Decision Support System for Adaptive Restoration Control of Transmission System

Ze Li, Yusheng Xue, Haohao Wang, and Lili Hao

Abstract—**The power system restoration control has a higher uncertainty level than the preventive control of cascading failures. In order to ensure the feasibility of the decision support system of restoration control, a decision support framework for adaptive restoration control of transmission system is proposed, which can support the coordinated restoration of multiple partitions, coordinated restoration of units and loads, and coordination of multi-partition decision-making process and actual restoration process. The proposed framework is divided into two layers, global coordination layer and partition optimization layer. The upper layer partitions the transmission system according to the power outage scenario, constantly and dynamically adjusts the partitions during the restoration process, and optimizes the time-space decision-making of inter-partition connectivity. For each partition, the lower layer pre-selects restoration targets according to the estimated restoration income, optimizes the corresponding restoration paths, and evaluates the restoration plans according to the expected net income per unit of power consumption. During the restoration process, if the restoration operation such as energizing the outage branch fails, the current restoration plan will be adaptively switched to the sub-optimal one or re-optimized if necessary. The framework includes two operation modes, i.e., the on-line operation mode and training simulation mode, and provides an information interaction interface for collaborative restoration with related distribution systems. The effectiveness and adaptability of the proposed framework is demonstrated by simulations using the modified IEEE 118-bus system.**

Index Terms—**Transmission system restoration, two-layer decision support framework, restoration risk and income, restoration uncertainty, sand table deduction.**

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I. Introduction

THE purpose of the power system restoration control is to restore power supply quickly, safely, and economically after a power outage occurs, reduce the outage losses, and mitigate the risks of losing stability from restoration operations [1].

Transmission system restoration is a cross-regional, multi-level, multi-stage, non-linear, and strongly uncertain problem [2], [3]. At present, there have been a large number of research works that usually focus on a specific sub-problem of transmission system restoration such as the restoration of units and system skeleton in a single partition [4], [5], the restoration of loads in a single partition [6]-[15], the coordinated restoration of units and loads in a single partition [16]-[20], the restoration of units or loads in multi-partitions [21], [22], and the coordinated restoration of units and loads in multi-partitions [23]-[26].

In order to achieve the adaptive restoration control, it is usually needed to take the coordination of partitions, coordination of units and loads, coordination of decision-making process and actual restoration process as a whole, which is rarely discussed in the existing research works.

As to the partitioning method and inter-partition coordination method, most studies discuss the static partitioning method based on the initial power outage scenario considering the factors such as partition power balance [23], [24], whereas the partition adjustment strategy against various uncertain events in the actual restoration process is rarely discussed. The technical factors and operation process to be considered in the field of inter-partition connectivity are summarized in [25]. In [26], the decision of dynamic partitioning and inter-partition connectivity is made in the upper optimization layer, but there is no iteration with the lower layer to take into account the dynamic restoration plans of each partition, which makes it difficult to coordinate the intra-partition optimization and inter-partition coordination.

The studies on the decision-making of restoration plans of units and loads generally consider a specific restoration stage, optimizing unit restoration plans [27], skeleton restoration plans [28], and load restoration plans [29] separately, and rarely analyze and optimize all of them as a whole. The restoration benefits of units and loads are compared with static weights in [30] and [31] without consideration of the time-space characteristics of the restoration income of units and loads in different outage scenarios and restoration stages.

In order to deal with the high-dimensional uncertainties in power outage scenarios, external environments, and restoration processes, in addition to evaluating the expected restoration incomes and security risks of restoration plans in the decision-making process [26], [32], some studies propose the on-line decision-making frameworks to monitor the operation results of restoration plans and trigger the re-optimization process when necessary [26], [33], [34], but there is still a lack of adaptive strategies to deal with uncertain events in multi-partitions.

Besides, there is little research on collaborative restoration with distribution systems. The optimization strategies of collaborative restoration of transmission and distribution systems in a specific restoration stage are proposed in [35] and [36], but the actual information interaction interface is not discussed.

Since the power system restoration problem is difficult to be solved only by using expert knowledge [37], [38] or mathematical programming [33], [39], the idea of developing a decision support system by comprehensively applying expert knowledge, expert rules, optimization algorithms, and numerical simulations has received widespread attention.

Based on this idea, this paper proposes a risk optimization model that uniformly quantifies the economy and security of restoration plans, and proposes a two-layer framework for the transmission system restoration on-line decision support system (TRDSS) that decouples the sub-problems of coordination of partitions, coordination of units and loads, and coordination of decision-making process and actual restoration process. The contributions of this paper are summarized as follows.

1) The multi-partition optimization is achieved using the proposed two-layer framework. The upper layer dynamically adjusts partitions and simultaneously optimizes the time-space decision-making of inter-partition connectivity by iterating with the lower layer. For each partition, the lower layer pre-selects restoration targets considering the factors such as direct and indirect restoration incomes as well as satisfaction rate of restoration demand, and evaluates restoration plans according to the expected net income per unit of power consumption index *NC*.

2) An adaptive coordination strategy is introduced in the proposed framework to coordinate the risk decision-making process and actual restoration process to deal with the uncertain events that occur during the multi-partition restoration process.

3) An information interaction interface between the transmission system and related distribution systems is provided to support collaborative restoration control of transmission and distribution systems. The information of distribution system needed for transmission system restoration decision-making is analyzed and utilized, and the information of transmission system needed for distribution system restoration decision-making is analyzed as well.

In addition, the proposed framework introduces two operation modes to meet different needs of on-line decision-making and simulation training. In the practical application, the on-line mode of TRDSS monitors the operation status of the transmission system in real time so as to quickly respond to the actual power outage, whereas the training simulation mode of TRDSS can be used for operator training, and even in the actual restoration process, and the training simulation mode can be used to preview the restoration processes of different restoration plans.

The rest of the paper is organized as follows. Section II presents the optimization model for transmission system restoration. Section III introduces the framework and operation modes of TRDSS. Section IV explains the specific optimization methods of the on-line operation mode of TRDSS. Section V explains the training simulation mode of TRDSS by highlighting its key differences with the on-line operation mode. Section VI shows the simulation results and analysis. Conclusions are summarized in Section VII.

II. Optimization Model for Transmission System Restoration

A. Objective

The optimization task of restoration control is to coordinate the economy and security of restoration plans considering the influences of various uncertain events such as the uncertain security events in the restoration process [26]. By using the product of the probability and consequence of an uncertain security event to represent the security risk, the inequality constraints of securities can be converted into the expected security loss expressed in currency [40], and economy and security objectives can be unified in a monetized objective function. The security events in the restored power grid is used to evaluate the operation risk of power system, whereas the security events in the equipment being restored is used to evaluate the restoration operation risk.

The expected net income is defined as an algebraic sum of expected load restoration income, expected restoration cost, and expected security loss, i.e., security risk. The optimization objective is to maximize the expected net income of the restoration plan, and it is given by (1).

$$\max_{\boldsymbol{u}_k} \sum_{k=1}^{N_{\mathrm{K}}} \Big(I_{\mathrm{L}k}\big(\boldsymbol{x}_k, \boldsymbol{u}_k, \boldsymbol{p}_k\big) - C_k\big(\boldsymbol{x}_k, \boldsymbol{u}_k, \boldsymbol{p}_k\big) - R_k\big(\boldsymbol{x}_k, \boldsymbol{u}_k, \boldsymbol{p}_k\big) \Big) \quad (1)$$

where $k = 1, 2, \ldots, N_{\mathrm{K}}$ is the step number in restoration plan, and one step is to restore one restoration target by a restoration path $Path_k$, and N_{K} is the total number of steps in the restoration plan, and it can only be determined after the optimization model is solved; $I_{\mathrm{L}k}$, C_k, and R_k are the expected load restoration income, expected restoration cost, and security risk in step *k*, respectively; $\boldsymbol{x}_k$ is the vector of system state variables; $\boldsymbol{u}_k$ is the vector of control variables, and it includes the restoration sequences and restoration time of power equipment such as units, lines, and buses, the load restoration amount of each load bus, the outputs of on-line units, and the transmission power of tie-lines; and $\boldsymbol{p}_k$ is the vector of disturbance variables, which reflects the uncertainties of power outage scenarios, external environments, and restoration process.

In order to take account of the uncertainties in the restoration process of step *k*, a deterministic restoration process *i* is simulated by sampling the restoration process of $Path_k$, the sampling includes the time consumption of each operation and the fault occurrences during the restoration process. For the j^{th} failed operation that encounters a fault, the emergency control with the optimal emergency control cost $e_{k,i,j}$ [41] will be carried out to stabilize the system, and then the operation result will be sampled again or a spare restoration path will be chosen for the subsequent sampling adaptively. Thus, the deterministic restoration process might be the alternative restoration path of step k. The probabilities and consequences of uncertain events will be affected by the external environments indirectly.

For the obtained deterministic restoration process i, the load restoration income $I_{\mathrm{L}k,i}$ can be calculated by (2), the total emergency control cost $E_{k,i}$ can be calculated by (3), and the restoration cost $C_{k,i}$ can be calculated by adding up all the electricity costs during the restoration process.

$$I_{\mathrm{L}k,i}=\int_{t_{k,i}}^{t_{\mathrm{e}}}\alpha_{\mathrm{L}k,i}(t)\Delta P_{\mathrm{L}k,i}(t)\,\mathrm{d}t \tag{2}$$

$$E_{k,i}=\sum_{j=1}^{N_{\mathrm{F}}}e_{k,i,j} \tag{3}$$

where $t_{k,i}$ is the end time of the deterministic restoration process i based on step k; t_{e} is the preset end time of evaluation; $\Delta P_{\mathrm{L}k,i}(t)$ and $\alpha_{\mathrm{L}k,i}(t)$ are the capacity of the restored loads and restoration income per unit load of the restored loads at time t in the deterministic restoration process i, respectively; and N_{F} is the total number of faults in the deterministic restoration process i based on step k. $t_{k,i}$ and t_{e} define the time interval for evaluating $I_{\mathrm{L}k,i}$. $\Delta P_{\mathrm{L}k,i}(t)$ and $\alpha_{\mathrm{L}k,i}(t)$ can be obtained based on the information of the unrestored loads at all levels at each load bus, including the load capacity and restoration income per unit load, which can be estimated on the transmission system side or dynamically evaluated on the distribution system side. Admittedly, the restoration income per unit load of different loads are hard to evaluate precisely, but the differences between different priority loads are enough to guide us to restore the more important loads as soon as possible. And more suitable values of restoration income per unit load can be studied in the future work based on the user data from electricity utilities and demand side responses.

