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Article

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A dynamic partitioning method for power system parallel restoration considering restoration-related uncertainties

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Abstract

Online Decision Support System (DSS) for restorative control can be used to track the restoration process of power system dynamically and optimize the restoration plans online to support the decision-making of dispatchers' online restorative control. Parallel restoration can improve the restoration efficiency effectively, but the division of the restoration partitions should match the real-time conditions of the power grid. This paper proposes a dynamic partitioning method for power system restoration considering the restoration capabilities of partitions, which can be used to refresh the partitioning results dynamically based on the power system restoration process so as to cope with the restoration-related uncertainties. Furthermore, the restoration targets (outage power plants and outage substations) of partitions will be filtered and evaluated based on its restoration values to maximize the overall restoration revenues. A decision support system for restorative control is developed and a case study using data of a real regional grid in China is conducted to illustrate the flexibility and effectiveness of the proposed method in dealing with restoration-related uncertainties.

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Keywords: Restorative control; Decision support system; Dynamic partitioning; Parallel restoration

1. Introduction

Large-scale power system blackouts have occurred in the United States, China, India and other countries from 2003 to 2019. In China, extreme natural disasters such as typhoons have caused blackouts in some provincial and municipal power grids repeatedly. As mentioned in Xue et al. [1], restorative control refers to the rapid, safe and economic restoration of power supply to the outage grid after a blackout with as little operational risk as possible.

If the outage power grid retains more than one power system (start-up power source, hereinafter the same) after a blackout, it may be considered to restore the grid in parallel by multiple power systems to speed up the grid

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restoration process. Various forms of power systems may emerge after a blackout or during the restoration process: (1) the black-start power plants after self-starting; (2) remaining isolated power systems consisting of some power plants, substations and lines without power outage; (3) power systems with power supplies from the upper-level power system or adjacent power systems; (4) power systems with power supplies from distribution networks in which large-capacity and controllable distributed power sources are connected.

Partitioning method is essentially an algorithm for pre-planning of the restoration areas for power systems for parallel restoration. A reasonable partitioning method will be able to maximize the restoration efficiency of each power system and prevent the restoration targets and the power transmission paths from being conflicted between partitions. It would be necessary to consider the power transmission capability of each power system, the distribution of outage power plants and substations in the grid, the capacity and importance of the outage loads comprehensively while partitioning.

A lot of researches about partitioning have been done by teams worldwide. Arash Nezam Sarmadi et al. [2] presented a partitioning method for the build-up strategy in power system restoration considering various constraints such as black-start capabilities of generators, power supply–demand balance and independence of islands, and the restoration process of each partition would be fully observable utilizing the Wide Area Measurement System (WAMS). A partitioning method based on complex network theory was presented in Lin et al. [3] while considering the locations of black-start units and the characteristics of power systems. Wang et al. [4] presented a partitioning method based on ordered binary decision diagram (OBDD) to find the splitting points between partitions quickly while satisfying black-start constraints, generation-load balance constraints, and voltage stability constraints. Quirós-Tortós et al. [5] proposed a partitioning method based on spectral clustering theory with the physical properties of the network considered. Quirós-Tortós et al. [6] proposed a partitioning method based on ‘cut-set’ matrix while considering the topology and asset availability of the network after the blackout. Liu et al. [7] presented a bi-level programming approach for partitioning while taking into account both the characteristics of the cold load pickup and the features of generator startup. A two-step network partitioning method for parallel power system restoration was presented in Sun et al. [8] with a grouping model for non-black-start units developed first, and a power network partitioning model based on the graph theory presented afterwards. In order to achieve coordinative restoration of interconnected grids in Europe, Stefanov et al. [9] proposed a decision support methodology to determine the optimal utilization of tie lines and/or black-start units to crank non-BS units. Wang et al. [10] established a framework for online decision support system for restorative control, and developed a two-layer optimization strategy of “independent optimization in each partition in the lower layer, dynamic partitioning and coordinating in the upper layer”, but the partitioning and coordinating strategy of multiple partitions was not studied in it.

Most of the above methods on partitioning used to make a one-time partition division in the initial stage of restoration, and the power system in each partition is responsible for supplying power support to the outage power plants, substations and lines correspondingly, which requires taking into account the impacts of restoration plans in each partition.

