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REVIEW ARTICLE

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Review on optimization methodologies in transmission network reconfiguration of power systems for grid resilience

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Abstract

Background: When a power system blackout occurs, it affects the economy of the country and every aspect of human life. Cascading failures can easily occur and cause a major blackout in the power grid due to the breakdown or failure of important nodes or links. Recently, transmission network reconfiguration (TNR) becomes a hot topic and has made many concerns after major blackouts of power systems.

Aims: TNR is the second-stage action plan to restore power systems and plays a major role in the process of power system restoration. On the other hand, grid resilience involves a quick dynamic reconfiguration of power systems to minimize the propagation of attack influences on the grid. The motivations to include the works in this survey are based on the quality of the research performed in the transmission network reconfiguration problem for grid resilience. In this article, the state-of-the-art review of recent progress in the network reconfiguration problem of the transmission system for grid resilience is discussed with practical challenges, technical issues, and power industry practices.

Materials & Methods: In this paper, complex network theory-based indices with advantages, disadvantages, and their applications have been discussed to assess the important nodes and lines for network reconfiguration problem during sudden disturbances in power systems. Furthermore, optimization models have been presented with objective functions as well as their constraints. Taken together, optimization methodologies have been discussed to solve network reconfiguration problem with merits and demerits.

Results: This survey paper presents current trends in research and future research directions concerning transmission network reconfiguration for academic researchers and practicing engineers. Furthermore, the most current studies in improving transmission network reconfiguration problem are reviewed by highlighting their advantages and limitations.

Discussion: Based on a thorough comparison of literature some future perspectives are also discussed for transmission network reconfiguration problem for grid resilience.

Conclusion: This review paper provides a comprehensive review of current practices applied to transmission network reconfiguration. The core focus of this paper will remain on complex network theory-based indices, optimization models, optimization methodologies, challenges, and technical issues, and discusses future direction for transmission network reconfiguration problem for grid resilience. Furthermore, the most current studies in improving transmission network reconfiguration problem are reviewed by highlighting their advantages and limitations.

KEYWORDS

complex network theory, network reconfiguration, optimization methodologies, power system restoration

1 | INTRODUCTION

Due to the social and economic development, more and more demand for reliable power supply is needed. Furthermore, with the increase of the interconnection and the complexity of power grids, power systems have drawn considerable interest and attention from researchers nowadays.[1] It is vital to obtain quick recovery from the interrupted power supply after a blackout. To reduce the risks of power system failures, it is important to strengthen the structure of a power system and its management optimization. The emergent convolution of power systems and uncertainties in power system operation increase the risks of power system failures. After the blackout of the power grid, there is a need for an appropriate resilience-based strategy for restoring the power grid in the aspect of extreme weather conditions.[2] Grid resilience has the ability to restore itself in the usual operating state with minimum human interference after any disturbance or outages.[3]

Decision support tools can be applied for the fast recovery of the power system to overcome the manual recovery operation.[4] Generation restart, network reconfiguration, and load recovery are the three stages of power system restoration. Network reconfiguration is a critical stage out of three stages and plays a vital role in building the skeleton network.

Many research efforts have been devoted to the network reconfiguration problem of power systems. Power networks have features of complex networks (CNs).[5] Complex network theory (CNT) has many applications such as the power grid,[6,7] internet, web topology, transportation system, airports, communication network, and also social networks. CNT-based indices have been applied to evaluate the important nodes and edges in the network. One important concern is that the nodes and edges in the network have different network connections and their functions. Now a question arises, how to detect or identify critical nodes and links in the network and their impact on the network topology of the power grid. Researchers suggest that as long as 4% of the total nodes with a large load in the power grid break down, the connectivity of the power grid will decrease by 60%.[8] Node and line importance evaluation contributes to the targeted protection of important nodes and links in the power grid. Node importance degree and efficiency indices have been used for network reconfiguration.[9] A self-healing transmission network reconfiguration algorithm based on CNs[10] and node importance based on the concept of regret have been proposed.[11] Similarly, the line contraction concept has been used for evaluating the importance of various lines.[12] Furthermore, the node importance degree based on node contraction has also been used to build the skeleton network.[9]

There are three phases of optimization network reconfiguration such as start-up sequence of generating units, skeleton network, and then to optimize the restoration paths[12] taking all restoration constraints into consideration.[13] Artificial intelligence techniques can be used in the network reconfiguration process to restore the power system quickly within a short period of time. Decision-making methods have been proposed to solve the network reconfiguration problem. These methods were applied to evaluate the unit's start-up sequence,[11,14-16] to build the skeleton network,[17] and to obtain restoration paths.[16,18-20] Aiming to obtain the global optimal solutions, several optimization techniques such as numerical methods[4,21,22] and optimization algorithms[9,13,23-33] have been applied to solve network reconfiguration problem.

So far, a number of survey papers have been published on power system restoration. However, the TNR, which is the second action plan to restore power, still requires much research. For example, in Reference 34, a review of the role of wind power plants, high-voltage direct current (HVDC), battery energy storage system (BESS), solid-state transformer (SST), and wide-area measurement systems (WAMS) in the restoration process has been studied. Dynamic restoration issues related to voltage and frequency control have been explained in Reference 35. In Reference 36, a brief review of optimal network topology reconfiguration and distributed generators (DGs) islanding has been discussed for power system resilience enhancement during contingencies. In Reference 37, the research progress of black-start, network reconfiguration, and load restoration of the power system restoration from 2006 to 2016 has been discussed in detail. Some advanced methods and key techniques are also discussed in the context of the integration of variable renewable energy and the development of the smart grid. The review paper[37] only discussed the optimization methods for power system restoration. The optimization models, challenges, and decision variables of optimization models are not discussed in Reference 37.

To the best of our knowledge, the comprehensive review on transmission network reconfiguration has not been studied yet, while most of the review papers have been carried out in the field of distribution network reconfiguration. The motivations to include the works in this survey are based on the quality of the research performed in the transmission network reconfiguration problem for grid resilience. This review article provides a comprehensive and critical review of current practices applied to transmission network reconfiguration. The core focus of this article will remain on CNT-based indices, optimization models, optimization methodologies, challenges, and technical issues, and discusses future direction for transmission network reconfiguration problem for grid resilience. Furthermore, the most current studies in improving transmission network reconfiguration problem are reviewed by highlighting their advantages and limitations.

The contributions of this review article are summarized as follows:

- Comprehensively review the state-of-the-art research in transmission network reconfiguration optimization models for grid resilience.
- CNT-based indices are discussed to access the important nodes and lines for the transmission network reconfiguration problem.
- Optimization approaches have been discussed for the evaluation of modeling and simulation of transmission network reconfiguration problem.
- It presents current trends in research and future research directions concerning transmission network reconfiguration for academic researchers and practicing engineers.

The rest of the article is discussed as follows. Section 2 presents an overview of network reconfiguration. In Section 3, CNT-based indices for network reconfiguration are discussed. There is also a discussion about optimization models for network reconfiguration in Section 4. Finally, practical challenges, issues, and industry practices and conclusions are discussed in Sections 5 and 6, respectively.