By repeating the above simulation of restoration process for multiple times, $I_{\mathrm{L}k}$, R_k, and C_k of step k can be further calculated as:

$$I_{\mathrm{L}k}=\sum_{i=1}^{N_{\mathrm{P}}}\frac{I_{\mathrm{L}k,i}}{N_{\mathrm{P}}} \tag{4}$$

$$R_k=\sum_{i=1}^{N_{\mathrm{P}}}\frac{E_{k,i}}{N_{\mathrm{P}}} \tag{5}$$

$$C_k=\sum_{i=1}^{N_{\mathrm{P}}}\frac{C_{k,i}}{N_{\mathrm{P}}} \tag{6}$$

where N_{P} is the total number of the simulated deterministic restoration processes.

B. Constraints

The constraints of single partition restoration optimization are discussed in the following. The presented constraints can be extended to the case of multiple partitions.

1) Power Supply Constraints

Equations (7) and (8) represent the output constraints of an on-line unit i at time t_k. Equations (9) and (10) represent the power supply capacity constraints of external tie-lines. Equation (11) represents the cold restart and hot restart constraints of outage units. The output ramping model of a restored unit can be found in [37].

$$\min\left\{P_{\mathrm{G}i,k-1},P_{\mathrm{G}i}^{\mathrm{th}}\right\}\le P_{\mathrm{G}i,k}\le\min\left\{P_{\mathrm{G}i}^{\mathrm{N}},P_{\mathrm{G}i,k-1}+R_{\mathrm{G}i}\left(t_k-t_{k-1}\right)\right\} \tag{7}$$

$$Q_{\mathrm{G}i}^{\min}\le Q_{\mathrm{G}i,k}\le Q_{\mathrm{G}i}^{\max} \tag{8}$$

$$0\le P_{\mathrm{O},mn,k}\le P_{\mathrm{O},mn,k}^{\max} \tag{9}$$

$$Q_{\mathrm{O},mn,k}^{\min}\le Q_{\mathrm{O},mn,k}\le Q_{\mathrm{O},mn,k}^{\max} \tag{10}$$

$$\left(t_{\mathrm{G}i}^{\mathrm{c}}-T_{\mathrm{G}i}^{\mathrm{hot}}\right)\left(T_{\mathrm{G}i}^{\mathrm{cold}}-t_{\mathrm{G}i}^{\mathrm{c}}\right)\le 0 \tag{11}$$

where $P_{\mathrm{G}i,k}$ and $Q_{\mathrm{G}i,k}$ are the active and reactive power outputs of a unit i at time t_k, respectively; $P_{\mathrm{G}i}^{\mathrm{th}}$, $P_{\mathrm{G}i}^{\mathrm{N}}$, $R_{\mathrm{G}i}$, $Q_{\mathrm{G}i}^{\min}$, and $Q_{\mathrm{G}i}^{\max}$ are the minimum technical output, rated active power capacity, ramping rate, lower limit of reactive power, and upper limit of reactive power of a unit i, respectively; $P_{\mathrm{O},mn,k}$ and $Q_{\mathrm{O},mn,k}$ are the active and reactive power supports that bus m receives from the external system through a tie-line mn at time t_k, respectively; $P_{\mathrm{O},mn,k}^{\max}$, $Q_{\mathrm{O},mn,k}^{\min}$, and $Q_{\mathrm{O},mn,k}^{\max}$ are the power support limits of the external system through tie-line mn at time t_k; and $t_{\mathrm{G}i}^{\mathrm{c}}$, $T_{\mathrm{G}i}^{\mathrm{hot}}$, and $T_{\mathrm{G}i}^{\mathrm{cold}}$ are the outage time before start-up, maximum hot restart time, and minimum cold restart time of an outage unit i, respectively. For the units such as hydropower units and gas turbine units, the values of $P_{\mathrm{G}i}^{\mathrm{th}}$ and $T_{\mathrm{G}i}^{\mathrm{cold}}$ are taken as zero, and the value of $T_{\mathrm{G}i}^{\mathrm{hot}}$ is taken as a large positive value.

2) Power Flow Constraints

The power flow constraints at time t_k are:

$$\boldsymbol{PF}\left(P_{\mathrm{G}i,k},Q_{\mathrm{G}i,k},P_{\mathrm{O}m,k},Q_{\mathrm{O}m,k},P_{\mathrm{L}m,k},Q_{\mathrm{L}m,k}\right)=\boldsymbol{0} \tag{12}$$

where $\boldsymbol{PF}(\cdot)$ is the AC power flow function; $P_{\mathrm{O}m,k}$ and $Q_{\mathrm{O}m,k}$ are the active and reactive power supports that bus m receives from the external power system through tie-line at time t_k; and $P_{\mathrm{L}m,k}$ and $Q_{\mathrm{L}m,k}$ are the restored active and reactive load capacities at bus m at time t_k, respectively.

3) Branch Constraint

At time t_k, the capacity constraint of lines and transformers is:

$$S_{mn,k}\le S_{mn}^{\max} \tag{13}$$

where $S_{mn,k}$ and $S_{mn}^{\max}$ are the power transmission volume on branch mn at time t_k and power transmission upper limit on branch mn, respectively.

4) Frequency Constraints

Equations (14) - (16) represent the spinning reserve constraints of the restored power grid. Equation (17) represents the transient frequency constraint, which can take into account the influences of the external power supports [42]. For single large-capacity loads such as auxiliary systems of power plants and large user substations, the transient frequency security of the restoration plan should be verified by numerical simulation programs [43].

$$\Delta P_k \le P_{\mathrm{res},k-1} - \max_{i\in\Omega_{\mathrm{G}}}\left\{u_{\mathrm{G}i,k-1}P_{\mathrm{G}i}^{\mathrm{N}}\right\} \tag{14}$$

$$\Delta P_k = \sum_{i\in\Omega_{\mathrm{G}}}\left(u_{\mathrm{G}i,k}-u_{\mathrm{G}i,k-1}\right)P_{\mathrm{G}i}^{\mathrm{st}} + \sum_{m\in\Omega_{\mathrm{B}}}\left(P_{\mathrm{L}m,k}-P_{\mathrm{L}m,k-1}\right) \tag{15}$$

$$P_{\mathrm{res},k-1} = \sum_{i\in\Omega_{\mathrm{G}}}u_{\mathrm{G}i,k-1}\left(P_{\mathrm{G}i}^{\mathrm{N}}-P_{\mathrm{G}i,k-1}\right) + \sum_{mn\in\Omega_{\mathrm{O}}}u_{\mathrm{O},mn,k-1}\left(P_{\mathrm{O},mn,k}^{\max}-P_{\mathrm{O},mn,k-1}\right) \tag{16}$$

$$\Delta P_k^1 \le \alpha_f\left[\sum_{i\in\Omega_{\mathrm{G}}}\left(u_{\mathrm{G}i,k}-u_{\mathrm{G}i,k-1}\right)P_{\mathrm{G}i}^{\mathrm{N}} + \sum_{mn\in\Omega_{\mathrm{O}}}\left(u_{\mathrm{O},mn,k}-u_{\mathrm{O},mn,k-1}\right)P_{\mathrm{O},mn,k}^{\max}\right] \tag{17}$$

where ΔP_k is the increment of active power in the restored power grid in step k; $P_{\mathrm{res},k-1}$ is the spinning reserve of the restored power grid at time t_{k-1}; Ω_{G} is the set of units; $u_{\mathrm{G}i,k-1}$ is the status of unit i at time t_{k-1}, where $u_{\mathrm{G}i,k-1}=1$ means the unit has been restarted and connected to the power grid, and $u_{\mathrm{G}i,k-1}=0$ means the unit has not been restarted or has not been connected to the power grid after being restarted; $P_{\mathrm{G}i}^{\mathrm{st}}$ is the start-up power demand of unit i; Ω_{B} is the set of buses; Ω_{O} is the set of available tie-lines from the external power systems; $u_{\mathrm{O},mn,k-1}$ is the status of tie-line mn at time t_{k-1}, where $u_{\mathrm{O},mn,k-1}=1$ means on-line, and $u_{\mathrm{O},mn,k-1}=0$ means unrestored; ΔP_k^1 is the active power volume of a single restoration target restored in step k; α_f is the comprehensive frequency response rate of on-line generators and power support from external power systems, and in this paper, it is set to be 0.2 [42].

5) Voltage Constraints

Equation (18) represents the steady-state voltage constraint of a restored bus m. The transient voltage security of the restoration plan should also be verified by numerical simulation programs.

$$V^{\min} \le V_{m,k} \le V^{\max} \tag{18}$$

where $V_{m,k}$ is the steady-state voltage of restored bus m at time t_k; $V^{\min}$ and $V^{\max}$ are the minimum and maximum steady-state voltages, and in this paper, they are equal to 0.9 p.u. and 1.1 p.u., respectively.

6) Other Specific Constraints

Some additional specific constraints should also be considered, including the constraints that the restoration operation should not cause system oscillation, protection device action, or equipment damage, the technical constraints for inter-partition connectivity, and other constraints.

III. Framework and Operation Modes of TRDSS

The framework of the TRDSS is shown in Fig. 1, which includes two operation modes, i. e., the on-line operation mode and training simulation mode.