These partitioning methods are on the premise that each partition can be restored successfully. While engineering practices have shown that there are strong uncertainties in the actual power system restoration process, such as the uncertainty of electrical equipment’s state and operability, the uncertainty of regional natural environment and natural disasters, the uncertainty of results of restoration operations, etc. Therefore, there may be great differences in restoration process between partitions due to the accompanying uncertainties, which may affect the feasibility of the original parallel restoration plans. For example, if an important non-black-start generator fails to restart within the time limitation of hot restart, the overall restoration progress of that partition will be greatly delayed, which means the dispatchers will have to re-optimize the parallel restoration plans with limited information within limited time. In addition, in the partitioning methods mentioned above, it is generally considered that there is no overlapping area between partitions, but in fact, there is often an overlapping area between partitions whose power systems are close to each other due to the randomness of the spatial distribution of power systems. That is, the outage power plants and substations in a partition may be restored by power systems from other partitions. Therefore, it is necessary to cope with these kinds of conflicting scenarios in determining the restoration targets of partitions.

In order to better cope with the uncertainties in the restoration process and achieve coordinated parallel restoration of all partitions, a dynamic partitioning method for online decision support system for restorative control is proposed according to the latest operating conditions of power systems and the outage grid. And a multi-partition coordination ideology is also proposed based on the restoration values of the restoration targets so as to guide the restoration direction of each partition dynamically. A case study is carried out to illustrate the rationality and effectiveness of the proposed method.

2. The framework of online decision support system for restorative control

The decision support system for restorative control is divided into three subsystems: information subsystem, analysis subsystem and decision-making subsystem. The information subsystem obtains the operational status data of the electrical equipment from SCADA. Analysis subsystem is used for managing the model of electrical equipment, analyzing the latest status of the power systems, managing the alternative restoration plans, and monitoring the restoration process. Decision-making subsystem generates the alternative restoration plans for each partition according to the latest operating conditions of the power systems to provide the dispatchers with online decision support for restorative control. The framework of the online decision support system is shown in Fig. 1.

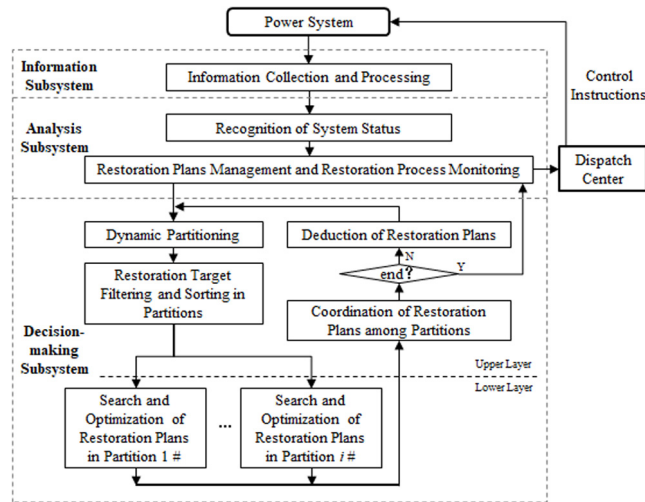


Fig. 1. Framework of online decision support system for restorative control.

3. Dynamic partitioning

3.1. Objective of dynamic partitioning

The proposed dynamic partitioning method is to determine the potential power transmission paths and maximize power transmission distances of the power systems online through simplified indicators considering the power transmission capability of the power system and the topology state of the power grid comprehensively. The objective function of dynamic partitioning is:

$$\max f = \sum_{1 \leq i \leq N_S} D_{S_i} \quad (1)$$

D_{S_i} is the number of outage power plants and substations within the power transmission range of power system S_i , N_S is the number of power systems at current time.

The key to dynamic partitioning is to search for the qualified power transmission paths from power system S_i to the restoration target O_j ($1 \leq j \leq N_O$, and N_O is the number of restoration targets in the outage grid). There may be multiple power transmission paths with the same length from power system S_i to outage station O_j . The grid topology is first simplified into a connected graph according to the graph theory, and due to the non-directionality of the power grid graph, all the stations in power system S_i can be taken as the starting node for power transmission path to the outage station O_j . Each station in power system S_i may also have multiple power transmission paths to the outage station O_j , and the length of each path may also be different.