2 | TRANSMISSION NETWORK RECONFIGURATION FOR GRID RESILIENCE

In the aftermath of unprecedented disasters and attacks in recent years, resilience has become a buzzword in power system discipline.[38] Furthermore, the scope of grid resilience becomes large and covers various features, such as technical, economic, social, and policy. Technically, it includes multi-disciplinary knowledge, such as power system, civil and structure, geography, computer science, probability, and meteorology. The study of grid resilience also relates to many organizations such as utility corporations, disaster management agencies, and national weather services. The impact of interdependency with other areas is beyond the scope of this review. The research and development in the area of power system resilience are still being carried out by many institutions.

The power system resilience is defined as anticipation, absorption, restoration, and adaptability.[39,40] Another definition according to the National Infrastructure Advisory Council (NIAC) based on inherent features of resiliency and the properties of the power system is defined as resourcefulness, rapid recovery, robustness, and adaptability.[41] The relationship between resilience features and power system restoration application is shown in Figure 1. The power system resilience involves two typical structures such as grid assessment and grid enhancement. For the first one, grid

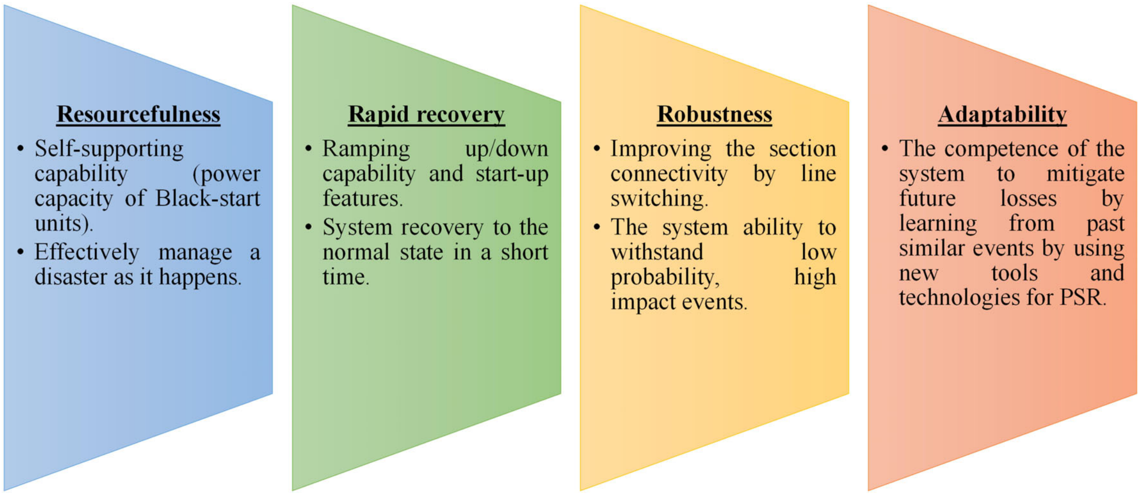

FIGURE 1 Relationship between resilience features and power system restoration applications

assessment is used to evaluate the grid condition by using hazard modeling and results in grid resilience indices and to compare one grid to another and then to further determine necessary actions to enhance the grid resilience. There are four conditions for the grid assessment process, anticipation (prevention state), absorption (degradation state), restoration (restoration state), and adaptability (adaptation state). For the second one, the grid enhancement approaches can be implemented on physical hardiness and operational capability systems of the power grid.[42] Restoring the power system within a short period of time is the objective of grid operational capability after power system blackout.[42-45]

Both transmission and distribution systems are gaining importance in the field of resilience enhancement. Although, the transmission system gained more significant interest due to its complex and dynamic nature (bi-directional flow of power, and mesh/loop topologies)[38] as compared to the distribution system.[46] The transmission network system is a source of feeding sub-transmission networks and is used to interconnect the power grids. So far, it is a big challenge to make a resilience model of the transmission system affected by extreme weather conditions due to its stochastic and unexpected nature and behaviors.

The whole restoration process after a complete power system blackout is done for grid resilience; it can be categorized into three phases, such as black start process, network reconfiguration, and full load restoration. The objectives of the network reconfiguration problem are to build a stable skeleton network,[20] to obtain desirable combinations of sources, loads, and transmission lines,[23] and to prepare for load pickup.[47] Fast restoration is the most salient feature of the resilient power system and plays a vital role in grid resilience enhancement.[39] Moreover, network reconfiguration is the second action plan to restore a power system after a blackout. Network reconfiguration can be treated as a multi-time-step restoration process,[47] in which several plants and substations are energized by cranking power with a certain time-step. It means that temporary backup during the outage of the main power through an emergency power supply or reconfiguration of the grid topology (fast topology reconfiguration) are the main options for enhancing the grid resilience.[39] Furthermore, substation relocation and transmission and distribution lines rerouting may be an option to enhance the grid resilience despite its high costs. Mobile DC de-icing devices scheduling and routing to improve the resilience of electric power transmission systems have been presented in Reference 48. Transmission system reconfiguration has been comprehensively studied in Reference 49. The equivalent generator resilience index is defined to determine the generator start-up priority.[50] There are many indices and optimization techniques that have been used by researchers to evaluate the network reconfiguration problem for grid resilience.

In the previous research work, several optimization techniques are proposed to obtain the global optimal solutions. CNT has been applied to solve the network reconfiguration problem.[9-12] Decision-making optimization methods have been applied to solve the network reconfiguration problem in References 11,14,17-20,51,52. Optimization algorithms have been used to solve the power system network reconfiguration problem. A genetic algorithm (GA) has been proposed for network reconfiguration problem in References 30-32,53.

Power system islanding techniques have been used for network reconfiguration problem in References 54-56. Network reconfiguration has been proposed for the sake of electricity outage recovery,[57] to recover the critical points or components,[58] and to obtain real-time assessment after cascading failures. Transmission system network reconfiguration problems are large scale and complex optimization problem due to the large size and non-linearity of power system.[59] Transmission network reconfiguration using transmission line switching has been proposed to recover the load and to maximize grid resilience.[60] Optimization of transmission lines was used to improve power system performance with the state of switches (network operation).[61] It has been utilized to restore the main networks and quick loads restoration.[9] It has been investigated in Reference 62. The main objectives of transmission line restoration are to optimize grid structure as well as to minimize line losses to overcome load outages,[63] to minimize restoration time,[64,65] and to overcome the failures of transmission line energization.[66]

Optimal network reconfiguration problem for grid resilience can be evaluated by using many approaches such as indices and optimization techniques to help operators for evaluating the recovery options and implementation. It is important to reconfigure the power grid for customers after a complete blackout, attack, or disruption. In this review, the first CNT-based indices used for power system network reconfiguration have been discussed. Second, optimization models and techniques used for network reconfiguration of power systems have been presented and discussed.

