A Review on Decision-making Methods for Restoration Control of Transmission and Distribution Systems

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Abstract. Power system blackouts can't be avoided fundamentally, so it is of great significance to realize the adaptive and collaborative restoration control of transmission and distribution system to improve the power system blackout defense capability. In this paper, the existing researches are summarized from three aspects, i.e., decision-making of transmission system restoration control, decision-making of distribution system restoration control, decision-making of transmission and distribution coordinated restoration control, the research difficulties are expounded, and the future research directions are prospected. In view of the characteristics of multi-level, cross-regional, multi-stage and strong uncertainty of collaborative restoration control of transmission and distribution systems, it is pointed out that the establishment of restoration decision support system by comprehensive application of optimization algorithms, expert rules and numerical simulation programs is an important mean to realize adaptive restoration control.

1. Introduction
In recent years, with the increase of renewable energy penetration, the extensive application of power electronic equipment, the frequent occurrence of extreme natural disasters and the increase of malicious attacks on power systems, the risk of blackout caused by local faults has greatly increased [1]. The purpose of the power system restoration control is to restore power supply quickly, securely, and economically after a power outage occurs, reduce the outage losses, and mitigate the risks of losing stability from restoration operations [2]. The restoration experience of blackouts in the world shows that the restoration process of transmission and distribution systems are influenced by each other, and the restoration control requires the coordination of transmission and distribution systems. In addition, because it is difficult to accurately model the actual restoration control process, and there are high-dimensional uncertainties in the control process and the external environment, it is necessary to adaptively adjust the restoration control scheme according to the actual restoration control process. In summary, it is of great significance to study the adaptive and collaborative restoration control of transmission and distribution systems.

The adaptive and collaborative restoration control of transmission and distribution systems is a multi-level, cross-regional, multi-stage and highly uncertain spatio-temporal coupling problem [3,4]. The existing research on restoration control decision-making is usually divided into two kinds of single-level power system restoration decision-making problems: transmission system restoration decision-making and distribution system restoration decision-making. The transmission system side studies mainly include partitioning and phased restoration methods, while the distribution system side studies mainly include single-step or multi-step reconfiguration methods, without considering the
restoration decision-making of spatio-temporal coordinated transmission and distribution systems. At present, there are a few researches on collaborative restoration control of transmission and distribution systems, which mainly focus on the collaborative restoration of transmission and distribution systems in specific partition and specific restoration stage, and less comprehensive consideration is given to the cross-regional, multi-stage and strong uncertainty characteristics of transmission and distribution coordinated restoration control, which cannot support the realization of collaborative and adaptive restoration control of transmission and distribution systems.

Based on this, this paper summarizes the existing research achievements from three aspects: the decision-making of transmission system restoration control, the decision-making of distribution system restoration control, and the decision-making of transmission and distribution coordinated restoration control. Then the research difficulties are expounded, and the future research directions are prospected.

2. Physical Description of Restoration Control of Transmission and Distribution Systems
Considering the operation characteristics of transmission and distribution systems and the restriction of dispatching jurisdiction, power system restoration control is usually divided into transmission system restoration control and distribution system restoration control, which have a coupling relationship in time and space dimension.

2.1. Description of Restoration Control of Transmission System
The task of restoration of the transmission grid is to gradually restore the power failure equipment in the transmission grid through a series of restoration control operations for the transmission grid under the restored state, and to quickly, safely and economically restore the power supply to the distribution system, and return the power system to an acceptable operating state with the cooperation of the restoration control of the distribution system. The main restoration operations during the period include: preparation before restoration; restart the black start unit; restore the non-black starting unit; power grid connection and output adjustment; restoration of power transmission and transformation equipment; restoration of power supply to the distribution system; paralleling and loop closing of restored power grid, etc.

2.2. Description of Restoration Control of Distribution System
The task of distribution system restoration is to comprehensively utilize the power sent from the transmission system and the distributed generation in the distribution system, restore the load power supply quickly, safely and economically, reduce the power outage loss and avoid the new instability risk introduced by restoration measures. According to the power outage range of distribution system, distribution system restoration can be divided into two types: large-scale power outage restoration and local power outage restoration. The former is usually caused by power failure of transmission system, and there may be faults in distribution system. The latter is usually caused by internal faults in the distribution system. After the fault is isolated, it is necessary to use the power support of adjacent uninterrupted feeders and other power sources to restore load power supply through local distribution system reconstruction (such as power outage load transfer) and other measures.