In this paper, the power transmission paths are searched out layer by layer from the nodes in power system S_i . The power transmission paths with a length of l (initialized to 1) from power system S_i to outage station O_j is first searched. The searched paths set is denoted as $R_{i,j,l} = \{r_{i,j,l}^1, r_{i,j,l}^2, \dots, r_{i,j,l}^{N_r^{i,j,l}}\}$, where $N_r^{i,j,l}$ means the number of paths in $R_{i,j,l}$. If at least one path $r_{i,j,l}^k$ ($1 \leq k \leq N_r^{i,j,l}$) satisfies the constraints of dynamic partitioning, it will be

considered that the outage station O_j belongs to partition A_i of power system S_i , and the power transmission paths with a length of $l+1$ will not further be searched. Fig. 2 shows the power transmission paths set $R_{i,j,3}$ from power system S_i to outage station O_j .

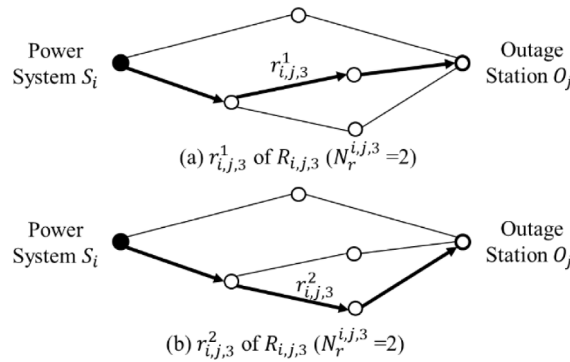


Fig. 2. Power transmission paths set $R_{i,j,3}$ from power system S_i to outage station O_j .

3.2. Constraint conditions for dynamic partitioning

A. Recoverability constraint of the power transmission path

After a power system blackout (especially a blackout caused by natural disasters) occurs, some electrical equipment may fail to operate due to some faults. Therefore, it is necessary to ensure the recoverability of the electrical equipment involved in the power transmission path.

Define the recoverability status of the electrical equipment E_m (m is the sequence number of the electrical equipment) as:

$$u_{E_m} = \begin{cases} 0, & \text{outage and unrecoverable} \\ 1, & \text{outage but recoverable} \\ 2, & \text{running} \end{cases} \quad (2)$$

At present, the recoverability statuses of power equipment such as switches, bus bars, transformers and generators involved in the power transmission path are considered to ensure the recoverability of the path.

The connectivity constraint of the path $r_{i,j,l}^k$ can be described as:

$$\prod_{E_m \in r_{i,j,l}^k} u_{E_m} \geq 1 \quad (1 \leq i \leq N_S, 1 \leq j \leq N_O, 1 \leq k \leq N_r^{i,j,l}) \quad (3)$$

B. Safety constraint of the power transmission path

Considering the characteristics of power systems and the outage grid, the power system may not be able to transmit power to all outage stations in the grid.

According to the types of power sources, the restoration strategy can be divided into two categories: Top-down strategy and Bottom-up strategy. Top-down strategy means getting power supply from the adjacent power systems or upper-level power system, while the Bottom-up strategy is to get power supply from a black-start unit or an isolated power system. The reactive power control capability of the power system limits its ability to charge the outage lines or transformers, thereby limiting the maximum power transmission distance of the power system; the adequacy of active power in the power system limits its maximum capacity sent out to the outage stations, thereby limiting the restoration capability of the power system to the loads in outage stations (including the auxiliary equipment of the power plant); the stability of the power system limits its ability to withstand the fluctuations during restoration.

For example, the small isolated 220 kV power system formed from a black start power plant generally has a small short-circuit capacity. If there is no corresponding reactive power adjustment measures, the nominal frequency overvoltage and the switching overvoltage are likely to occur when charging the high-voltage long distance line or the large-capacity transformer with little load. The power system with power support from the upper-level power

system or adjacent power systems through 500 kV lines usually has a better reactive power control capability and higher active power capacity than the small isolated 220 kV power system formed from a black start power plant, and can restore big power plants, charge some 500 kV lines directly and even charge multiple lines simultaneously.

The safety constraint of the power transmission path need to be considered from the two aspects: the reactive power control capability of the power system and the characteristics of the outage grid. From the perspective of the power system, the stronger the reactive power control capability of the power system is, the longer the outage lines can be charged safely, and the longer the potential power transmission path is. From the perspective of the outage grid, the smaller the capacitance of the lines involved in power transmission path and the less the number of voltage conversions is, the smaller the demand for the reactive power control capability of the power system is.