3 | CNT-BASED INDICES FOR TRANSMISSION NETWORK RECONFIGURATION

With the gradual construction of ultra-high voltage (UHV) transmission and the increase of large-scale power transmission cross-regional power systems, the interconnection between regional power grids is becoming more tight, increasing the size of the power grid, and complicating its form.[67] Although a large-scale power grid improves the economy and reliability of power transmission, it increases the possibility of tremendous power outages and catastrophic accidents caused by partial failures.[68] When a blackout occurs, the power grid exhibits characteristics and patterns of reaction, the same as CNs.[69] Blackout sequences follow the integrated behavioral pattern,[69] and power laws, as complex systems operating near a critical point. The power grid is clearly amenable to such studies, and a number of these have been performed on the high voltage grid.[70]

The novelty of using CNT is to provide a design tool for infrastructure planning and evolution of the power systems. With the development of CNT, its applications in power systems have been paid more and more attention. As the size of electrical networks increases, the electrical networks are becoming one of the CNs and have some universal topological features with other CNs,[70] such as communication networks. It also made an influence on power system planning studies and analysis. On the other hand, the advancement in the field of a CN and the range of application areas has allowed their extension to the field of power systems. Most complex systems are graph-like, and they have a framework to better understand those systems that are composed of many interacting parts in a network in order to grasp the overall behavior of the system. Other important features of complex systems are the absence of a centralized controller and the evolution of the system over time. The application of CN-based analysis on power system networks has been helpful in solving many long-lasting challenges and the research also highlights the use of network methodology in analyzing power system networks. The study of CNs is part of CNT, which is the multidisciplinary scientific branch that studies systems with many interacting parts (or agents) in which the overall evolving behavior of the system cannot be deduced by the observation of the single parts.

Consequently, CNT-based indices and techniques are useful to analyze and control a large-scale power grid considering these complex factors.[69] The system designated for the prevention of blackouts is not working well due to a series of blackouts. The researchers are seeking solutions from alternative means. Likewise, the latest advancement in the field of CNT attracts the researchers of power systems to model and analyze the power grid under CNT. The power grid has complex dynamic characteristics due to the control actions of various protection and control apparatuses.[71] In Reference 70, a review of main studies conducted on different power grid networks using emerging CNT-based metrics and techniques gives the overall view of the power grid as a complex system. CNT-based techniques are applied to identify most connected nodes and key edges that keep the network connected for optimal reliability of the high voltage grid. CNT is utilized to identify the category of the grid structure, and to analyze the real systems and general topographies of network topology and network dynamics and has attained productive results. These methods can help power system engineers in the planning stage or while upgrading the infrastructure (eg, add a new transmission line).[72]

On 4 October 2015, the typhoon "Rainbow" caused a blackout in a large part of Guangdong power system in China due to extreme weather event, led to large-area outage and huge economic cost. To overcome these extreme events which cause a blackout in the future, an action plan proposed by Guangdong Power Grid Corporation in China to identify a skeleton-network including important nodes and branches for the Guangdong power system.[17] By implementing this action plan, the power devices and transmission towers could be protected to the greatest extent under extreme events and hence facilitate transmission network reconfiguration after a complete or partial blackout.[17,37,52] Given this background, it is essential to identify the importance of degrees of nodes for determining the skeleton network of the power system concerned. At this juncture, the CNT-based framework is used for modeling, simulating, and analyzing both the unintentional and malicious outages for the tolerance of electric power grids.

When a power system blackout occurs, it is important to restore the power system for grid resilience in the future. As already discussed, network reconfiguration is the second action plan for power system restoration. Moreover, the skeleton network plays an important role in the network reconfiguration phase, which consists of important nodes and transmission lines. This review focuses on the CNT-based indices applied for the power network reconfiguration, which can help analyze the current state of the grid infrastructure and consider possible evolution in the future. Given this background, it is necessary to evaluate the importance of nodes and lines in the skeleton network of the power system concerned.[17,52] The main task of skeleton-network optimization is to reserve critical nodes and lines which are important in the topology structure and operation state of a power system. Before the critical line's identification, evaluation indexes need to be selected first to evaluate the importance degrees of lines.

A graph is a set of vertices (nodes) joined by a set of edges (lines) and has natural correspondences to network elements, which can provide a different point of view for any network or system. The graph makes the network much simpler and can provide the appropriate tools for solving the problem. Applying CNT to a system means using a graph-theoretic representation. CNT is the branch of pure mathematics; whose early research is an emphasis on structural properties of very large graphs and random graphs. CNT provides a set of techniques for analyzing graphs structure in a system of interacting agents.

CNT has been applied in many fields such as the internet, web topology, transportation system, airports, communication network, and social networks. CNT analysis is classified into two groups such as pure models (weighted and undirected) and extended models (weighted and directed). Firstly, pure models only evaluate node and line importance from the perspective of the topology of the power grid. CN analysis can be done by topological definitions such as degree centrality, closeness centrality, betweenness centrality, clustering coefficient, and efficiency. The disadvantage of the pure model is that it cannot be applied for operational characteristics of the power grid because pure network models neglect or ignore the weight and direction of nodes or edges. So, all vertexes and edges are identical and highlight that the topological approach may lead to inaccurate results because it does not capture some of the properties of power grids described by Kirchhoff's laws.[73] Secondly, extended network models in References 74-77 consider electrical properties of the grid such as impedance of the line is considered as the weight of an edge, active power flow, load capacity, and generator capacities.[74] In practical, node and line importance are not only related to the topology of the power grid, but it is also important to consider operational characteristics of the power grid such as power flow, power source, and load capacity. The node and line importance evaluated by this method is consistent with the operating state of the power grid. It takes the load, power source, value, and direction of power flow into consideration. These factors closely reflect the operational characteristics of the power grid.[6]

The main objective of this research is to review the CNT-based indices and optimization techniques that are used for power network reconfiguration. CNT can be used to solve many problems by reducing the problem to a standard graph problem. An optimal solution can be provided by making use of CNT-based algorithms. There are many algorithms used for solving CN problems, such as trivial algorithms (degree, clustering coefficient, degree distributions, and so on), shortest path algorithms (breadth-first search, depth-first search, closeness centrality, Freeman betweenness, edge betweenness, Dijkstra's algorithm, and so on), eigenmodes algorithms (eigenvector centrality, algebraic connectivity, and so on), graph partitioning and clustering algorithms, and maximum flow algorithms. Moreover, centrality measures are used to quantitatively indicate important nodes and lines in CN problems. Centrality can be categorized into two groups in CNT. The first one is the closeness of nodes or edges such as degree centrality and closeness centrality. The second one evaluates the tie between two edges or two nodes such as flow betweenness centrality and efficiency (shortest path).

Centrality measures are used to quantitatively indicate important nodes and lines in the CN problems. In CNT-based problems, the most used centrality measures/indices are degree centrality/electrical degree centrality, eigenvector centrality, clustering coefficient, closeness centrality/electrical closeness centrality, betweenness centrality/electrical betweenness, and efficiency. (a) The individual who has more links with other nodes or more information is defined as degree centrality, and it evaluates the structural importance of nodes. Furthermore, electrical degree centrality, the node, which has more links (number of transmission lines connected) means power flowing in the adjacent links has more information as compared to other nodes. (b) Eigenvector centrality is used to identify the significance of the node if it is connected by another important node. (c) The clustering coefficient measures the degree by observing nodes in a graph that tend to cluster together. (d) Closeness centrality determines the degree to which a node is close to all other nodes in the network or to quantify the independence of various nodes. Line impedance is used to determine the shortest path between pairs of nodes that run through that edge (or vertex) for the power grid. (e) Betweenness centrality of node or edge is employed to determine the hub of one node or edge in the topology of a CN, either because of their location in the grid or by the amount of power they convey. This measure can describe the importance of a node or edge by identifying the number of the shortest paths between pairs of nodes that run through that node or edge. This means that the larger the node or edge's betweenness is, the more important role the node or edge plays in the network. Many shortest paths among all pairs of vertices in the network would become longer when the node or edge with the maximal betweenness is removed.[10] (f) Efficiency index is used to identify the tolerance of the power grid, and the performance of the power grid by identifying the critical nodes or edges whose removal causes the biggest drop in the efficiency of the power system.