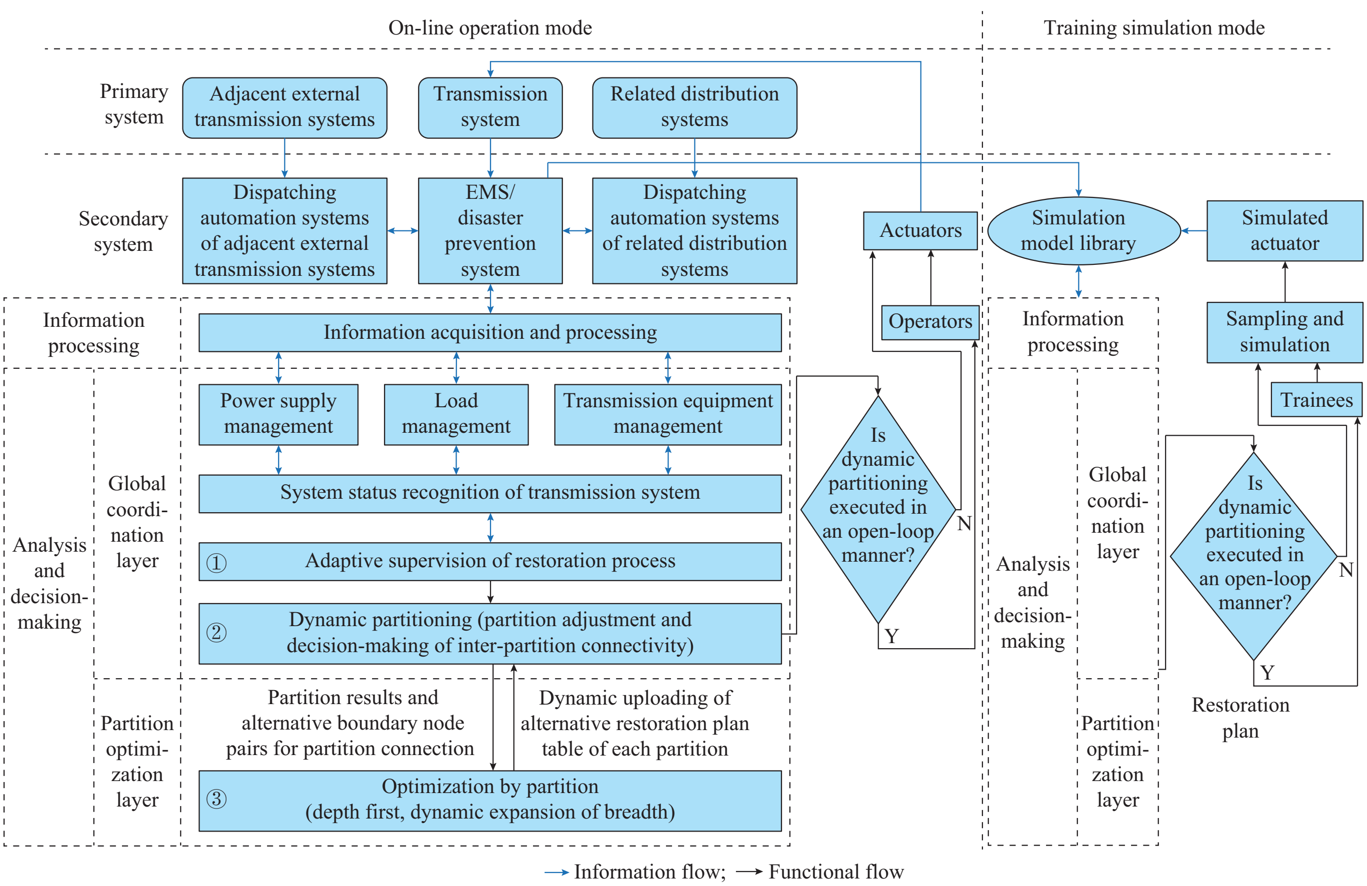

Fig. 1. Overall framework of TRDSS.

In the on-line operation mode, the real-time information about system restoration is obtained from the dispatching automation systems, the effects of restoration operations are continuously monitored, and the restoration plans are adjusted adaptively to provide system operators with decision support for restoration control. The TRDSS framework includes two parts, i.e., the information processing part and the analysis and decision-making part. The latter adopts a two-layer optimization framework of global coordination and partition optimization, where the upper layer denotes the global coordination layer and the lower layer denotes the partition optimization layer. Restoration operations can be executed in an open-loop, closed-loop, or mixed manner. In an open-loop manner, the system operator confirms the restoration plans and issues restoration instructions. In a closed-loop manner, the TRDSS issues restoration instructions to the actuators directly. In a mixed manner, the restoration instructions are issued to the actuators automatically and the system operator can adjust the instructions when necessary.

The training simulation mode provides trainees with a simulation environment for power system restoration control and improves their emergency disposal ability for restoration. Compared with the on-line operation mode, this mode has the same functional architecture, which includes information processing, analysis, and decision-making, and the same execution manners. The differences between the training simulation mode and the on-line operation mode are as follows.

1) The source of input information of the training simulation mode is the output of power system simulation, and not the response of actual power system. The input information includes the system model data and system operation data, which are obtained from the energy management system (EMS) and disaster prevention system, or from locally stored historical data.

2) The results of restoration operations, including the time consumption of the operations and whether the operations succeed or fail, are obtained by sampling and simulation, and the system model is modified accordingly.

Sand table deduction is an interactive decision-making method: based on the given power outage scenario, search the restoration plans; simulate the system restoration process according to each restoration plan, and update the power outage scenario accordingly; perform the plan searching and restoration-process simulation alternately until reaching the predefined deduction width and depth, and evaluate the expected restoration income, expected restoration cost, and security risk of different restoration processes.

As shown in Fig. 1, the three sub-problems, i.e., ① sub-problem 1, the coordination of decision-making process and actual restoration process, ② sub-problem 2, the coordination of partitions, ③ sub-problem 3, the coordination of units and loads, are solved by three independent modules. The detailed algorithms of each module and the relationships among these modules are introduced in Section IV-B and Section IV-C.

IV. On-line Operation Mode

A. Information Acquisition and Processing Module

The information acquisition and processing module provides the information interaction interface with the EMS, disaster prevention system, and other dispatching automation systems. It obtains the transmission system data required for restoration decision-making such as operation information of the transmission system, power support information of neighboring external transmission systems, and warning information of external disasters. The obtained data are cleaned, converted, maintained, and updated accordingly. In addition, the interface can interact with the dispatching automation systems of related distribution systems to obtain different information such as load demand and restoration progress of related distribution systems, and send the information such as maximum power supporting capability and actual power supporting capability to the related distribution systems.

B. Global Coordination

As shown in Fig. 1, the management and system status recognition modules in the global coordination layer analyze power outage scenarios according to the latest information. The adaptive supervision module of the restoration process monitors the restoration process of each partition based on the restoration plans recommended by the dynamic partitioning module, and adaptively sends the plan switching or re-optimization instructions to the dynamic partitioning module. The dynamic partitioning module is responsible for coordinating the optimization process of all partitions. First, it adjusts the partitions and makes decision-making of inter-partition connectivity, and sends the partition results and alternative boundary node pairs for inter-partition connectivity to the partition optimization layer. Second, it obtains the alternative restoration plan table of each partition dynamically uploaded by the partition optimization layer, and optimizes and recommends restoration plans of all partitions to system operators.

1) Real-time Information Management and System Status Recognition

The power supply management module analyzes the status, available power capacity, and other parameters of various available power sources in the transmission and distribution systems such as black-start units, electrical islands operating independently after an outage, and power supplies from adjacent external transmission and distribution systems. The load management module analyzes the load restoration progress of each load bus and manages the load information at each load bus, which includes capacities of unrestored loads at all levels, and the restoration income per unit load of unrestored loads at all levels. The transmission equipment management module analyzes the status, restoration progress, and other information of each transmission equipment.

The system status recognition module of transmission system is to analyze the status of power plants and substations on the transmission system side and identify both isolated and non-isolated power outage regions, where the isolated power outage region refers to the power outage area in which there is no recoverable path between the outage area and any electrical node in transmission system, and the node generally refers to various types of buses such as generator terminal bus, load bus, or tie-line bus. The isolated power outage region can be restored by the power supplied by adjacent distribution systems, or it can be restored after it becomes a non-isolated power outage region. When the transmission and distribution systems are restored collaboratively, the system status recognition module of transmission system sends the information to each related distribution system through the information acquisition and processing module, including the information on the estimated maximum power supporting capability $\boldsymbol{P}_{T\Sigma}$ of the transmission system to the distribution systems, and the information on whether the transmission system needs power support from the distribution systems.

2) Adaptive Supervision of Restoration Process

The flowchart of the adaptive supervision module of the restoration process is shown in Fig. 2. After the power outage, this module initiates the first-time optimization of the restoration plans. During the restoration process, this module adaptively determines whether it is necessary to switch the current restoration plan to the sub-optimal plan or to re-optimize the plans according to the actual execution process of each partition.