2.3. Coupling Relationship of Restoration Control of Transmission and Distribution Systems
In this paper, the bus of 220kV substation is taken as the boundary of transmission and distribution systems, which is called transmission and distribution system interfacing bus (TDB). Restoration control after blackout requires coordination between transmission system and regional distribution system. On the one hand, as a distribution system of electric energy, the distribution system can receive the time-varying power from multiple TDBs and distribute the power to the end load users according to the radial topology; On the other hand, when conditions permit, the controllable distributed generation in the distribution system can also send power to the transmission system.
through TDB, which can be used to restore the non-black start-up units and other important goals in the transmission system [5], so as to improve the overall restoration efficiency.

3. Transmission System Restoration Control Decision-making

In view of the decision-making problem of the restoration control of the transmission system, sub-issues such as partitioning and coordination among partitions, unit and load restoration in a single partition, and decision support system construction have been widely concerned.

3.1. Decision-making Method for Restoration of Transmission System

Transmission system restoration control decision-making is a highly nonconvex mixed integer nonlinear programming problem. At present, there is no mature solution method that can give consideration to the optimality and rapidity of solving the problem. Heuristic methods such as experience and rules [6] can quickly reduce the decision-making space of the problem, but they can only give the local optimal solution of the problem, and it is difficult to model and maintain the experience and rules. Mathematical programming method [7] has obvious advantages in solving the optimal solution. Usually, the model is simplified by means of model linearization, model decoupling and iteration, time-sharing optimization, etc., so as to reduce the difficulty of problem solving. However, it is impossible to generate a restoration operation sequence and evaluate its feasibility and safety, and its difficulty of solving will increase sharply with the increase of the complexity and scale of the problem. The algorithm of meta-heuristic methods such as particle swarm [8] is concise and clear, but it can only give a locally optimal solution and cannot guarantee the efficiency of the solution.

3.2. Dynamic Partitioning

After the occurrence of a power outage, the various forms of available power sources that may exist in the transmission grid (such as black-start units, electrified areas operating independently after the blackout, power support of adjacent external transmission and distribution systems, etc.) can be used to perform multi-regional concurrent restoration of the transmission grid to speed up the restoration process of the transmission grid.

Existing partition methods mainly focus on initial partition, including partition methods based on ordered binary decision tree [9], complex system theory [10], community partition theory [11], cut set matrix [12]. According to the partial power outage scenario of the transmission grid, literature [13] formed a hierarchical partition restoration scheme according to the steps of power outage area partitioning, restoration strategy selection, and two-stage multi-objective optimization, and used the comprehensive advantage relationship evaluation method to achieve the matching of restoration partition and restoration strategy. Literature [14] considers the influence of unit and load restoration scheme in the partition, and readjusts the partition result if a feasible restoration scheme cannot be generated in the partition.

3.3. Optimization of Restoration Scheme for Single Partition

According to experts’ experience, the restoration process in a single partition of transmission system is divided into several restoration stages with sequence, such as black start/unit restoration, grid restoration and load restoration [15], and each stage is independently optimized to reduce the difficulty of decision-making. Among them, the main restoration targets of black-start and grid restoration stage are black-start units, non-black-start units and important substations, while the load restoration stage refers to the gradual restoration of the load carried by each substation when the units and backbone grid have been restored.

3.3.1. Unit Restoration. There are various methods to solve the unit restoration scheme, which usually aim at maximizing the unit restoration capacity [16] and minimizing the unit restoration time [17], and adopt mathematical programming [7], expert system [18], analytic hierarchy process [19], data
envelopment analysis [20], group decision-making [21], multi-agent [22] and other methods to solve the problem. Literature [23] puts forward a decision-making method for grid restoration based on multi-attribute group decision-making, and proposes a three-stage restoration strategy, in which the main restoration objectives are main units, important substations, inter-regional interconnection or supporting adjacent partitions. In [24], a multi-objective optimization model for unit restoration was established, and differential evolution-distribution estimation algorithm was introduced to solve it. At the same time, the restoration sequence of the non-black start unit and the target backbone grid are obtained.

3.3.2. Load Restoration. In the load restoration stage, the optimization objectives are to maximize the weighted load restoration amount [25] and minimize the load restoration time [26], and optimization methods such as mathematical programming [27], heuristic [28] and meta-heuristic [29] are adopted to solve the problem. Literature [30] puts forward a closed-loop control strategy for load restoration based on wide area measurement system. According to the measured frequency of the system, unit climbing rate, unit frequency response characteristics and load frequency response characteristics, solve the load restoration position, restoration amount and restoration time. After the load restoration is implemented, the measured system frequency is used as feedback to correct the load restoration decision-making model in the next step. Literature [31] further considers the uncertainty of renewable energy power output and load demand when making load restoration decision, and adopts the risk assessment method based on conditional value at risk, which converts the uncertainty problem into a deterministic problem and then solves it.