In this section, there is a discussion about indices based on a CNT framework to evaluate the node importance and edge importance for the network reconfiguration problem. Some of them use only pure topological based indices. While others proposed both pure topological as well as extended-based indices. CN analysis consists of a set of nodes connected by a set of lines or arrows. Any power system network can be represented as a graph $G = (v, e, w)$, where v denotes the vertices or nodes, e indicates the edges or links and w represents the weight of edges. An element $e = (x, y)$ of the edge set e is directed from x to y. y is called the head and x is called the tail of the edge. w is the set of weights whose elements are the weight of edges, and there exists a one-to-one correspondence between set e and set w.[74]

3.1 | Degree centrality

It is a simple form of degree centrality for nodes that have more links to become more important in the network. The electrical degree centrality index has been proposed based on the analogy between Laplacian and network admittance.[78] Local centrality measure is called local rank which mainly considers fourth-order neighbors information of node.[79] Another new index in Reference 67 considers the electrical distance and capacity degree of node based on power transmission capacity.

3.1.1 | Electrical degree centrality

In Reference 17, an index named electrical degree centrality based on generation capacity has been proposed for skeleton-network reconfiguration of a power system. The generators with larger generation capacities should be given priority to restart and the load nodes with more important load demand should be re-supplied power first. Electrical degree centrality $E_{DC}(u)$ of node u can be formulated as

$$E_{DC}(u) = \frac{\sum_{v \in \Gamma(u)} A_{uv}}{N-1} e^{-\frac{S_{GC,max} - (S_{GC,u} + S_{LC,u})}{S_{GC,max}}}, \tag{1}$$

where A_{uv} denotes the adjacent matrix of $N \times N$, and $\Gamma(u)$ is the set of the adjacent nodes of node u. $S_{GC,max}$ is the maximum generation capacity among the generators, and $S_{GC,u}$ is the generation capacity u and $S_{LC,u}$ is the load power at node u.

3.1.2 | Eigenvector centrality

The degree of a node only tells the highest degree, which has more links to become more significant in the network.[78] Eigenvector centrality is proposed to overcome this problem and defined that a node is significant if it is connected by another important node. The proposed eigenvector centrality index is used to evaluate the importance node degree for skeleton network reconfiguration in terms of pure topological properties. Eigenvector centrality index $E_v(u)$ is formulated in Reference 17, as

$$E_v(u) = \frac{1}{\lambda}\sum_{v=1}^{N} A_{uv} e_v, u, \tag{2}$$

where λ is denoted as the dominant eigenvalue and $e = [e_1, e_2, ..., e_N]^T$ is represented as the dominant eigenvector of the $N \times N$ adjacency matrix A of a given network with N nodes.

3.1.3 | Clustering coefficient

The node with the highest degree which has more links becomes more significant in the network is determined by the degree of a node, whereas the clustering coefficient is used to measure the degree by observing nodes in a graph that tend to cluster together. The objective of the clustering coefficient is defined as how well a node is connected is discussed in References 9,13. Clustering coefficient C_i is formulated as

$$C_u = 2t_u / x_u(x_u - 1). \tag{3}$$

If there are x_u number of nodes in the neighborhood of node$u$, a fully connected group has connections $x_u(x_u - 1)/2$ and t_u is the number of connections existing in fact.

3.1.4 | Node importance degree

To scale the importance of nodes resolved by the concept of degree centrality, some key nodes are not with larger node degrees. Node importance degree based on node contraction has been proposed to resolve the discrepancy. The node contraction is defined as the reduction in the size of the actual network. It causes a decrease in the average shortest distance after node contraction.[9,13] The node importance degree N_u is formulated as

$$N_u = 1/n_u . L_u \tag{4}$$

$$L_u = \frac{\sum_{u,v \in V_u} D_{min,uv}}{n_u(n_u - 1)/2}, \tag{5}$$

where n_u represents the total number of nodes in the new network after node u contraction. L_u is the average of the shortest distance in the new network after node u contraction. $D_{min,uv}$ denotes the shortest distance between nodes u and v, V_i is the set of all nodes in the new network after node contraction.

3.1.5 | Line importance degree

The contraction concept is extended for evaluating the importance degrees of various lines in a scale-free network-based online contraction concept. The proposed line importance degree is used to assess the importance degrees of various lines based on the line contraction concept. Line importance degrees γ_u has been explained in Reference 12 based on line contraction method, and is formulated as

$$\gamma_u = x_u / y_u, \tag{6}$$

where $x_u = I_g^t A I + I_p^t A I - 2$ indicates the degree of the node after the contraction of line u; and A is the adjacency matrix of the network for N nodes. Node g and node p are the two end nodes of line u and I_g indicates the N-dimensional column vector, in which only the gth element equals to 1 and else 0. I_g indicates the N-dimensional column vector, in which only the pth element equals to 1 and else 0. I indicates the N-dimensional column vector, in which all the elements equal to 1. $\gamma_u = \frac{\sum_{u,v \in V_u} D_{min,uv}}{n_u(n_u - 1)/2}$ denotes the average minimum distance of the network and n_u is the total number of nodes in the new network after node u contraction. $D_{min,uv}$ indicates the shortest distance between nodes (u,v). V_u denotes all the nodes in the new network after node contraction as discussed in Reference 12.

3.1.6 | Importance degree of a node

It has been presented in Reference 11 that the electrical connection of the nodes cannot be rationally reflected in the contracted network because the lines directly linked to the node are also contracted. To overcome this problem, a new index named as importance degree of a node has been proposed by combining the regret value of losing topological connectivity with that of increased restoration cost. The entire reconfiguration procedure may be pretentious due to the un-restoration of the node. To overcome this problem, the regret value of losing topological connectivity has been proposed to obtain a number of non-deliverable node pairs. The objective of the regret value of the increased restoration cost index is to restore the minimum cost by considering the total weight of the lines in the restoration path as the restoration cost. The objective of the proposed regret value of an increased restoration cost index is to assess the performance of supplying power from a node connecting with node m to the rest of the nodes. The importance degree of a node of node m is given as

$$D_m = P_m + \mu C_m, \tag{7}$$

where $P_m = \sum_{(u,v) \in V_m} \left(\beta^*_{(u,v)} - \beta^{*'}_{(u,v)} \right)$ denotes the regret value of losing topological connectivity, $C_m = \sum_{(u,v) \in V_m} \left(\gamma^{min\prime}_{(u,v)} - \gamma^{min}_{(u,v)} \right)$ is represented as the regret value of increased restoration cost and μ is the ratio coefficient for adjusting the relative importance of P_m and C_m. The comprehensive evaluating index of the evaluated node m compares the strategy that restoring the evaluated node m with that of not restoring it. Vm is the set of node pairs directly connecting node m. $\beta^*_{(u,v)}$ denotes the path decision value of the node pair of original networks and $\beta^{*'}_{(u,v)}$ denotes the path decision value after node m is removed. $\gamma^{min\prime}_{(u,v)}$ denotes the minimum restoration cost after applying the same strategy and $\gamma^{min}_{(u,v)}$ represents the minimum restoration cost of the evaluated node m is allowed with that of not restoring it. V_m is the set of node pairs directly connecting node m, and $\beta^*_{(u,v)}$ denotes the path decision comprehensive evaluating index of the evaluated node m compares the strategy that restoring the evaluated node m is allowed. Furthermore, the merits and demerits of degree centrality have been discussed in Table 1.