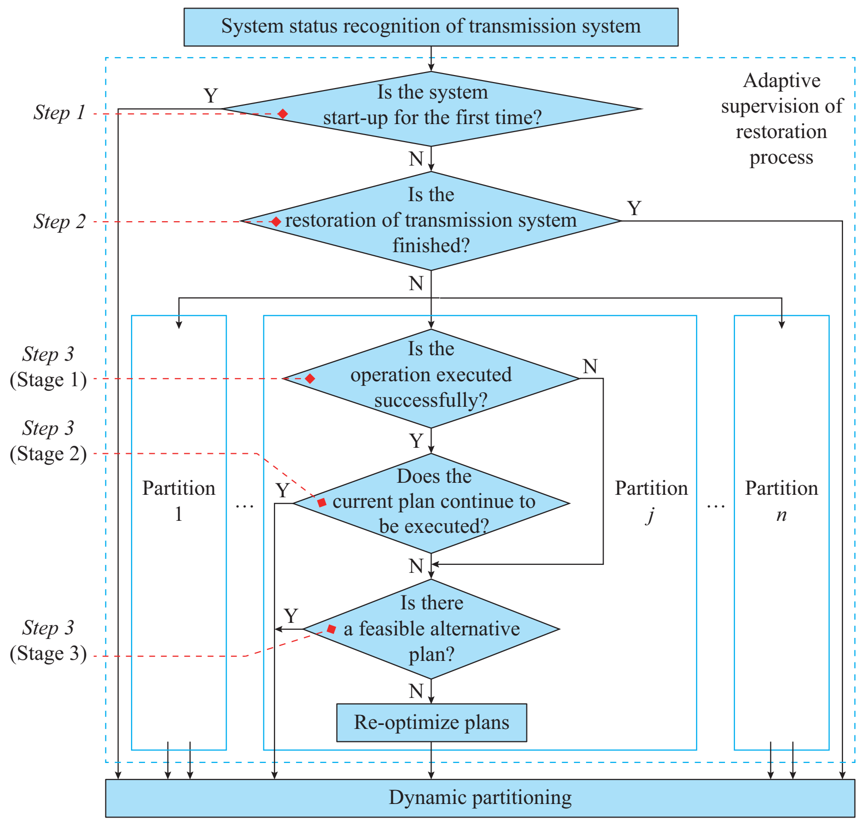

Fig. 2. Flowchart of adaptive supervision of restoration process.

The steps of the adaptive supervision of the restoration process are as follows.

Step 1: determine whether to initiate the first-time optimization of the restoration plans. If the optimization is initiated, send the first-time optimization instruction to the dynamic partitioning module; otherwise, go to *Step 2*.

Step 2: identify whether the restoration of transmission system is finished. If it is finished, send the restoration end signal to the dynamic partitioning module; otherwise, go to *Step 3*. When both the ratio of equipment restoration quantity and the ratio of load restoration quantity reach the preset levels, the restoration of the transmission system will be regarded as finished.

Step 3: perform the adaptive supervision of the restoration process of each partition.

1) Stage 1: identify whether the current restoration operation is executed successfully. If it is executed successfully, go to Stage 2; otherwise, go to Stage 3. The restoration operations include equipment energization, load pickup, unit start-up or parallel operation, and inter-partition connectivity. For the equipment experiencing the permanent fault during the restoration process, record its status as unrecoverable until the fault is eliminated.

2) Stage 2: identify whether to continue the current plan. If yes, send a continue execution instruction to the dynamic partitioning module; otherwise, go to Stage 3. Considering the influences of uncertainties of the restoration process and external environments on the economy and security of restoration plans, the following conditions should be met when continuing the current plan: ① there are subsequent operations in the current plan and the related equipment can still be restored; ② there is no new outage node in the restored power grid; ③ compared with the time when the current plan is generated, the variations in the path restoration risk and power system operation risk do not exceed the predefined thresholds (the thresholds depend on the dispatcher's risk preference and experience); ④ the maximum difference between the estimated restoration income of the current restoration target and that of other restoration targets in the partition does not exceed the predefined threshold.

3) Stage 3: identify whether there is a feasible sub-optimal alternative restoration plan. If yes, send an instruction to the dynamic partitioning module to switch to the alternative plan and continue the execution process; otherwise, send a re-optimization instruction to the dynamic partitioning module. The feasibility conditions of the alternative plan are the same as those listed in Stage 2.

When the transmission and distribution systems are restored collaboratively, the adaptive supervision module of the restoration process exchanges the information with the related distribution systems through the information acquisition and processing module, thus informing the related distribution systems about various system parameters such as the actual power supporting capacity $\boldsymbol{P}_{\mathrm{T}j}$ that can be delivered to distribution systems by the current transmission system partition j, and also receiving the restoration result information that is dynamically sent by distribution systems.

3) Dynamic Partitioning

According to the instructions issued by the adaptive supervision module of the restoration process, the dynamic partitioning module adjusts partitions and makes a decision on inter-partition connectivity according to the power outage scenario and restoration process.

If the adaptive supervision module issues the first-time optimization or re-optimization instruction, the dynamic partitioning module will determine the initial partitions or adjusts the partitions, make recommendations on the inter-partition connectivity, and send the partition results and alternative boundary node pairs for the inter-partition connectivity to the partition optimization layer. After the partition optimization layer uploads the alternative restoration plan table of each partition, the optimal restoration plan of each partition and the plans of inter-partition connectivity will be optimized and recommended. Before adjusting the partitions, it is necessary to mark status and original partition of each device. The status can be on-line, under restoration, scheduled to be restored, remaining to be restored, or unrecoverable. Devices in scheduled-to-be-restored status can be restored according to the current plans, whereas the devices in remaining-to-be-restored status need to re-optimize its restoration plans.

If the adaptive supervision module issues the continue execution instructions, the dynamic partitioning module will continue to recommend the current or alternative plans and will simultaneously receive the alternative restoration plan table of each partition dynamically expanded by the partition optimization layer.

If the adaptive supervision module sends the transmission system restoration end signal, the dynamic partitioning module will stop the optimization and recommendation of restoration plans and provide the system operators with relevant information.

1) Partition adjustment submodule

The partition adjustment submodule determines the initial partitions according to the initial power outage scenario and adjusts the partitions according to the actual restoration process of each partition during the restoration process. The partitioning steps are as follows.

Step 1: based on the current power outage scenario, determine the power transmission range of each electrical node considering the power balance, voltage levels, switching operation times, voltage conversion times, and other factors of the transmission path.

Step 2: for the on-line nodes, under-restoration nodes, and scheduled-to-be-restored nodes, determine one by one which partition it belongs to. When adjusting the partitions, the under-restoration and scheduled-to-be-restored nodes do not change their partitions.

Step 3: distribute the remaining-to-be-restored nodes one by one to the partition that is capable of sending power to them and has the shortest power transmission path. In the case that a node can be distributed to multiple partitions, if the node is connected with units directly, it will be distributed to the partition with the largest active power deficiency; otherwise, it will be distributed to the partition with the smallest active power deficiency.

After obtaining partition results by conducting the above steps, the decision-making of inter-partition connectivity and partition optimization are carried out in turn, and the global expected net income of the restoration plans of all partitions is calculated. If other partitioning strategies are adopted, different partition results can be obtained, but for each type of partition result, its global expected net income can still be calculated according to the same decision-making process, and then the optimal partition results can be determined.

2) Submodule of decision-making of inter-partition connectivity

Based on the partition results, the submodule of decision-making of inter-partition connectivity optimizes the inter-partition connectivity plans and modifies them dynamically during the restoration process. First, this submodule recommends alternative boundary node pairs for inter-partition connectivity and sends the partition results and alternative boundary node pairs to the partition optimization layer. It should be noted that the boundary node pair has one node in each of the two partitions, and when both nodes of a boundary node pair are restored by each of the partition, the two partitions can be connected. For two partitions with boundary node pairs, if the restoration ratio of nodes in each partition has reached the predefined threshold, or the two partitions satisfy the condition of $\left(I_{\mathrm{c}}-I_{\mathrm{nc}}\right)/I_{\mathrm{nc}}>\varepsilon_1$, the connectivity will be recommended. I_{c} is the estimated restoration income after the two partitions are connected, which represents the maximum estimated restoration income generated by the sum of the available power of the two partitions, including the capacities of both the spinning reserve and the under-restoration units. I_{nc} is the sum of the estimated restoration income of each partition when the two partitions are not connected. ε_1 is the predefined threshold according to the system operators' experience.

The submodule of decision-making of inter-partition connectivity can optimize the inter-partition connectivity plans after obtaining the alternative restoration plan table of each partition (which will be introduced in the partition optimization subsection) uploaded by the partition optimization layer. For the partitions that are not suggested for connectivity, the optimal restoration plan of each partition is the multi-step restoration plan with the largest *NC* value in the alternative restoration plan table, and the NC value can be taken from the alternative restoration plan table. Whereas for the two partitions that are suggested for connectivity, the optimal restoration plans of the two partitions can be determined according to the following steps. Assuming that these two partitions are denoted as partitions i and j, the flowchart of the decision-making process of inter-partition connectivity between partitions i and j is shown in Fig. 3.

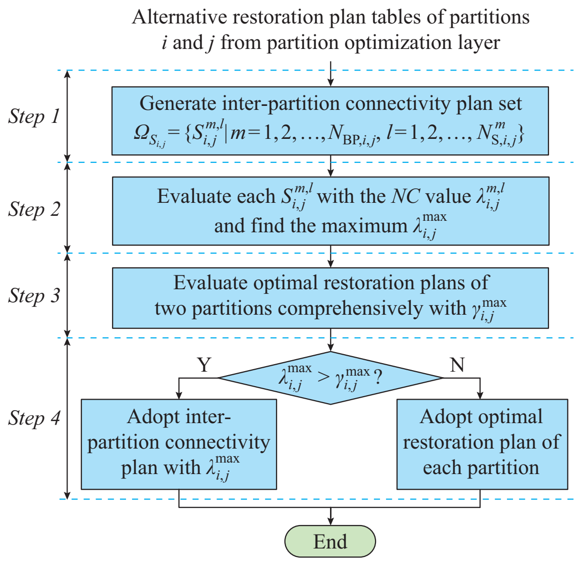

Fig. 3. Flowchart of decision-making process of inter-partition connectivity between partitions i and j.

Step 1: search for the feasible boundary node pairs between partitions i and j based on the alternative restoration plan tables of these partitions. Denote the m^{th} boundary node pair as $BP_{i,j}^{m}$, which is composed of the boundary node BP_{i}^{m} in partition i and boundary node BP_{j}^{m} in partition j. Denote the l^{th} inter-partition connectivity plan of $BP_{i,j}^{m}$ as $S_{i,j}^{m,l}$, which includes the restoration plan of BP_{i}^{m} in partition i, the restoration plan of BP_{j}^{m} in partition j, and the connectivity plan between BP_{i}^{m} and BP_{j}^{m}. Thus, the inter-partition connectivity plan set $\Omega_{S_{i,j}}=\left\{S_{i,j}^{m,l}|m=1,2,\ldots,N_{\mathrm{BP},i,j}, l=1,2,\ldots,N_{\mathrm{S},i,j}^{m}\right\}$ can be generated, where $N_{\mathrm{BP},i,j}$ is the total number of boundary node pairs between partitions i and j, and $N_{\mathrm{S},i,j}^{m}$ is the total number of inter-partition connectivity plans at $BP_{i,j}^{m}$.