3.3.3. Coordinated Restoration of Unit and Load. In the actual restoration process of transmission system, the restoration of units, grids and loads is usually carried out alternately, the restoration sequence of units and loads needs further coordination and optimization. Literature [32] established integer programming models for grid restoration, station restoration and load restoration respectively, and solved the unit and load restoration schemes step by step by dictionary sorting algorithm, analytic hierarchy process and backtracking algorithm. In reference [33], mathematical programming models for unit, grid and load restoration were established respectively, and the three models were solved in sequence by commercial solvers, then the restoration scheme was solved by sequential iteration among the models.

3.4. Coordination and Optimization Among Partitions
Coordination among partitions includes: dynamically partitioning after a new available power supply appears; dynamically adjust the range of each partition in case of power failure and equipment damage on the restoration path in a certain partition; when connectivity is feasible among partitions, optimize connectivity scheme to expand restoration range and share restoration power, and readjust the scope of each partition according to the power failure scenario after connectivity. Literature [34] puts forward the restoration control optimization framework of "independent optimization within partitions and dynamic coordination among partitions". The upper layer realizes dynamic partitioning and coordination among partitions, and the lower layer refreshes the restoration scheme in each partition online. Literature [35] points out that when intra-partition restoration fails, it is necessary to coordinate inter-partition power support among dispatching departments and merge partitions. The research on inter-partition connectivity decision-making mainly focuses on the elaboration of connectivity ideas and the safety conditions to be met for connectivity [36]. However, in the actual restoration process, there may be the need for active connectivity between partitions. For example, if the available power is abundant but the remaining load to be restored is relatively minor, it is necessary to send power to the partitions with insufficient power and important load in time to restore the important load as soon as possible.
3.5. Deal with the Uncertainty of Restoration Process

The decision-making of transmission system restoration should also take into account the coping methods of power failure scenarios, external environment and high-dimensional uncertainties in the restoration process. In view of the decision-making process, Literature [34] proposes to evaluate the safety of different restoration schemes according to the risk method, so as to avoid the new instability risk introduced by restoration measures. For the implementation process, most studies refresh the restoration scheme according to the actual restoration process [37], but they do not distinguish the influence of different uncertain events in the restoration process, such as the equipment failure probability changed due to the influence of external environmental factors such as natural disasters, the capacity demand of the load to be recovered under the bus and the unit restoration income changed significantly, and a more important target can be recovered due to the emergence of new successfully repaired equipment, etc.

3.6. Transmission System Restoration Decision Support System

The decision-making to restore the transmission grid requires comprehensive consideration of various complex factors such as the operating conditions of each restored power grid, the operable state of each equipment, the conditions that each operation needs to meet, the integrity of the grid structure, and various safety constraints [38], which is difficult to be dealt with by single expert experience, mathematical programming, meta-heuristic and other methods. The idea of establishing a decision support system by comprehensively using optimization algorithms, expert rules and numerical simulation programs has attracted widespread attention. Literature [36] puts forward a decision support system based on general restoration milestones, which classifies the restoration scheme optimization into six independent optimization sub problems. Literature [39] makes a decision on the black-start scheme based on the dispatcher training system, and can call various functional modules of the dispatcher training system to verify the security of the generated candidate scheme. Literature [40] designed the framework of decision support system for adaptive restoration control of transmission system, and proposed a two-level optimization method for multi-partition dynamic coordinated restoration of transmission system.

4. Distribution System Restoration Control Decision-making

4.1. Decision-making Method for Restoration of Distribution System

The restoration decision-making of distribution system is essentially a semi-structured problem with multi-region, multi-step, strong nonlinearity and uncertainty [41]. The restoration decision-making of large-scale power outage in distribution system usually aims at minimizing power outage loss [42], switching operation times [43], etc. The restoration scheme is solved by mathematical programming [44], multi-agent [45] and heuristic methods [46]. The common methods for decision-making of local outage restoration in distribution system include fuzzy evaluation [47], multi-agent [48], meta-heuristic [49], mathematical programming [50] and so on.