In order to determine the potential power transmission range of the power system quickly in dynamic partitioning, it is necessary to design a simplified safety constraint indicator that takes into account the characteristics of both the power system and the outage grid. The detailed safety check of the restoration plans will be completed by the subsequent optimization modules in the decision support system. The simplified safety constraint for the path $r_{i,j,l}^k$ can be described as:

$$\sum_{L_n \in r_{i,j,l}^k} X_{L_n} \leq W_i^{max} \quad (1 \leq i \leq N_s, 1 \leq j \leq N_o, 1 \leq k \leq N_r^{i,j,l}) \quad (4)$$

X_{L_n} is the per-unit value of the reactance of line L_n where n is the sequence number of line, W_i^{max} denotes the reactive power control capability of power system S_i , which can be determined by expert experience according to the type of the power source of the power system.

3.3. Dynamic partitioning procedure

The procedure for dynamic partitioning is shown in Fig. 3. The status of power plants and substations can be classified into 3 states (outage, partial restored and fully restored) according to the recoverability status of the electrical equipment in the station. The outage station can be seen as a restoration target if at least one generator in the outage power plant can be restarted, or at least one bus bar in the outage substation can be charged, and added to the restoration target station set $\Omega_o = \{O_1, O_2, \dots, O_{N_o}\}$. A power network with charged stations connecting to each other through charged lines can be identified as one power system, and power system set $\Omega_s = \{S_1, S_2, \dots, S_{N_s}\}$ includes all the power systems. $N_r^{i,max}$ is the maximum acceptable length of the searched power transmission path from power system S_i to outage station O_j which is determined by expert experience.

4. Restoration targets filtering and sorting in each partition

After the grid is partitioned, the restoration targets of each partition need to be determined, after which the optimization and verification of restoration plans of each partition will be conducted. However, it is easy to fall into local optimization in each partition because it is impossible to coordinate the restoration targets and restoration plans between partitions from the perspective of each partition. Therefore, the ‘‘Restoration Target Stations Filtering and Sorting in Partitions’’ module is put after the ‘‘Dynamic Partitioning’’ module to arrange the restoration targets of each partition rationally from a global perspective in Fig. 1.

4.1. Filtering and sorting method for restoration targets

The ultimate goal of restorative control is to restore the outage loads. Therefore, the restoration value of each outage station can be evaluated by calculating the relevant load restoration revenues. The restoration value of each outage station can be divided into direct value and indirect value. Restoring a substation has only direct value, that is, the revenues on restoring loads in the substation. The direct value of restoring a power plant is from restoring loads in substations around the plant when the newly restored generator in the plant increases the output power after being connected to the power system. The indirect value of restoring a power plant is that it will enable the power system to restore the large-capacity outage power plant that could not be restored at present, so that it can generate greater load restoration revenues in the future.

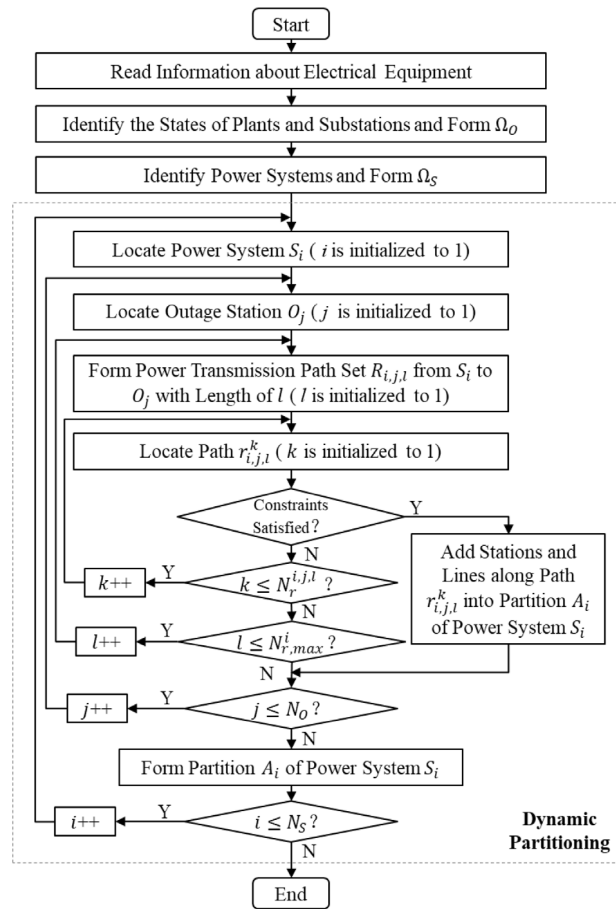


Fig. 3. The procedure for dynamic partitioning.