Step 2: calculate the NC value $\lambda_{i,j}^{m,l}$ of the inter-partition connectivity plan $S_{i,j}^{m,l}$ by (19), and then take the connectivity plan with largest NC value as the optimal inter-partition connectivity plan and denote its NC value as $\lambda_{i,j}^{\max}$.

$$\lambda_{i,j}^{m,l}=\frac{NI_{i}^{m,l}+NI_{j}^{m,l}-\Delta R_{i,j}^{m,l}}{W_{i}^{m,l}+W_{j}^{m,l}} \tag{19}$$

where $NI_{i}^{m,l}$ and $W_{i}^{m,l}$ are the expected net income and power consumption of the l^{th} restoration plan of boundary node BP_{i}^{m}, which is a part of the connectivity plan $S_{i,j}^{m,l}$; $NI_{j}^{m,l}$ and $W_{j}^{m,l}$ are the expected net income and power consumption of the l^{th} restoration plan of boundary node BP_{j}^{m}, which is also a part of the connectivity plan $S_{i,j}^{m,l}$; and $\Delta R_{i,j}^{m,l}$ is the increment in the power system operation risk after partitions i and j are connected according to the connectivity plan $S_{i,j}^{m,l}$, which can be calculated by (5). The calculation method of the expected net income and power consumption will be introduced in Section IV-C. $NI_{i}^{m,l}$, $W_{i}^{m,l}$, $NI_{j}^{m,l}$, and $W_{j}^{m,l}$ can be taken from the alternative restoration plan table of the corresponding partition.

Step 3: suppose partitions i and j are restored according to the optimal restoration plan of each partition and evaluate the comprehensive NC value $\gamma_{i,j}^{\max}$. The corresponding calculation formula is:

$$\gamma_{i,j}^{\max}=\frac{NI_{i}^{\max}+NI_{j}^{\max}}{W_{i}^{\max}+W_{j}^{\max}} \tag{20}$$

where $NI_{i}^{\max}$ and $W_{i}^{\max}$ are the expected net income and power consumption of the optimal restoration plan of partition i, respectively; and $NI_{j}^{\max}$ and $W_{j}^{\max}$ are the expected net income and power consumption of the optimal restoration plan of partition j, respectively. $NI_{i}^{\max}$, $W_{i}^{\max}$, $NI_{j}^{\max}$, and $W_{j}^{\max}$ can be taken from the alternative restoration plan table of the corresponding partition.

Step 4: if $\lambda_{i,j}^{\max}$ is greater than $\gamma_{i,j}^{\max}$, the optimal inter-partition connectivity plan will be adopted; otherwise, the optimal restoration plan of each partition will be adopted.

C. Partition Optimization

The partition optimization layer optimizes the restoration plan tree of each partition in parallel. The restoration plan tree of a partition is shown in Fig. 4, where each directed branch represents a step of the restoration process. Starting from the power outage scenario corresponding to the root node of the tree, the process of restoring to the scenario corresponding to the leaf node of the tree is recorded as a multi-step restoration plan.

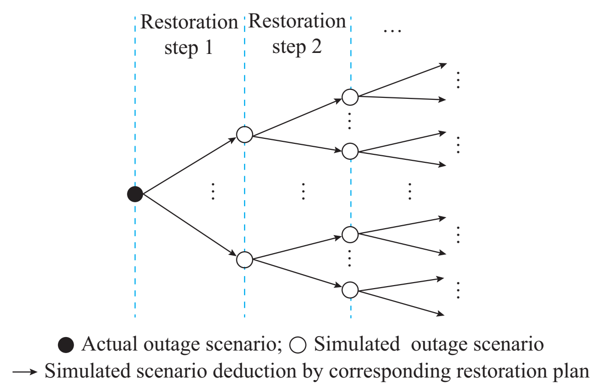

Fig. 4. Restoration plan tree of a partition.

The breadth deduction is to optimize the restoration plans of different restoration targets starting from the same actual outage scenario or simulated outage scenario. There can be multiple restoration plans for the same restoration target. The depth deduction continues until the number of steps reaches the predefined threshold. All the multi-step restoration plans in the plan tree constitute an alternative restoration plan table of a partition, which is uploaded to the submodule of decision-making of inter-partition connectivity.

In the presented optimization strategy, there is a combination explosion problem, and it is needed to balance the contradiction between the optimization quality and the calculation burden. To settle this problem, the number of scenarios can be reduced by screening the restoration targets, limiting the breadth and depth of the tree, and limiting the plan number of the same restoration target. In addition, the results of some important subtrees can be uploaded first, and the restoration plan tree can be expanded dynamically according to the actual execution results of the restoration plan, for instance, by adding branches for alternative restoration paths when the restoration of an important node fails, and adding branches for more steps.

1) Partition Optimization Steps

The flowchart of the partition optimization process is shown in Fig. 5, and the corresponding steps are as follows.

Step 1: based on the power outage scenario, generate the sequence of units to be restored Ω_{G} and the sequence of substation buses to be restored Ω_{B} by screening and sorting of restoration targets, and then merge the two obtained sequences as $\Omega_{\mathrm{O}}=\left\{O_r|r=1,2,\ldots,N_{\mathrm{O}}\right\}$ according to the estimated restoration income of the restoration target O_r, which will be described in the follow-up subsection. N_{O} is the total number of restoration targets in Ω_{O}.

Step 2: select a restoration target O_r (r is initialized as 1) from the restoration target sequence Ω_{O} in order.

Step 3: optimize restoration plans of the selected restoration target O_r.

1) Stage 1: generate the restoration path set $\Omega_{\mathrm{Path},r}=\left\{Path_{r,h}|h=1,2,\ldots,N_{\mathrm{Path},r}\right\}$ by searching several short restoration paths of the restoration target O_r, where $N_{\mathrm{Path},r}$ is the total number of candidate restoration paths of the restoration target O_r. The restoration paths are spare for each other.

2) Stage 2: perform security verification of $Path_{r,h}$ (h is initialized as 1). If the security check is passed, go to Stage 3; otherwise, go to Stage 4.

3) Stage 3: evaluate the expected unit restoration income $I_{\mathrm{G}r,h}$, expected load restoration income $I_{\mathrm{L}r,h}$, security risk $R_{r,h}$, and expected restoration cost $C_{r,h}$ of $Path_{r,h}$ using the method introduced in Section II-A, and generate new simulated outage scenario according to $Path_{r,h}$. The calculation method of $I_{\mathrm{G}r,h}$ is the same as that of $I_{\mathrm{L}r,h}$ except that the unit restoration income of a deterministic restoration process is calculated by the method introduced in the following subsection instead of using (2). If the boundary node is included in the path or is the restoration target of a deterministic restoration process, the potential connectivity income, which is expressed as $I_{\mathrm{c}}-I_{\mathrm{nc}}$, should also be considered in $I_{\mathrm{L}r,h}$.

4) Stage 4: set $h=h+1$. If $h\leq N_{\mathrm{Path},r}$, go to Stage 2; otherwise, set $r=r+1$, and go to *Step 4*.

Step 4: since the plan tree is generated branch by branch in a breadth-first manner, if the breadth deduction in the current scenario is completed, or $r>N_{\mathrm{O}}$, go to *Step 5*; otherwise, go to *Step 2* to continue generating the next branch.

Step 5: if the deduction depth of the plan tree has not reached the predefined limit, switch to the next simulated outage scenario, and go to *Step 1*; otherwise, go to *Step 6*. If there are boundary nodes in a partition, which are suggested by the submodule of decision-making of inter-partition connectivity, it is necessary to check whether all boundary nodes are included in the target nodes or path nodes of the plan tree, and if they are not, the corresponding restoration plans should be supplemented accordingly.

Step 6: evaluate all the multi-step restoration plans of the current partition according to the *NC* value which will be introduced in the following subsection, generate the sorted alternative restoration plan table, and send it to the submodule of decision-making of inter-partition connectivity.

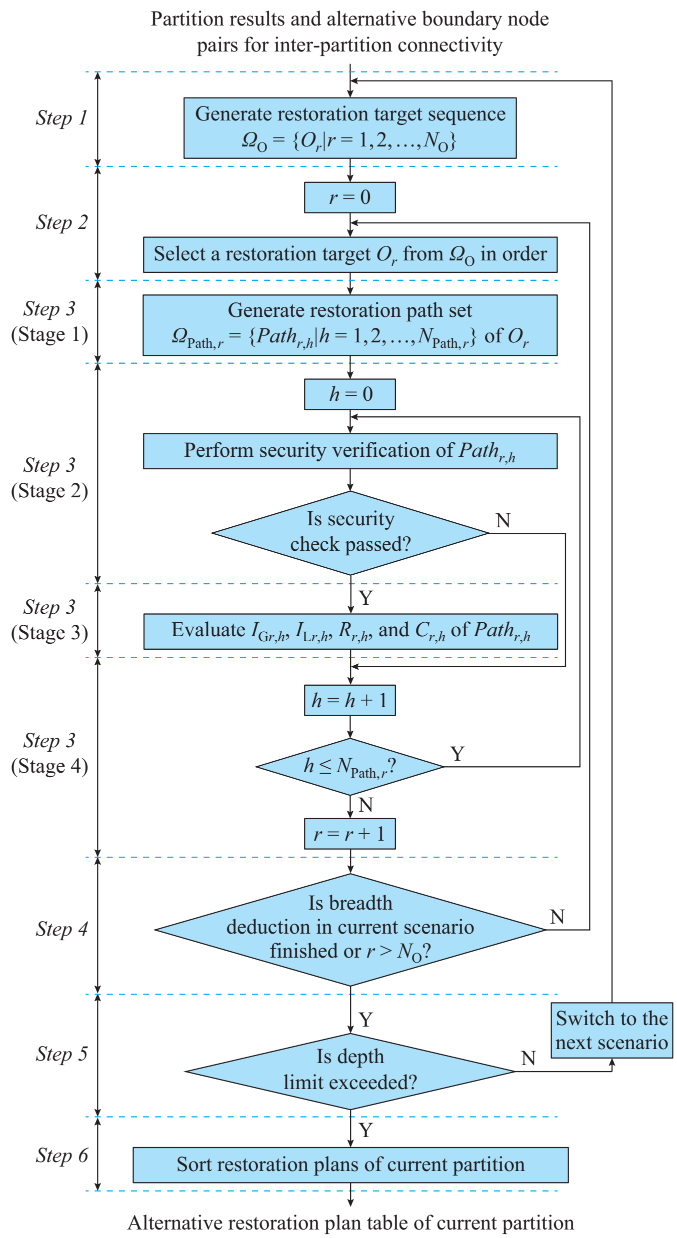

Fig. 5. Flowchart of partition optimization process.