3.2 | Closeness centrality

Closeness centrality is defined as to quantify the independence of various nodes within an electrical power grid.[78] The closeness centrality index is used for power system contingency analysis. It mainly considers the reactance of the link,[78] charging capacitance considers for transmission lines and transformer branches.[17] Closeness centrality based on the capacitance of the transmission line has been proposed.

3.2.1 | Electrical closeness centrality

The main objective of the proposed index is to evaluate the restoration path for skeleton network reconfiguration. This proposed method is used to obtain less restoration time and lower charging capacitance to reduce overvoltage due to the consideration of fewer transmission lines and transformer branches.[17] Electrical closeness centrality $E_C(u)$ can be expressed as

$$E_C(u) = {}^{N-1}\!\Big/\!{\textstyle\sum_{v=1, v \neq i}^{N}} D^{Q_C}_{min,uv}, \tag{8}$$

where $D^{Q_C}_{min,uv}$ represents the number of transmission lines and transformer branches in the shortest electrical path (minimal total capacitance) between node u and node v.

TABLE 1 Merits and demerits of complex network theory (CNT)-based indices

Index	Merits	Demerits
Electrical degree centrality[17]	• Evaluate the structural importance of nodes	• Degree of a node only tells the highest degree which has more links become more significant in the network • To scale the importance of nodes resolved by concept of degree centrality, and some key nodes are not with larger node degrees.
Eigenvector centrality[17]	• Node is significant if it is connected by another important node	• All nodes in the neighborhood of the *i*-th node contribute equally to its centrality, which is in general false leading to a poor ranking
Clustering coefficient[9,13]	• Measure the degree by observing nodes in a graph that tend to cluster together	• Degree and clustering coefficient evaluate the structural importance of nodes
Node importance degree based on node contraction[9,13]	• Causes a decrease in average shortest distance after node contraction	• The electrical connection of the nodes cannot be rationally reflected in the contracted network because the lines directly linked to the node are also contracted
Line importance degree based on line contraction[12]	• Transmission lines importance has been considered for skeleton network	• The electrical connection of the lines cannot be rationally reflected in the contracted network because the nodes directly linked to the lines are also contracted
Electrical closeness centrality[17]	• Less restoration time to obtain less restoration time and lower charging capacitance to reduce overvoltage due to consideration of fewer transmission lines and transformer branches	• Only considers the shortest path
Electrical betweenness[10]	• Functional importance by relating a nodes structural position to the efficient flow paths throughout the network	• Betweenness centrality based on the shortest path
Electrical betweenness centrality[17]	• Impact of the power grid topology on the transmission process	• Only considers the node importance
Network reconfiguration efficiency[9,13]	• Restoration target instead of switching sequences for load nodes[9]	• Network efficiency index proposed by Reference 9 consists of only power sources and important loads but transmission lines evaluation cannot be scaled properly due to the random selection[13]

3.2.2 | Rate of change of network closeness centrality

Node contraction method discussed in Reference 9 and the rate of change of network closeness centrality based on node removal has been proposed to restore a node for skeleton-network reconfiguration. The objective of the rate of change of network closeness centrality $N_C(u)$ index is to restore a node before and after node u and its adjacent nodes are contracted which is formulated in References 17,80. The rate of change of network closeness centrality $N_C(u)$ index is formulated as

$$N_C(u) = 1 - \tau(G)/\tau\left(G'_{u_i}\right) \tag{9}$$

$$\tau(G) = (N-1)/\left(2\sum\nolimits_{1 \le a < b \le N} D^{X_L}_{min,a_b}\right) \tag{10}$$

$$\tau\left(G'_{u_i}\right) = (N_C - 1)/\left(2\sum\nolimits_{1 \le a < b \le N_C} D^{X_L}_{min,a_b}\right), \tag{11}$$

where G'_{u_i} is the new network attained after the removal of node i (ie, u_i) in the original network. $\tau(G)$ and $\tau\left(G'_{u_i}\right)$, respectively, are the network closeness centralities of G and G'_{u_i}. N_C represents the number of nodes in the new network.

3.2.3 | Rate of change of spanning-tree

Another new index has been proposed for the analysis of node removal named as the rate of change of spanning tree. Spanning trees are used to identify the skeleton network for transmission network reconfiguration. The number of spanning trees can be reduced by removing some key nodes from the network.[17,80] Rate of change of spinning tree index $T_s(u)$ has been formulated as

$$T_s(u) = 1 - \phi(G - v_u)/\phi(G), \tag{12}$$

where $\phi(G)$ is the number of spanning trees of the network G and $\phi(G - v_u)$ denotes the number of spanning trees of the network G after removal of node u (v_u), respectively. Moreover, the merits and demerits of closeness centrality have been discussed in Table 1.

3.3 | Betweenness centrality

To regulate information flowing within networks, this index has been considered for the measurement of power flow in the network.[72,81] The degree and clustering coefficient evaluate the structural importance of nodes. While betweenness centrality measures their functional importance by relating a node's structural position to the efficient flow paths throughout the network. It is defined on the basis of random walk,[82] flow betweenness centrality, and betweenness centrality based on efficient flow paths throughout the network.

3.3.1 | Electrical betweenness

Electrical betweenness B_l for restoration, the path is defined as restoration priority of non-black start generators as explained in Reference 10 with consideration of important loads restoration. It can be expressed as

$$B_l = \sum_{i \in \Omega_U} \frac{\alpha_1 G_{Pi} + \beta_1 L_{Pi}}{e^{D_{si} - 1}}, \tag{13}$$

where G_{Pi} represents the generation capacity of generating unit in node i. L_{Pi} is the active power of important load in node i. α_1 and β_1 are the coefficients for measuring the relative importance of generation nodes and load nodes in the calculation of electrical betweenness of a candidate restoration path respectively. e is the given coefficient of exponential decay. $D_{si} = \sum_{a \in l} Z_a$ is the shortest restoration path length.