4.2. Evaluation of the direct restoration value of restoration targets

The restoration value of an outage station is specific to each power system. The greater the power capacity the power system supplies and the shorter the time consumption of the power transmission path takes, the earlier and bigger the loads can be restored. Therefore, it is necessary to evaluate the restoration value of the outage station separately with respect to different power systems.

The restoration value of an outage substation is related to the capacities and unit values of the restored loads, the time of charging, and the time span of evaluation, and eventually evaluated as the integral of the load restoration revenue curve on the time axis. An outage substation can be charged by different power systems and resulting in different restoration revenues.

From the perspective of the time consumption of the power transmission path, when there is a large amount of outage important loads near the power system, it is always the priority to restore these important outage loads in or near the power system instead of restoring the outage substations distant from the power system even though there are many important loads inside the substations.

The restoration value of an outage power plant can be evaluated approximately by calculating the restoration revenue of the loads restored by the newly restored generators in the outage power plant. Similar to the direct restoration value of the outage substation, the restoration value of an outage power plant differs when charged by different power systems due to the difference in the time consumption of power transmission path.

4.3. Evaluation of the indirect restoration value of an outage power plant

Some outage power plants might be unable to be restored by any of the power systems temporarily when the active power capacity or reactive power control capability of each power system is relative limited, or the electrical equipment involved is unrecoverable. If restoring an outage power plant O_j enables the power system S_i to restore a large-capacity outage power plant that could not be restored by any power system at present, the load restoration revenues generated by the large-capacity outage power plant can be calculated approximately and taken as the indirect value of restoring outage power plants O_j by power system S_i .

The gross restoration value of an outage station relative to a power system is the sum of the direct restoration value and the indirect restoration value. According to the gross restoration value, the restoration targets of each partition can be sorted to guide the restoration directions of each partition from a global perspective.

5. Case study

A decision support system for power system restoration is built using C++ programming language, and a case study is conducted on the decision support system using data of a real regional power grid in China. There are 10 power plants with a total installed capacity of 5812 MW and 42 substations in the regional power grid, the load before the blackout is 8136 MW. The geographical diagram of the grid is shown in Fig. 4, and the data about power plants and generators is shown in Table 1. Assuming that the restoration of a 220 kV line and its opposite station takes 5 min, and restoration of a 500 kV line and its opposite station takes 10 min. The evaluation time T is 1200 min, and the initial time of the restoration is 0:00.

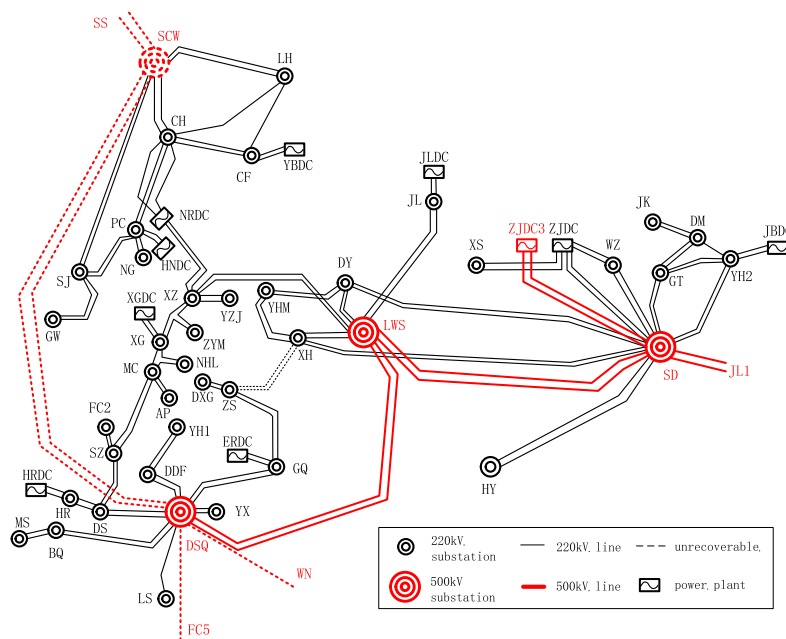


Fig. 4. Geographical diagram of the regional power grid.