2) Screening and Sorting of Restoration Targets

The restoration targets refer to units and substation buses remaining to be restored, which are sorted according to the estimated restoration income separately.

For the units to be restored, screen out the units that do not satisfy the spinning reserve constraints and transient frequency constraint, and the units that cannot be hot restarted or cold restarted, and then evaluate the restoration income of the rest of units, and generate the sequence of units to be restored in descending order (denoted as Ω_{G}). The unit restoration income is equal to the increased load restoration income after the unit is restored and connected to the power grid minus the restoration cost of the unit. The higher the rated capacity of the unit is, the more loads can be restored after the unit is connected to the power grid. Also, the higher the ramping rate of the unit is, the faster the loads can be picked up. Besides, the more important loads to be restored in the power transmission range of the unit are, the higher the load restoration income can be generated after the grid-connection of the unit. Further, the smaller the overlapping area between the power transmission range of the unit and the partition is, the more favorable the unit is for multi-point concurrent restoration. Furthermore, the lower the satisfaction rates of the partition restoration demand or power system restoration demand are, the more it is needed to restore the units, where the satisfaction rate of the restoration demand is the ratio of the sum of capacities of the spinning reserve, under-restoration units, and scheduled-to-be-restored units to the capacity of loads to be restored.

Therefore, the unit restoration income I_G can be evaluated as:

$$I_G = \left(\beta_G I_{G,L} - C_G\right) e^{-\min\left\{\eta_{sys}, \eta_{part}\right\}} \tag{21}$$

where $I_{G,L}$ is the estimated load restoration income generated after the unit is connected to the power grid, which can be calculated by (2) in which the end time of this restoration step is obtained by estimating the shortest path restoration time and the pickup time of loads according to the ramping rates of on-line units; β_G $(0<\beta_G\leq 1)$ is the conversion coefficient of the indirect restoration income of a unit, which indicates the delay effect of time consumption of the restoration process after the unit is connected to the power grid on the restoration income; C_G is the cost of restoring a unit; and η_{sys} and η_{part} are the satisfaction rates of the power system restoration demand and partition restoration demand, respectively. Equation (21) reflects the correlation between the unit restoration income and power outage scenario, and it changes dynamically with the actual restoration process.

For the substation buses to be restored, the restoration income is obtained by (22), and a sequence of substation buses to be restored is generated and sorted in descending order, which is denoted as Ω_B.

$$I_B = \left(\beta_B I_{B,L} - C_B\right)\left(1 - e^{-\min\left\{\eta_{sys}, \eta_{part}\right\}}\right) \tag{22}$$

where $I_{B,L}$ is the estimated load restoration income of a substation bus, i.e., the maximum load restoration income calculated by (2) supposing that all available power of a partition is used to restore the loads under the substation bus and the loads within its peripheral power transmission range; β_B $(0<\beta_B\leq 1)$ is the conversion coefficient of the bus restoration income; and C_B is the restoration cost of the loads at the bus. For boundary node buses, it is also necessary to consider their potential connectivity income $I_c - I_{nc}$.

3) Restoration Plan Evaluation

When evaluating the restoration plans of a partition, it is necessary to comprehensively consider the direct restoration income of loads and the indirect restoration income of a unit. The restoration income of loads is limited by the available power capacity of the partition. Unit restoration can increase the available power capacity and thus affect the load restoration income indirectly. Therefore, the *NC* value γ is proposed to comprehensively evaluate the restoration plan of a partition, and it is calculated as:

$$\gamma = \sum_{k=1}^{N_D}\left(I_{Gk} + I_{Lk} - R_k - C_k\right) \Big/ \sum_{k=1}^{N_D} W_k \tag{23}$$

where N_D is the total steps of the restoration plan of a partition, and it is restricted to the deduction depth of the plan tree; W_k is the power consumption of the restoration plan of step k, including the power consumption of a unit; and I_{Gk} is the expected indirect restoration income of the unit of the restoration plan of step k. I_{Gk} is calculated by the method in Stage 3 of Fig. 5. The numerator and denominator in (23) denote the expected net income and power consumption of the multi-step restoration plan of the partition, respectively.

V. Training Simulation Mode

The decision-making process of the training simulation mode is similar to that of the on-line operation mode, but the restoration process of the actual power system needs to be simulated in a training environment.

According to the information on the initial power outage scenario, a simulated power system restoration model is constructed in the simulation model library. The initial power outage scenario information includes the information on the transmission system operation, the power support information of adjacent external transmission system and related distribution systems, and the warning information of external disasters. The restoration training can be further conducted in this mode. During the training process, a trainer can update the model parameters based on the information obtained from the EMS and disaster prevention system, so as to retrain the trainees according to the latest initial power outage scenario.

The sampling and simulation module is used to simulate the actual restoration process of each partition. Namely, according to a given fault set and the corresponding fault probabilities, the results of restoration operations of the restoration plan in each partition are obtained by sampling one by one to determine the uncertainties, including the time consumption of the operations and whether the operations succeed or fail. Before the sampling and simulation, a trainer or trainees can adjust the information such as fault set and fault probabilities. The simulated actuator module updates the power system status according to the sampling results, checks the rationality of the power flow results of the restored power grid, and updates the simulation model library.

VI. Simulation Results and Analysis

In order to verify the effectiveness and adaptability of the proposed decision support framework, a prototype TRDSS is developed using C++ programing language, and the training simulation mode is tested on the modified IEEE 118-bus system [44]. The essential parameters such as the start-up parameters of units that are not included in the IEEE system are supplemented. The total installed generation capacity of the system is 8196 MW, and the total active load before the power outage is 4242 MW. The technical parameters of the units, the load data at each load bus before the power outage, and simulation parameters are given in Appendix A. All simulations are performed on a personal computer (PC) with Intel Core i5-3470 CPU @ 3.20 GHz and 8 GB RAM.

It is assumed that there are only two available power sources in the power system after the complete blackout: bus B1 is re-energized by the adjacent external transmission system, and the available power is 200 MW; black-start unit G110 restarts successfully, and the available power is 250 MW.

A. Optimization and Execution of Restoration Plans

Based on the initial power outage scenario at 00:00, the adaptive supervision module of the restoration process of TRDSS initiates the first-time optimization of the restoration plans, and sends the first-time optimization instruction to the dynamic partitioning module in the upper layer, then the restoration plans are optimized as follows.

1) In the upper layer, the partition adjustment submodule determines the initial partition 1 and partition 2.

2) In the upper layer, the submodule of decision-making of inter-partition connectivity recommends no alternative boundary node pair for inter-partition connectivity, and sends the partition results and inter-partition connectivity recommendations to the lower partition optimization layer.

3) In the lower layer, the alternative restoration plan table of each partition is optimized independently and parallelly based on the procedures shown in Fig. 5. The depth limit of the restoration plan tree in each partition is set as two steps. Then these tables are sent to the submodule of decision-making of inter-partition connectivity in the upper layer.

4) In the upper layer, the submodule of decision-making of inter-partition connectivity optimizes the inter-partition connectivity plans based on the procedures shown in Fig. 3 after obtaining the alternative restoration plan table of each partition. Since the partition 1 and partition 2 are not suggested for connecting, the optimal restoration plan of each partition is the two-step restoration plan with the largest *NC* value in the alternative restoration plan table of each partition.

The obtained optimal restoration plans of the two partitions are given in Table I. The restoration operations of each partition are executed accordingly and separately by TRDSS, and the adaptive supervision module of the restoration process continues to monitor the restoration process of these two partitions.

The power outage scenario at 00:34 is shown in Fig. 6. At this time, the first two step restoration plans of each partition have been executed, and units G40 and G80 are being restored in partitions 1 and 2, respectively. The restoration plans besides Table I are generated by the partition optimization layer through the dynamic expansion of the restoration plan tree of each partition during the restoration process. During the restoration process, partition 2 encounters a permanent line fault when restoring line B100-B92, and the alternative restoration path B100-B94-B92 is chosen to continue the restoration, whereas the restoration process of partition 1 is not affected.

TABLE I
OPTIMAL RESTORATION PLANS OF TWO PARTITIONS (OPTIMIZATION RESULTS AT 00:00)

No.	Estimated completed time	Partition	Main restoration path	Restoration target	
				Unit	Substation bus
1	00:10	1	B1-B2-B12(10)-G12(6)	G12	
2	00:11	2	B110-B103-G103 (20)	G103	
3	00:25	1	B12-B14-B15-B19-G19(23)	G19	
4	00:28	2	B103-B100-B92-B89-G89(20)	G89	

Note: the figures in brackets refer to the active power consumed by the corresponding nodes in this step, in MW.