4.2. Partition and Intra-partition Restoration Decision

The closed-loop design of the distribution system can obtain the top-down spatio-temporal power support of the transmission grid through multiple TDBs [51], and at the same time, it can also use a large number of distributed power sources in the distribution system for rapid bottom-up restoration [52].

For each electrified domain powered by TDB, due to the open-loop operation constraint of distribution system, such electrified domains must be restored independently by partitions, and cannot be connected in the restoration process. The partition results will directly affect the restoration decision-making space of each restored power grid and the topological structure of each electrified domain formed by final restoration. For each electrified domain formed by the restoration of available power sources in the distribution system from bottom to top, its partitioning is more flexible. The
existing partition methods of distribution system are mainly aimed at the scene when the distributed generation is restoring from bottom to top, and the commonly used methods include mathematical programming [53], heuristic method [54] and so on. Literature [55] determines the partition range of each microgrid by generating the restoration path tree of each microgrid, verifying all paths in it, then establishing the maximum coverage problem model and solving it to determine the final power supply area of each microgrid. In [56], the distributed generation in distribution system is divided into different partitions based on graph theory and tabu search, aiming at maximizing the adequacy of partitions and minimizing the power imbalance in partitions.

The research on optimization of intra-partition restoration scheme mainly focuses on load restoration. Literature [57] takes maximizing the load-weighted restoration as the optimization objective, and adopts two-stage optimization strategy to solve the problem. The first stage optimizes the power grid topology, and the second stage optimizes the load restoration scheme and power output. Literature [51] comprehensively utilizes the power support of the transmission system and distributed generation to restore the load of the distribution system, relaxes the nonlinear three-phase unbalanced power flow and distribution system component model into a convex quadratic programming model, and optimizes the solution by alternating direction multiplier method.

4.3. Coordination and Optimization Among Partitions
The coordination and optimization of distribution system restoration between partitions include the optimization and pre-adjustment of the operation mode of the restored power grid of the distribution system, as well as the connectivity decision-making between partitions.

4.3.1. Optimization and Pre-adjustment of Operation Mode of Distribution System in Restored Power Grid. Most of the existing partition methods and intra-partition restoration scheme optimization methods are carried out in a single real-time power outage scenario. However, in the actual restoration process, it is affected by many factors such as the power transmission scheme of the transmission grid at each TDB, the time-varying nature of the load capacity of the distribution system and its unit restoration income, and the uncertainty of the restoration process. In a given power outage scenario, there may be a mismatch between available power, system structure, and load demand. In this regard, on the basis of real-time power failure scenarios, through the optimization and pre-adjustment of the operation mode in the restored power grid [59], such as live load transfer, power output adjustment in the restored power grid, etc., more anticipated power failure scenarios can be provided for partitioning, and more matching schemes of available power sources and targets to be restored can be added. At present, however, there is no decision-making method to optimize the pre-adjustment scheme of the live-line operation mode from a global perspective.

4.3.2. Connectivity between Partitions. The electrified domains formed by the restoration of the available power sources in the distribution system from bottom to top can be connected with each other in the restoration process, or can be connected with the electrified domains of the distribution system powered by TDB. In this regard, Literature [60] divides the restoration of large-scale power failure in distribution system into three stages: the restoration of distributed generation to form independent running restored power grid, the interconnection between independent running restored power grid, and the interconnection between independent running restored power grid and the superior power grid. Microgrid partitions are determined according to the radial topology before power failure in distribution system, and the interconnection between partitions is made at the tie switch. Literature [61] discusses the technical conditions that need to be met when the internal power supplies of microgrid are connected.

4.4. Deal with the Uncertainty of the Restoration Process
The decision-making of distribution system restoration should have the ability to adapt to various uncertain events in the restoration process, and existing studies usually deal with uncertain events in
the restoration process through refresh schemes [58], but the characteristics and influences of various uncertain events are not distinguished, so it is difficult to adaptively control the restoration process in a targeted manner.

4.5. Decision Support System for Distribution System Restoration

By designing the framework and functional modules of DSS, we can integrate the advantages of various optimization methods such as heuristic and mathematical programming, adapt to various power failure scenarios, and dynamically give better feasible solutions. Among them, the heuristic method is fast, and can give a detailed switch operation sequence that satisfies the transient safety constraints. Mathematical programming method can give the staged or final target grid and a set of switch state adjustment schemes. The numerical simulation program can be used to verify the security of the scheme. At present, the related research mainly focuses on the early distribution system restoration expert system for feeder-level outages [59].