At 0:00, there are only two remaining power systems in the power grid: the power plant HRDC is disconnected from the power grid and runs with the local plant load (power system S_1); the 500 kV substation SD which is connected to adjacent power system JL1 through 500 kV lines remains partially running (power system S_2). At this moment, the rest of the power grid is completely blackout. The initial power systems of the power grid after blackout are shown in Table 2.

The results of first round partitioning at 0:00 is shown in Table 3. Substation SCW is not included in partition A_1 due to recoverability constraint of the power transmission path. There are conflicting power plants (JLDC) and

Table 1. Data of power plants and generators.

Power plant name	Generator name	Nominal capacity (MW)	Current status	Power demand for starting up (MW)	Climb rate (MW/min)	Minimum output (MW)	Time limitation of hot/cold restart (min)	Time consumption of hot/cold restart (min)
HRDC	HRDC_1	60	R	7	1.0	40	60/120	30/150
XGDC	XGDC_1	120	H	6	1.5	70	60/180	30/150
	XGDC_2	120	H	6	1.5	70	60/180	30/150
ERDC	ERDC_1	125	H	6	1.5	70	60/180	30/150
	ERDC_2	125	C	6	1.5	70	60/180	30/150
NRDC	NRDC_1	600	H	30	8.0	280	300/500	120/600
	NRDC_2	600	H	30	8.0	280	300/500	120/600
YBDC	YBDC_1	61	H	3	1.0	40	60/120	30/150
	YBDC_2	41	C	2	1.0	30	60/120	30/150
HNDC	HNDC_1	320	H	16	4.0	165	200/300	90/420
	HNDC_2	320	H	16	3.0	165	200/300	90/420
JLDC	JLDC_1	390	H	20	4.0	280	200/300	90/420
	JLDC_2	390	H	20	4.0	280	200/300	90/420
ZJDC3	ZJDC3_1	1000	H	50	10.0	600	380/580	150/650
	ZJDC3_2	300	H	15	3.0	150	200/300	90/420
ZJDC	ZJDC_1	300	H	15	3.5	150	200/300	90/420
	ZJDC_2	300	H	15	3.5	150	200/300	90/420
JBDC	JBDC_1	320	H	16	3.0	160	200/300	90/420
	JBDC_2	320	U	16	3.5	160	200/300	90/420

(R: running; H: hot standby; C: cold standby; U: unrecoverable now).

Table 2. Initial power systems of the grid after blackout.

Power system	Power plants included	Substations included	Current active power available (MW)
S_1	HRDC	HR	20
S_2	(power from JL1)	SD	1500

Table 3. Results of dynamic partitioning at 0:00.

Partitions	Power plants included	Substations included
A_1	HRDC, ERDC, XGDC, JLDC	HR, DS, DSQ, SZ, FC2, MC, DDF, GQ, YX, LWS, LS, BQ, XG, NHL, AP, YH1, ZS, XH, DY, JL, MS, ZYM, XZ, DXG, YHM
A_2	ZJDC3, ZJDC, JBDC, JLDC	SD, HY, XH, DY, WZ, GT, YH2, LWS, YHM, DM, JL, XZ, DSQ, XS

substations (LWS, XH, DY, XZ, YHM) between partition A_1 and partition A_2 . There are also stations which do not belong to any partition at present.

For comparative analysis, Table 4 gives the partitioning results obtained according to the method in Lin et al. [3]. In the partitioning results, there is no conflicting station between partition A_1 and partition A_2 , and all the stations in the grid are included in these two partitions, and partition A_2 includes more stations than that in partition A_1 , which is in contrast to the results in Table 3.

Table 4. Results of partitioning according to method in Lin et al. [3].

Partitions	Power plants included	Substations included
A_1	HRDC, XGDC, NRDC, HNDC, YBDC	HR, DS, SZ, FC2, MC, AP, XG, NHL, ZYM, XZ, YZJ, GW, SJ, NG, PC, CH, CF, LH
A_2	ZJDC3, ZJDC, ERDC, JBDC, JLDC	MS, BQ, DSQ, LS, YX, DDF, YH1, GQ, ZS, DXG, LWS, XH, YHM, DY, JL, SD, HY, XS, WZ, GT, YH2, DM, JK

Although there are conflicting power plants and substations between partitions A_1 and A_2 , the restoration values of these conflicting stations are different with respect to power system S_1 and power system S_2 .