At 00:35, the node B89 in partition 2 trips due to the instantaneous fault, which causes the second outage of B89 and G89, but the fault is eliminated immediately. After monitoring the mentioned events, the adaptive supervision module of the restoration process does not find any feasible alternative plan and triggers repartitioning of partitions and re-optimizing the restoration plan of each partition, and at the same time, suspends the execution process of the third step restoration plan of partition 2 (restoring unit G80), whereas the third step restoration plan of partition 1 (restoration unit G40), which is under execution, is not affected. The re-optimized restoration plans are shown in Fig. 7. The scope of partition 1 is expanded, and its new restoration plan is to continue to restore unit G40, and then to restore the important unit G56 and the important loads at bus B49, which are originally in partition 2. The scope of partition 2 is reduced correspondingly, and its new restoration plan is to restore unit G80 first and then to restore unit G89.

At 01:46, the adaptive supervision module of the TRDSS finds that there are permanent faults on paths B75-B77 and B76-B118, and there are no feasible alternative plans, so it issues a re-optimization instruction to the dynamic partitioning module, and the submodule of decision-making of inter-partition connectivity judges that if partitions 1 and 2 were connected proactively, the global restoration income would be improved significantly. Based on the optimization results of the partition optimization layer, two inter-partition connectivity plans are recommended by the submodule of decision-making of inter-partition connectivity. Plan 1 is as follows: partition 1 restores the boundary node B69 through the path B49-B69; partition 2 restores the boundary node B77 through the path B80-B77, and finally, the two partitions are connected via the path B69-B77. Plan 2 is as follows: partition 1 restores the boundary node B68 through the path B49-B69-B68; partition 2 restores the boundary node B81 through the path B80-B81, and finally, the two partitions are connected via the path B68-B81. Plan 1 is chosen by the submodule of decision-making of inter-partition connectivity. When the two partitions are connected, the important loads which were in partition 1 originally, are restored preferentially in the new partition.

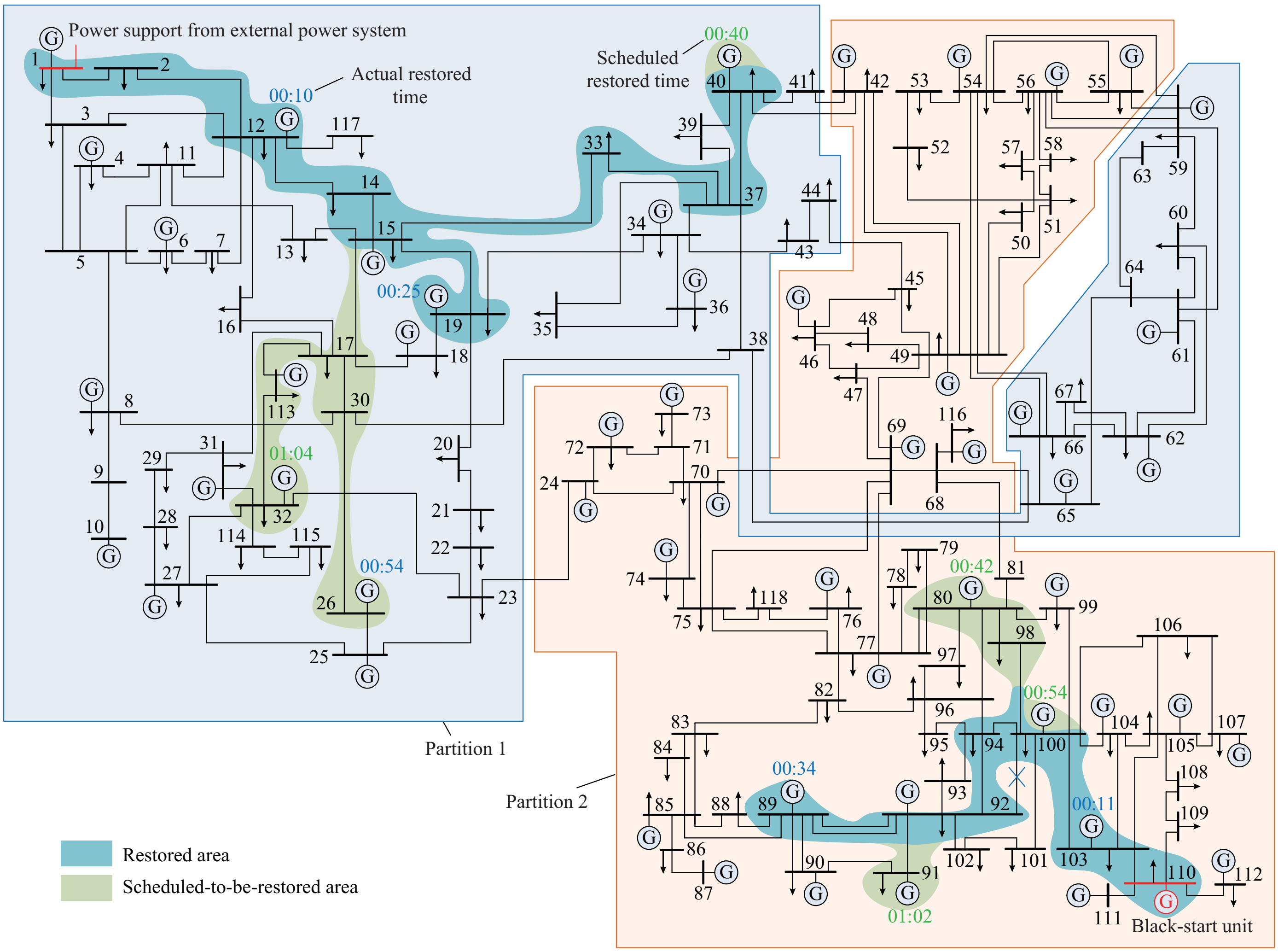

Fig. 6. Power outage scenario at 00:34.

The TRDSS continuously coordinates the execution and optimization process of the restoration plans until the restoration of the transmission system is completed. The entire restoration process is given in Appendix B. The total number of restoration steps for two partitions is 142, and the units, buses, and loads in all partitions are restored step by step. With the global coordination strategy in the upper layer, the partitions are adjusted twice, and the two partitions are connected at 02:00. With the partition optimization strategy in the lower layer, the restoration plans of units and loads of each partition are optimized independently, unless the partitions are adjusted or connected. By monitoring the actual execution process of each partition, the adaptive supervision module of the restoration process in the upper layer adaptively switches the current restoration plan to the sub-optimal plan or triggers the re-optimization of the plans.

Therefore, the proposed framework of TRDSS is capable of achieving multi-dimension coordinated restoration control, including the coordinated restoration of multiple partitions, coordinated restoration of units and loads, and the coordination of multi-partition decision-making process and actual restoration process.

B. Comparisons with Methods Without Global Coordination

The proposed global coordination method in the upper layer of the TRDSS, including the dynamic partitioning and inter-partition connectivity, is compared with two other conventional methods to demonstrate its advantages. In comparison method 1, there is no dynamic partitioning, but the partitions are connected according to the offline plans [45], and the proposed partition optimization method in the lower layer is still adopted. In comparison method 2, there is neither dynamic partitioning nor inter-partition connectivity [24], but the proposed partition optimization method in the lower layer is still adopted.

The net income curves of restoration plans obtained by the three methods are shown in Fig. 8. By 07:08, the actual net income of the proposed global coordination method increases by 4.1% and 14.3% compared with the two comparison methods, respectively. The reasons are as follows.

1) At 00:35, by adopting the adaptive dynamic partitioning, partition 1 restores the more important restoration targets (unit G56 and loads at bus B49) originally belonging to partition 2, which expands the concurrent restoration range of partition 1, and indirectly or directly improves the global load restoration income.

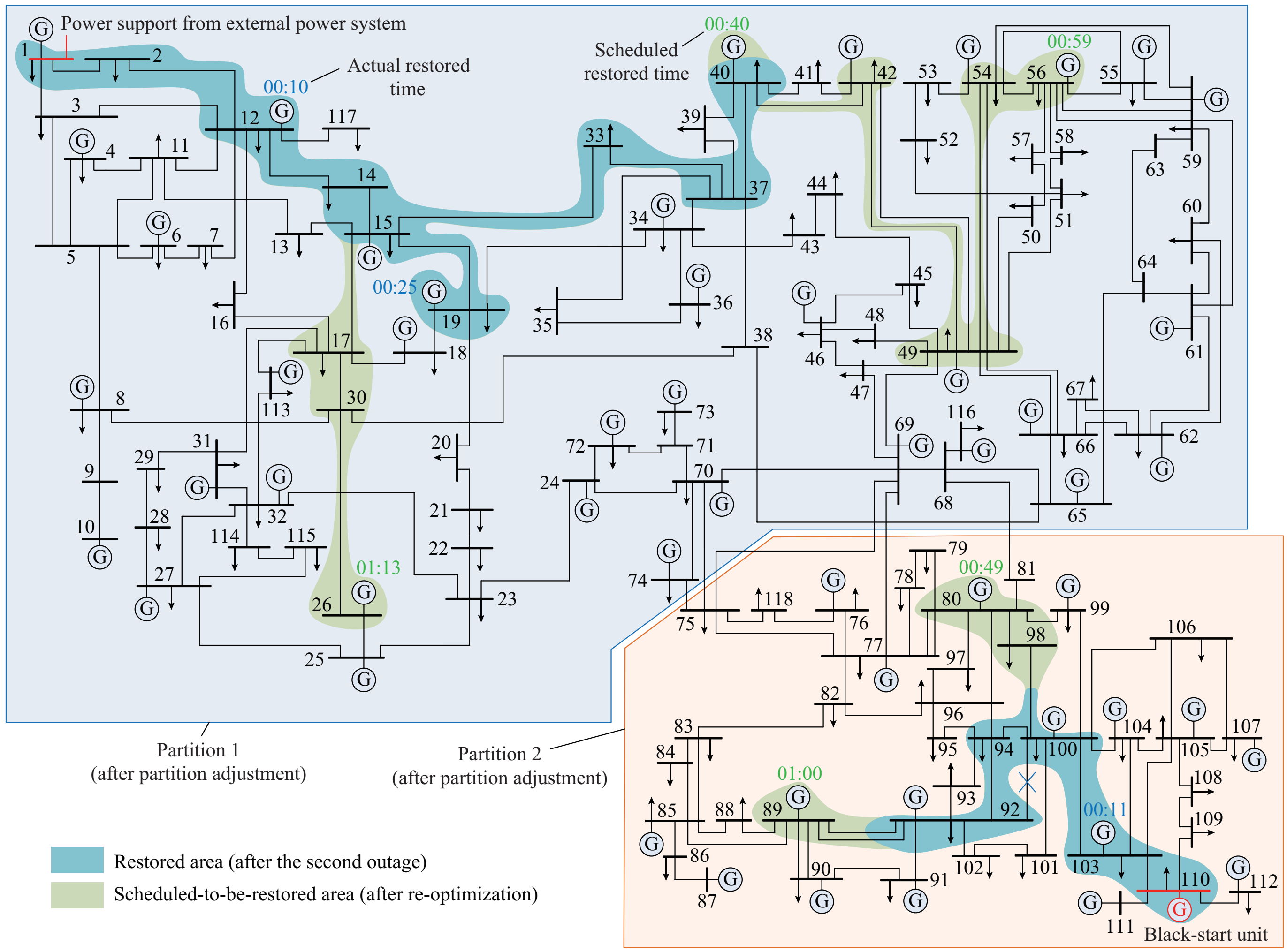

Fig. 7. Restoration plans after re-optimization at 00:35.