3.3.2 | Power transfer distribution factor (PTDF)

Many researchers have made use of betweenness centrality based on the shortest path, but power flow through all possible paths between the source node and load node instead of the shortest path. The power transfer distribution factor (PTDF) which considers the impact of the power grid topology on the transmission process has been proposed in Reference 1. The electrical betweenness centrality $E_B(u)$ based on PTDF has been investigated in Reference 17 that can be expressed as

$$E_B(u) = \sum\nolimits_{a \in \Omega_{SE}} \sum\nolimits_{b \in \Omega_{SK}} \left(\sum\nolimits_{v \in \Gamma(u)} \left| f_{uv}^{ab} \right| \right), \tag{14}$$

where Ω_{SE} denotes the power source set and Ω_{SK} represents the load set $f_{uv}^{ab} = \lfloor (Z_{ua}^{eq} - Z_{ub}^{eq}) - (Z_{va}^{eq} - Z_{vb}^{eq}) \rfloor$ ⍰ x_{ij} represents the power transferred from source node a to load node b through the transmission line connecting between node u and node v. x_{ij} is the reactance of transmission line between nodes i and j. Z_{ua}^{eq} denotes the equivalent impedance between node u and node a. $Z_{ua}^{eq} = (Z_{uu} - Z_{ua}) - (Z_{ua} - Z_{aa})$ denotes the transfer impedance from node u and node a. While Z_{uu} and Z_{aa} are the driving-point impedances of node u and node a, respectively.

3.3.3 | Line betweenness

The above-discussed indices have been proposed for node evaluation. Therefore, in Reference 13, a line betweenness index has been proposed to evaluate line importance. Line betweenness G_k is used to evalaute the frequency of a line passing through shthe ortest path between two nodes of the network to evaluate the frequency. The effect of branch k on the connectivity of the network is formulated as

$$G_k = \frac{\sum\limits_{u \neq v \in N} D_{uv}(k)}{\sum\limits_{u \neq v \in N} D_{uv}}, \tag{15}$$

where $\sum\limits_{u \neq v \in N} D_{uv}$ is the total number of the shortest path between any two nodes of the original network N and $\sum\limits_{u \neq v \in N} D_{uv}(k)$ denotes the number of the shortest path passing through branch k. Moreover, the merits and demerits of betweenness centrality have been discussed in Table 1.

3.4 | Efficiency

Efficiency index has been used to evaluate the overall performance of the power grid and detecting main components.[83,84] The reciprocal of the distance between two nodes is used to evaluate the efficiency of the transmission line in the power grid.[74] The information centrality index is defined as the sum of information transmitted between the nodes in the network. Information flowing from any two nodes is simply the inverse of the variance or effective resistance.[85] Average efficiency is defined as the exchange of flow of information or power in the network. This index is used to evaluate power grid performance. Electrical distance is used instead of the shortest path and power transmission capacity can also be considered. Removing one line from the power network could lead to an increase of the reactance of the line and decrease the network efficiency.[86]

3.4.1 | Network reconfiguration efficiency

Network reconfiguration efficiency has been proposed to obtain the restoration target instead of switching sequences. It is defined as the ratio of average node importance degree of load nodes as investigated in Reference 9. The network reconfiguration efficiency ξ_1 index is formulated as

$$\xi_1 = \alpha_2 / \beta_2, \tag{16}$$

where $\alpha_2 = \sum\limits_{u=1}^{m_K} C_u a_{Ku} / m_{KC}$ denotes the average node importance degree of load nodes selected. m_K denotes the total number of loads in the original network. C_u is the decision variable concerning load u. a_{Ku} is the node importance degree of load and m_{KC} is the total number of loads in the reconfiguration network. Average clustering coefficient is denoted as $\beta_2 = \sum\limits_{v=1}^{m_C} b_v / m_C = \sum\limits_{v=1}^{m_C} \frac{2t_i}{u_i(u_i - 1)} / m_C$ for all selected nodes such as source nodes and load nodes, If there are total u_i nodes in the neighborhood of node i, a fully connected group have $u_i(u_i - 1)/2$ connections and t_i denotes the number of connections existing in fact and m_C denotes the total nodes in the reconfiguration network. Subjected to some inequality operation constraints, length of transmission line L_b corresponding to the different voltage level for lines shorter than $L_{b.\ max}$ could be chosen in the reconfiguration process. The other two unequal constraints $\Gamma_u < \Gamma_{u.\ max}$ and $\Gamma_p < \Gamma_{p.\ max}$ are about operation performance when power flow analysis is performed concerning the reconfiguration network. $\Gamma_u = m_u/m_C$ represents the ratio of nodes unsatisfied m_u with voltage limits to total nodes m_C in reconfiguration network and $\Gamma_p = m_p/m_{kC}$ represents the ratio of branches m_p exceeding transmission capacity limits to total branches m_{kC} in the reconfiguration network. Only when m_u and m_p are smaller than their limits $\Gamma_{u.\ max}$ and $\Gamma_{p.\ max}$ that vary from different restoration requirements, respectively.

3.4.2 | Efficiency

Network reconfiguration may be feasible in practice and thus be worthy of a skeleton network as explored in Reference 9. In Reference 13, after a large-scale failure of power supply, network reconfiguration consists of two consecutive phases such as determination of a target system and the construction of a feasible operation sequence that leads to the target system. Skeleton network proposed to determine the target system in Reference 9 consists of only power sources and important loads but transmission lines evaluation cannot be scaled properly due to the random selection. Transmission lines are capable of coordinating and allocating the power reasonably. The network reconfiguration efficiency index has been proposed by considering line betweenness to identify key transmission lines. The objective of efficiency ξ index is to identify key nodes and lines as well as keeping its sparseness in order to alleviate the burden of reconfiguration as explained in Reference 13 and can be formulated as

$$\xi_2 = \alpha_3 + \mu\delta/\beta_3. \tag{17}$$

Length of transmission line $L_b < L_{b.\ max}$ selected must be limited corresponding to the different voltage levels in order to maintain the prescribed over-voltage limit. $\alpha_3 = \sum_{u=1}^{m_{KC}} A_u/m_{KC}$ average node importance degree for total m_{KC} load nodes selected in the target network. The value of A_u is normalized in terms of maximum A_u of all nodes with consideration of load nodes only. $\delta = \sum_{k=1}^{m_{kC}} B_k/m_{kC}$ denotes the average line betweenness for total transmission lines m_{kC} in the reconfiguration network. The value of G_k is normalized in terms of maximum G_k of all lines. $\beta_3 \sum_{k=1}^{m_C} G_k/m_C$ denotes the average clustering coefficient for total m_C nodes in the reconfiguration network considering both power source nodes and loads for the target network. Another index named network efficiency centrality that is proposed to evaluate the performance of skeleton-network reconfiguration before and after the node removal. The main objective of this index is to identify the core components of the network topology by considering electrical characteristics to evaluate the efficiency of the power network. Thus, the network efficiency centrality[17] $\eta_C(u)$ of node u is defined as the relative change of the network efficiency before and after the node is removed and formulated as

$$\eta_C(u) = (\eta - \eta_u)/\eta \tag{18}$$

$$\eta = \frac{1}{N(N-1)} \sum\nolimits_{a,b\epsilon V_N} \frac{1}{D^{X_L}_{min,ab_C}} \tag{19}$$

$$\eta_u = \frac{1}{(N-1(N-2))} \sum\nolimits_{a,b\epsilon V_N, a\neq u, b\neq u} \frac{1}{D^{X_L}_{min,ab}}, \tag{20}$$

where $D^{X_L}_{min,ab}$ denotes the number of transmission lines and transformer branches in the shortest electrical path with respect to line reactance node a and node b and V_N is the set of nodes in the original power network. η denotes the network efficiency of the power grid and η_u denotes the network efficiency of the power grid after removal of node u. Furthermore, the merits and demerits of the efficiency index have been discussed in Table 1.