For power system S_1 : the outage power plant JLDC cannot be restored by power system S_1 temporarily because the power demand for starting up of power plant JLDC is bigger than the active power capacity available in power system S_1 ; the length of power transmission path from power system S_1 to outage power plant ERDC is the shortest compared with other outage power plants in partition A_1 , but there are much more important loads around outage power plant XGDC, and the distance from XGDC to the outage power plants which cannot be restored at present, namely NRDC, HNDC and YBDC, is also shorter than that from other outage power plants in partition A_1 , so after comprehensive consideration, the outage power plant XGDC should be of top priority to be restored in partition A_1 .

For power system S_2 : the active power support of the adjacent grid is abundant, and the power transmission distances from S_2 to the outage power plants JLDC, ZJDC3, ZJDC and JBDC are also similar, the outage power plant ZJDC3 with the largest nominal capacity has the highest restoration value in partition A_2 .

The evaluation results above will be submitted to the subsequent calculation module “Search and Optimization of Restoration Plans in Each Partition” for further calculation, and finally the dispatcher will determine the restoration plans of each partition and issue control instructions based on the suggested restoration plans from the decision support system.

During the first round of restoration, power system S_1 sends power to the outage power plant XGDC via the path “HR-DS-SZ-MC-XG-XGDC” and tries to restore the generator XGDC_1 in the power plant, and power system S_2 sends power to the outage power plant ZJDC3 via the path “SD-ZJDC3” and tries to restore the generator ZJDC3_1 inside the power plant.

At 0:28, supposing a bus of power plant XGDC in partition A_1 has been successfully charged, but the auxiliary equipment in the plant fails to restart and results in the blackout of XGDC again. While at the same time, the power plant ZJDC3 in partition A_2 has been successfully powered and the generator ZJDC3_1 in the plant is in the process of hot restart. At this point, the decision support system decides to re-partition and re-optimize the restoration plans for power system S_1 . Table 5 gives the relevant information of power system S_1 , and Table 6 gives the results of dynamic partitioning at 0:28.

Table 5. Power system to be partitioned at 0:28.

Power system	Power plants included	Substations included	Current active power available (MW)
S_1	HRDC	HR, DS, SZ, MC, XG	18

Table 6. Results of dynamic partitioning at 0:28.

Partitions	Power plants included	Substations included
A_1	HRDC, NRDC, ERDC, JLDC	HR, DS, SZ, MC, XG, DSQ, FC2, AP, NHL, ZYM, XZ, DDF, GQ, YX, LWS, LS, BQ, TZJ, YH1, ZS, XH, DY, JL, MS, CH, DXG, YHM, CF, LH, PC

At this time, the scale of partition A_1 gets larger than that at 0:00, but the outage power plant XGDC will not be included in partition A_1 due to the restoration failure of it. The final optimization result is that power system S_1 will sent power to the outage power plant ERDC via the path “DS-DSQ-GQ-ERDC” and tries to restore the generator ERDC_1 in the power plant. Meantime partition A_2 is still under restoration according to the original plan. If any of the restoration of the partitions fails or succeeds, the decision support system will re-optimize the restoration plans for the power system dynamically. The optimization and implementation cycles will keep going until the end of the grid restoration.

By comparison, if the restoration plans of power system S_1 are calculated according to the partitioning results in Table 4, the outage power plant ERDC cannot be restored by power system S_1 because it does not belong to partition A_1 , which means the power plants NRDC, HNDC and YBDC which are father from power system S_1 than that of ERDC will be restored by power system S_1 , which is not conducive to the fast restoration of partition A_1 .

6. Conclusions

The case study has shown the superiority of dynamic partitioning in dealing with the uncertainties of grid restoration process. When the grid is performing parallel restoration with multiple power systems, the decision support system will refresh the restoration partitions and restoration plans for power systems that fail or succeed in restoration actions dynamically, and keep monitoring the restoration processes of power systems whose restoration processes go as planned. If the restoration process of the power system goes smoothly, the partition will expand dynamically, if a power system is blackout again due to some failure, its partition will be withdrawn and its restoration actions will be halted accordingly. The online decision support system for restorative control can solve the problem of confliction in restoration targets between partitions, and assist the dispatchers to achieve coordinated parallel restoration of multiple power systems effectively.

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