
<td>73.86</td>
<td>235.36</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>3–1</td>
<td>25–23</td>
<td>78.86</td>
<td>274.70</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>23–24</td>
<td></td>
<td>83.86</td>
<td>314.97</td>
<td></td>
</tr>
<tr>
<td>72</td>
<td>24–72</td>
<td></td>
<td>88.86</td>
<td>366.92</td>
<td></td>
</tr>
</tbody>
</table>

### Table 8: The parallel restoration result of the IEEE 118-bus system (Subsystem 2).

<table>
<thead>
<tr>
<th>Sub.</th>
<th>Unit startup sequence</th>
<th>Restoration path</th>
<th>Expansion path</th>
<th>Cranking time (min)</th>
<th>Power output (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>99</td>
<td>100–99</td>
<td>100–101</td>
<td>5</td>
<td>8.22</td>
<td></td>
</tr>
<tr>
<td>89,80</td>
<td>101–102–92–89</td>
<td>99–80</td>
<td>24.41,32.8</td>
<td>61.27</td>
<td></td>
</tr>
<tr>
<td>103</td>
<td>100–103</td>
<td></td>
<td>37.8</td>
<td>71.82</td>
<td></td>
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<tr>
<td>111,92,110</td>
<td>103–110–111</td>
<td></td>
<td>47.8,47.8,47.8</td>
<td>92.92</td>
<td></td>
</tr>
<tr>
<td>91</td>
<td>92–91</td>
<td></td>
<td>52.8</td>
<td>103.47</td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>91–90</td>
<td></td>
<td>57.8</td>
<td>117.29</td>
<td></td>
</tr>
<tr>
<td>104,105</td>
<td>103–104</td>
<td>103–105</td>
<td>62.8,62.8</td>
<td>141.80</td>
<td></td>
</tr>
<tr>
<td>107,112</td>
<td>105–107</td>
<td>110–112</td>
<td>67.8,67.8</td>
<td>181.35</td>
<td></td>
</tr>
<tr>
<td>85,77</td>
<td>89–85</td>
<td>80–77</td>
<td>72.8,72.8</td>
<td>234.02</td>
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</tr>
<tr>
<td>87,76</td>
<td>85–86–87</td>
<td>77–76</td>
<td>82.8,82.8</td>
<td>356.87</td>
<td></td>
</tr>
</tbody>
</table>
G65 → (G69, G49) → (G61, G62) → (G46, G59) → G54 → G56 → (G55, G70) → G74 → (G73, G42) → G40 → G34 → (G36, G19) → G116. For example, through restoration path 25–26, the first target unit, i.e., G26 in subsystem 1, is restarted at 13.86 min. At the same time, the next unit’s restoration path 25–27 is also restored. However, the cranking power is not enough to restore G27 at 13.86 min. Hence, with the ramp-up of G25, G27 gets adequate cranking power and is restarted at 18.86 min. The output power of the system is 28.16 MW at 18.86 min. Because of the restoration of expansion paths, G10, G12, and G8 are restarted simultaneously. In this case, the last unit, i.e., G116 in subsystem 3, is restarted at 109.84 min. The total output power of NBS units is 2801.05 MW. This case indicates that the proposed parallel restoration method is suitable for large-scale power systems.

### 6. Conclusion

This paper presents an online parallel restoration method based on the SIR model. The proposed method takes all buses of the system into S-, I-, and R-states based on the system situation online. Different types of viruses propagate among buses and change buses’ states, considering the constraints on partitioning and restoration. The parallel restoration strategies to accelerate the restoration process after blackouts are obtained. Case studies on the IEEE 39-bus and 118-bus test systems demonstrate that the proposed method can coordinate the partitioning scheme of the blackout system and restorative actions of subsystems and adapt to the system conditions in real-time.

### Data Availability

Previously reported data were used to support this study and are available at ELSEVIER [10.1049/iet-gtd.2018.6237] and IEEE Xplore [10.1109/PTC.2017.7980806]. These prior studies are cited at relevant places within the text as references [18, 21]. In addition, this paper also used other data from the standard example of IEEE 39 Bus System and IEEE 118 Bus System. The reference data used to support the findings of this study have been deposited in the Knowledge Base of the PSCAD repository (https://www.pscad.com/).

### Conflicts of Interest

The authors declare that they have no conflicts of interest.

### Acknowledgments

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### References


### Table 9: The parallel restoration result of the IEEE 118-bus system (Subsystem 3).

<table>
<thead>
<tr>
<th>Sub.</th>
<th>Unit startup sequence</th>
<th>Restoration path</th>
<th>Expansion path</th>
<th>Cranking time (min)</th>
<th>Power output (MW)</th>
</tr>
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<tbody>
<tr>
<td>65</td>
<td>66–65</td>
<td>66–49</td>
<td>10.69</td>
<td>24.55</td>
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<td>69,49</td>
<td>49–69</td>
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<td>80.02</td>
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<td>61,62</td>
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<td>102.98</td>
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<td>46,59</td>
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<td>203.66</td>
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<td>391.69</td>
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<td>34</td>
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<td>883.22</td>
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