Furthermore, some other indices have also been proposed to optimize the restoration paths, to obtain the skeleton network, and for optimizing the start-up sequence of generators for the reliable reconfigured network. The reliability index is proposed to obtain the reliability of restoration paths for the skeleton network, which is determined by the restoration successful rate of the transmission lines and transformers.[25] In Reference 87, the index named a number of restored lines has been proposed to identify the number of transmission lines for optimal skeleton network reconfiguration problem. The line stability index (L-index) is proposed to obtain optimal operating conditions with the best voltage stability for the original and the reconfigured networks in Reference 32. The outage cost recovery index has been proposed for minimizing the amount of total customer interruption costs via transmission topology reconfiguration for grid resilience.[57] The system flexibility index has been proposed for minimizing the time for the reconfiguration process for grid resilience.[57] In Reference 61, the voltage sag index is proposed to identify optimal network topology for minimizing the voltage sag indices. The two indexes named the regret value of losing topological connectivity and the regret value of increased restoration cost are proposed to optimize the skeleton network.[11] The risk index is proposed to obtain an optimal start-up sequence of generators for the reliable reconfigured network.[88] The equivalent generator resilience index has been proposed to maximize the equivalent generator resilience index at each step of the network reconfiguration process while considering the transmission paths.[50]

Furthermore, the merits and demerits of all CNT-based indices have been discussed in Table 1. In the following, the discussion of the main advantages of CNT-based indices are also highlighted as follows:

1. The CNT-based indices and techniques focused on aspects of the general features of network topology, topology generation mechanism, the network dynamics, and has achieved fruitful results. The indices discussed in References 11,25,32,50,57,61,87-89 for network reconfiguration problem do not consider the network dynamics and topology generation mechanism.
2. CNT-based indices considering physical characteristics (electrical parameters) are closer to reality, which has a proven track record of success in transmission network reconfiguration.
3. CNT-based techniques evaluate the path search and feasible studies for solving the transmission network reconfiguration problem.

Optimization models and techniques are the second part of this review. Emergent methodologies have been discussed to solve the network reconfiguration problem. Network reconfiguration is the second phase of power systems restoration, which means that network reconfiguration is the action to restore power systems after a blackout.

4 | OPTIMIZATION MODELS AND METHODOLOGIES FOR TRANSMISSION NETWORK RECONFIGURATION

Modern power systems become more vulnerable due to higher blackout risks which can affect society. To consider the main issue in terms of security of the power system after a complete blackout, black start and restoration of power system play vital roles. There are three stages of transmission network reconfiguration, that is, start-up sequence of generating units, skeleton network, and optimizing the restoration paths[12] with the satisfaction of all restoration constraints.[13] The main objective of the start-up sequence of generating units is to maximize the restored generation capacity.[15,90] The generator start-up sequence plays a key role in the restoration strategy that determines the time consumed in power system restoration,[50] accelerating the system recovery.[91] In the generator start-up sequence, the non-black start generators are cranked through black start generators via transmission lines.

Secondly, restoration paths play a vital role in the network reconfiguration to build cranking paths (restoring transmission lines one by one) from BSGs to NBSGs.[9,84] The goal of the optimization of restoration paths is to maximize the load served at all times, to minimize the restoration time, to minimize the number and magnitude of the control actions to be taken, and eventually to form a skeleton network.[9] An optimized restoration scheme will assist system operators to build a skeleton network for restarting the NBS units and restoring power supply to important loads.[87]

Finally, the skeleton networks consist of vital nodes (generators and critical loads) means the number of the nodes in the skeleton network is less than the original network. The burden of network reconfiguration can be reduced after obtaining a skeleton network. Cranking power with other generators without self-start ability named NBSG through transmission lines implies that the restoration will evolve into the network reconfiguration phase. These NBSGs will be passed through technical verifications such as self-excitation of generators, and over-voltage while energizing transmission lines, could be motivated by crank power first, and be able to connect with BSG for the network reconfiguration. Therefore, such NBSG should be included in the skeleton network with the highest priority.[9,84] The role of critical loads in the skeleton network is to stabilize system operation during transmission network reconfiguration, and other loads will be neglected for a while and dealt in the load restoration phase.[9,84] The transmission lines between all the generators and critical loads are chosen as components of the skeleton network. In this section, there is a discussion about optimization models for the network reconfiguration of the power system. Furthermore, the definition of some decision-variables used for the TNR optimization models have also been discussed in Table 2.

TABLE 2 The definition of some decision variables used for TNR

	Decision variables meaning
$f_{c,v}$	Output sag value at time t
$V_m^{t_u}$	The voltage amplitude of node m at time t_u
t_i	Time for skeleton network reconstruction including all destination nodes $(i = 1,...,m)$
$V_m^{t_u}$	Restored critical loads at time t
$t_{g,t}^{start}$	Power demanded by generator for start-up at time t
$P_{ij,t}$	Active power flow through the branch
p^i	Penalty at the i-th step
d_i	Total number of switching operations remaining to restore the entire system at i-th step
$Q_{g,t}^{G}$	The reactive power output of the generator at time t
t_{g}^{start}	Start-up time of the generator
C_k	Binary restoration status of the k-th critical load
P_n^{BS}	The restored output of the black start generating unit n
P_k^{NBS}	The restored output of non-black start generating unit k
P_{lb}	The active power of transmission line b
$C_{i,t}^{NBS}$	The restoration status of NBS generator i at a bus at time t
$C_{i,j,t}^{l}$	The restoration status of transmission line $i-j$ at a bus at time t
$C_{i,t}^{cload}$	Binary restoration status of critical load i at a bus at time t, 1 if the certain critical load is chosen in reconfiguration network and 0 otherwise;
f^{t_u}	The system frequency at the time t_u
R_{uv}	The restoration successful rate of the transmission line or transformer v in restoration path u
t_k	The total restoration time of the network skeleton

4.1 | Start-up sequence of generation units' models

Optimization of network reconfiguration is divided into three stages such as a start-up sequence of generating units, skeleton network, and optimizing the restoration paths[12] with the satisfaction of all restoration constraints.[13] The main objective of the start-up sequence of generating units is to maximize the restored generation capacity.[15,90] It is the main phase of the network reconfiguration phase.[11] In this section, there are discussions about some optimization models used for the start-up sequence of generating units.

The objective of the start-up sequence of generating units is to maximize the restored generation capacity as investigated in Reference 11. It is the main phase of the network reconfiguration phase and is formulated as

$$max\, P_t = \sum_{n=1}^{N_{BS}} P_n^{BS} + \sum_{k=1}^{N_{NBS}} P_k^{NBS} - \sum_{k=1}^{N_{NBS}} P_k^{NBSj}, \tag{21}$$

where N_{BS} indicates the black-start generating units and N_{NBS} denotes the non-black-start generating units restored in the network reconfiguration phase. P_n^{BS} represents the restored output of the black-start generating unit n and P_k^{NBS} denotes the restored output of non-black-start generating unit k. P_k^{NBSj} denotes the required start-up power of the non-black start generating unit k.

The following constraints should be respected in the network reconfiguration phase.