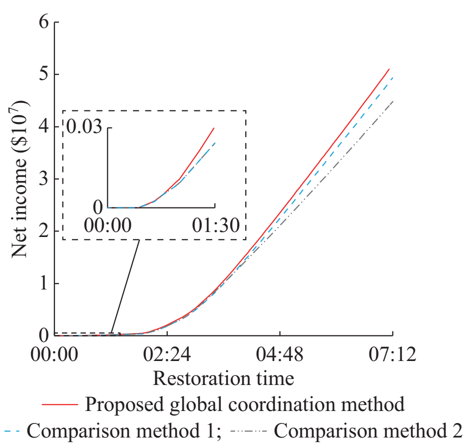

Fig. 8. Comparisons of net income curves of restoration plans obtained by proposed global coordination method and two comparison methods.

Without adopting the dynamic partitioning, partition 1 can only continue to restore the less important restoration targets such as G26 and G32 within partition 1, whereas the restoration time of more important restoration targets in partition 2 will be delayed significantly.

2) At 01:46, the important loads to be restored are concentrated in partition 1. When the proposed inter-partition connectivity is used, the more important targets in partition 1 are restored in advance with the abundant power in partition 2 by connecting the two partitions. If the two partitions are connected according to the offline plans, they can be connected only after the two partitions restore the corresponding boundary nodes according to the internal restoration needs, and different connectivity plans cannot be dynamically evaluated and optimized.

It is shown that global coordination among partitions, including the dynamic partitioning and inter-partition connectivity, is beneficial for parallel restoration by adaptively adjusting the multi-partition restoration plans according to changing outage scenarios.

C. Comparison with Method Considering Unit First Then Load

In order to demonstrate the advantages of the proposed partition optimization method for unit and load coordination in the lower layer of the TRDSS, the comparison method 3, i. e., unit first then load [39] while adopting the proposed global coordination method in the upper layer, is adopted for comparison.

The net income curves of restoration plans obtained by the two methods are shown in Fig. 9. By 05:52, the actual net income of the proposed partition optimization method increases by 7.3%. Since the restoration of units and loads is treated uniformly according to the restoration income, the satisfaction rates of partition restoration demand and power system restoration demand increase gradually with the restoration of units in each partition, and at 01:57, the *NC* values of the unit restoration plans in partition 2 are lower than that of restoring important loads under B108. Therefore, partition 2 restores the loads instead of continuing to restore the units remaining to be restored in the partition, thus improving the global restoration income. The coordination between the units and loads continues until the transmission system restoration is completed.

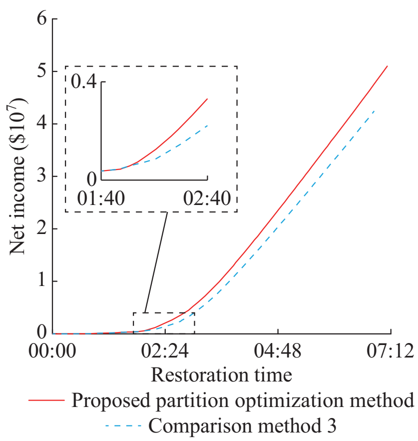

Fig. 9. Comparisons of net income curves of restoration plans obtained by proposed partition optimization method and comparison method 3.

It is shown that, compared with the conventional restoration stage division methods, coordinating the indirect restoration income of unit and direct restoration income of loads in a unified way is more adaptive for different restoration demands of outage scenarios.

VII. Conclusion

In this paper, a two-layer decision-making framework for adaptive restoration control of transmission system is proposed. According to the real-time actual power outage scenario, the upper layer dynamically makes necessary partition adjustments according to the global optimization objective and performs an adaptive time-space decision-making of inter-partition connectivity. The lower layer compares failure probabilities, control costs, and expected incomes of different restoration plans of each partition, and uniformly evaluates the restoration of the units and loads according to the *NC* value, instead of simply appointing the restoration stages of units and loads. The coordination between the two layers, including the dynamic partition adjustment and inter-partition connectivity, is beneficial to share the restoration power between partitions and reduce the restoration risks. During the actual restoration process, the restoration plans are adjusted adaptively against uncertain events such as operation failures. The decision support system also provides the information interaction interface necessary for collaborative restoration with the related distribution systems, thus realizing the coordinated training of restoration control for multi-level system operators, or providing on-line decision support for multi-level dispatching centers. Simulation results have shown the effectiveness and adaptability of the proposed framework to uncertainties such as power outage scenario uncertainties.

This paper aims to take a step forward to the practical application, but there are still many practical problems to be solved before put into online application such as the availability of the information from dispatching automation systems during the power outage, which can be discussed in the future researches.

Appendix A

Without loss of generality, the loads on a bus are divided into five priority levels according to the restoration income per unit load, and the initial restoration incomes per unit load of the five priority levels 1-5 are set to be 10000, 4000, 3000, 2000, and 1000 \$/MWh, respectively. More detailed information on the restoration income per unit load and capacity of the load to be restored at each level can be provided by the distribution system side. The end time of the load restoration income evaluation is 12:00. It is assumed that all equipment can be restored after the power outage, and the probability of various faults of buses and lines is 0.0001; β_{G} and β_{B} are the same and equal to 0.8.

The technical parameters of units are given in Table AI, where $t_{\mathrm{G}i}^{\mathrm{hot}}$ and $t_{\mathrm{G}i}^{\mathrm{cold}}$ are the time consumptions of the hot restart and cold restart of unit i, respectively. The active load data at each bus before power outage are given in Table AII.

TABLE AI
Technical Parameters of Units (Partial)

Unit	$P_{\mathrm{G}i}^{\mathrm{N}}$ (MW)	$P_{\mathrm{G}i}^{\mathrm{th}}$ (MW)	$P_{\mathrm{G}i}^{\mathrm{st}}$ (MW)	$Q_{\mathrm{G}i}^{\max}$ (Mvar)	$Q_{\mathrm{G}i}^{\min}$ (Mvar)	$T_{\mathrm{G}i}^{\mathrm{hot}}$ (min)	$T_{\mathrm{G}i}^{\mathrm{cold}}$ (min)	$t_{\mathrm{G}i}^{\mathrm{hot}}$ (min)	$t_{\mathrm{G}i}^{\mathrm{cold}}$ (min)	$R_{\mathrm{G}i}$ (MW/min)
G12	120	48	6	120	–35	140	240	40	80	3.0
G19	450	180	23	200	–147	150	250	60	120	5.0
G40	400	160	20	200	–67	150	250	60	120	5.0
G56	400	160	20	200	–67	150	250	80	160	4.0
G100	260	104	13	155	–50	140	240	60	120	3.0

TABLE AII
ACTIVE LOADS AT EACH BUS BEFORE POWER OUTAGE (PARTIAL)

Bus	Active load (MW)					
	Total	Level 1	Level 2	Level 3	Level 4	Level 5
B1	51.0	0.0	0.0	15.3	15.3	20.4
B12	47.0	28.2	4.7	4.7	4.7	4.7
B17	11.0	6.6	1.1	1.1	1.1	1.1

APPENDIX B

TABLE BI
ENTIRE RESTORATION PROCESS OF STUDIED CASE

No.	Completed time	Partition	Restoration path	Restoration target	
				Unit	Substation bus
1	00:10	1	B1-B2-B12(10)-G12(6)	G12	
2	00:11	2	B110-B103-G103(20)	G103	
3	00:25	1	B12-B14-B15-B19-G19(23)	G19	
4	00:34	2	B103-B100-B94-B92-B89-G89(20)	G89	
5	00:40	1	B15-B33-B37-B40-G40(20)	G40	
6	00:49	2	B100-B98-B80-G80(20)	G80	
7	00:59	1	B40-B42-B49(10)-B54-B56-G56(20)	G56	
8	01:00	2	B92-B89-G89(20)	G89	
9	01:13	1	B15-B17(10)-B30-B26-G26(17)	G26	
10	01:07	2	B92(20)-B91-G91(5)	G91	
⋮					
20	01:45	1	B56(10)-B59-G59(10)	G59	
21	01:52	2	B80-B77(20)		B77
22	01:54	1	B49-B69(0)		B69
23	01:57	2	B105-B108(30)		B108
24	02:00	1, 2	B69-B77	Inter-partition connectivity	
25	02:01	1	B56(44)		B56
⋮					
80	04:04	1	B8-B9-B10-G10(5)	G10	
81	04:08	1	B4-G4(12)	G4	
⋮					
141	07:05	1	B106(40)		B106
142	07:08	1	B83(38)		B83

Note: the figures in brackets refer to the active power consumed by the corresponding nodes in this step, in MW.

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