5. Collaborative Restoration Control of Transmission and Distribution Systems

Research on restoration decision-making of transmission system or distribution system alone usually does not consider the synchronization and coordination of boundary conditions of transmission and distribution systems. In this regard, there has been a small amount of research on collaborative restoration decision-making of transmission and distribution systems, which mainly focus on cooperative restoration of transmission and distribution in specific partition and restoration stage, such as collaborative unit restoration and collaborative load restoration of transmission and distribution systems.

5.1. Collaborative Unit Restoration of Transmission and Distribution Systems

To solve the problem of collaborative unit restoration of transmission and distribution systems, there have been hierarchical case reasoning [62], master-slave hierarchical decision-making [63], hierarchical cooperative restoration based on power receiving points [64] and so on. Literature [65] considers the active support capability of distributed generation when making the decision of unit restoration in transmission system, and adopts the objective cascade analysis method based on projection function to solve the problem. In [66], the mixed integer quadratic programming models for black-start of transmission and distribution systems were established respectively, and the iterative solution between the models was carried out based on the objective cascade analysis method.

5.2. Collaborative Load Restoration of Transmission and Distribution Systems

To solve the problem of collaborative load restoration of transmission and distribution systems, literature [67] decomposed the problem into mathematical programming models of transmission system side and distribution system side. The two models were coupled by the exchange power at TDB and the node voltage, and the iterative solution between the models was carried out based on the alternating direction multiplier method, thus determining the one-step load restoration scheme of transmission and distribution systems. Literature [68] further considered the uncertainty of load and power output, and solved the problem by a two-stage model predictive control method based on conditional risk value.

In fact, collaborative restoration decision-making and collaborative restoration execution of transmission and distribution systems run through the whole restoration process. However, there is still a lack of research on adaptive and spatio-temporal collaborative restoration control of transmission and distribution systems.

6. Research Prospect

To sum up, the research on restoration control decision-making of transmission and distribution systems has achieved fruitful results, but there are still the following problems that need further study.
6.1. Decision-making Method of Adaptive and Collaborative Restoration Control of Transmission and Distribution Systems

The restoration control of transmission and distribution systems is a large-scale mixed integer nonlinear problem that is difficult to be solved directly. To solve this problem, firstly, partition schemes, inter-partition connectivity schemes and intra-partition restoration schemes of power grids at all levels should be solved in turn based on any power failure scenario. Furthermore, during the implementation of the restoration scheme, it is necessary to adaptively control the restoration process of the transmission and distribution systems according to the restoration process of the transmission and distribution systems and various uncertain events occurring in the external environment. Therefore, how to comprehensively consider the above decision-making needs and make decision of adaptive and collaborative restoration control of transmission and distribution systems remains to be further studied.

6.2. Restoration Control Method with High Proportion of Renewable Energy Participation

The uncertainty of renewable energy output will adversely affect the security and restoration process of the power system. Therefore, only traditional stable and controllable power sources such as thermal power and hydropower are usually considered as available restoration power sources. However, with the improvement of the penetration rate of renewable energy sources in all levels of power grids, its value as an available restoration power source for transmission and distribution systems in the early restoration period is increasing. Therefore, it is necessary to study the ways and decision-making methods of renewable energy to participate in power grid restoration, so as to assist the coordinated restoration of transmission and distribution systems and avoid its adverse effects on power grid security.

6.3. Decision-making Method of Restoration Control Considering Equipment Emergency Repair

Some power equipment may be damaged to varying degrees during blackout and subsequent restoration. Timely repair of key equipment will help speed up the restoration process of power grid. The progress of equipment repair is affected by many external factors such as repair personnel, materials, traffic, weather, etc., and the urgency of equipment repair is affected by the restoration value of the target to be restored and its potential restoration path, and the scheme of equipment repair will further affect the decision-making result of power grid restoration, further research is needed on how to coordinate the restoration decision-making process with the repair decision-making process and adapt to various uncertain factors.

7. Conclusion

In this paper, three research directions of transmission system restoration control, distribution system restoration control and collaborative restoration control of transmission and distribution systems are summarized, and the future research directions are prospected. Over the years, a large number of researches on restoration control of transmission and distribution systems have been accumulated at home and abroad, but the researches on online adaptive restoration control are still relatively few. With the development of information and communication technology and the improvement of automation level of power systems at all levels, it is expected to further realize the adaptive and collaborative restoration control of transmission and distribution systems in the future, so as to improve the security and stability control level of large power system and the resilience of power system.

Acknowledgments

This work is supported by Science and Technology Project of State Grid Sichuan Electric Power Company (SGSC0000DDJS2000117).
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