1. The generation output constraints

$$P_{Gi}^{min} \le P_{Gi} \le P_{Gi}^{max}, \forall i \in \Omega_G \tag{22}$$

$$Q_{Gi}^{min} \le Q_{Gi} \le Q_{Gi}^{max}, \forall i \in \Omega_G, \tag{23}$$

where P_G^{min} denotes the minimum active power and P_G^{max} is the maximum active power; Q_G^{min} is the minimum reactive power and Q_G^{max} denotes the maximum reactive power of generators;

2. The constraints of voltage amplitudes and phase angles at nodes

$$V_u^{\min} \le V_u \le V_u^{\max}, \forall u \in \Omega_N \tag{24}$$

$$|\theta_{ub} - \theta_{vb}| \le \theta_b, \forall b \in \Omega_L, \tag{25}$$

where V_u, V_u^{min}, V_u^{max} are the voltage amplitude, minimum voltage, and maximum voltage of node u, respectively; θ_{ub} and θ_{vb} are the voltage angles at the two ends of line b; Ω_N and Ω_L are the set of all nodes and set of all lines, respectively.

3. The constraints of transmission line capacities

$$P_{lb} \le P_{lb}^{max}, \forall b \in \Omega_L, \tag{26}$$

where P_{lb} denotes the active power and P_{lb}^{max} denotes the maximum transmission capacity of line b for the set of all lines.

4. The constraint of the system frequency

$$f^{min} \le f \le f^{max}. \tag{27}$$

The constraint of the system frequency f should be within lower frequency limits f^{min} and upper-frequency limits f^{max}.

5. The constraint of the critical maximum interval of a generator

$$0 \le T_1^n \le T_{max}^n, \forall i \in \Omega_G, \tag{28}$$

where T_1^n is the time when the generator obtains the cranking power between zero and a critical maximum interval of generator T_{max}^n.

The objective of the unit start-up sequence is to obtain maximum output power within specified time intervals as highlighted in Reference 92. Meanwhile, the objective of load recovery is to restore the most important load nodes within the shortest restoration time. The coordinated three objectives such as start-up sequence, network reconfiguration, and load recovery in the form of the mathematical model can be presented as

$$maxf_1 = \sum_{u_1=1}^{N_1} \int_T C_{u_1}(t)(P_{u_1}(t) - P_{cr,u_1})dt \tag{29}$$

$$minf_2 = \sum_{u_2=1,T}^{N_2} C_{u_2}\omega_{u_2} l_{u_2} \tag{30}$$

$$maxf_3 = \sum_{u_3=1,T}^{N_3} C_{u_3}\omega_{u_3} L_{u_3}, \tag{31}$$

where f_1 represents the unit's start-up model and T shows the time step. P_{u_1} denotes the cranking power of generator and C_{u_1} represents the state of the generator. Network reconfiguration objective function is denoted by f_2, C_{u_2} denotes the state of the line l_{u_2} and ω_{u_2} denotes the weight of a line l_{u_2}. f_3 denotes the objective function of load recovery, C_{u_3} denotes the state of the load L_{u_3} and ω_{u_3} denotes the weight of a line L_{u_3}. N_1 denotes the number of generators, N_2 denotes the number of lines, and N_3 denotes the number of loads.

Several constraints are one of the key reasons that make restoration problems challenging to solve. The main constraints contained in the model are as follows.

1. Units cranking power constraints, that is, the cranking power requirements are given by

$$\sum_{u=1}^{N_1} \mathrm{P}_{cr,u} < \Delta P_{\sum}(k), \tag{32}$$

where $\sum_{u=1}^{N_1} \mathrm{P}_{cr,u}$ is the cranking power of unit and $\Delta P_{\sum}(k)$ is the increased power in the time step.

2. Critical starting time limitation

$$0 < T_{S,u} < T_{CH,u} \tag{33}$$

$$T_{S,u} > T_{CC,u}, \tag{34}$$

where $T_{CH,uv}$ denotes the maximum critical hot-start time limit constraint for the hot-start unit and $T_{S,u} > T_{CC,u}$ denotes minimum critical cold-start time interval for the cold-start unit.

3. System power flow constrains must meet the following conditions

$$P_y = V_y \sum_{z=1}^{N_3} V_z\left(G_{yz}\cos\theta_{yz} + B_{yz}\sin\theta_{yz}\right) \tag{35}$$

$$Q_y = V_y \sum_{z=1}^{N_3} V_z(G_{yz}\cos\theta_{yz} - B_{yz}\sin\theta_{yz} \tag{36}$$

$$P_G^{min} < P_G < P_G^{max} \tag{37}$$

$$V_u^{min} \le V_u \le V_u^{max}, \tag{38}$$

where P_y, Q_y and $I_{BV,u}$ are the active power, reactive power, and voltage at node y: G_{yz}, B_{yz}, θ_{yz} are corresponding electrical parameters of transmission lines in the power system: where P_G^{min} denotes the minimum active power and P_G^{max} is the maximum active power; where V_u, V_u^{min}, V_u^{max} are the safe ranges of bus steady-state voltage amplitude, minimum voltage, and the maximum voltage of node u, respectively.

4. The system frequency stability constraint, that is, frequency change limitation of the system is given by

$$\delta P \le \delta P_{max}. \tag{39}$$

In Reference 12, an index has been proposed for assessing the importance degrees of various lines based on the line contraction concept. After that, important elements in the network reconfiguration are determined by interpretative structural modeling (ISM). The restoration path with the minimum charging capacitance is selected from the candidate paths to minimize the restoration failure. The restoration benefit is next defined based on restored generation capacity and the importance of each relevant line. The start-up sequence of generating units and the restoration paths are optimized simultaneously by using the proposed method to find the optimal network restoration strategy. Evaluation of the importance degrees of various lines[12] based on the line contraction method is formulated and discussed in Equation (6). The optimization formulation for determining the generating units to be restored and is given as

$$\max_{i\in G_{UR}} G_m = \sum_{u\in\tau} \frac{\gamma_u}{N_\tau} + \xi . \frac{P_G}{P_{G,base}}, \tag{40}$$

where G_{UR} denotes the set of the unrestored generating units and γ_u line importance degree after the line contraction. τ is set of the lines in the selected restoration path for generating unit and N_τ is the number of the unrestored lines in the selected path. P_G is generation capacity of generating unit n with ξ ratio for adjusting the relative importance of the two terms and $P_{G,base}$ is the reference value used to normalize the generation capacity and can be specified by domain experts.

The following constraints should be considered in the restorative self-healing phase.

1. The generation outputs constraint

$$P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max}, \forall i \in \Omega_G \tag{41}$$

$$Q_{Gi}^{min} \leq Q_{Gi} \leq Q_{Gi}^{max}, \forall i \in \Omega_G, \tag{42}$$

where P_G^{min} denotes the minimum active power and P_G^{max} is the maximum active power: Q_G^{min} is the minimum reactive power of the generator and Q_G^{max} denotes the maximum reactive power; Ω_G is the set of all the generators.

2. The voltage amplitudes at nodes

$$V_u^{\min} \leq V_u \leq V_u^{\max}, \forall u \in \Omega_N, \tag{43}$$

where V_u is the voltage amplitude of node u between the minimum voltage V_u^{min} and maximum voltage V_u^{max}; Ω_N is the set of all nodes.

3. Transmission line capacities

$$P_{lb} \leq P_{lb}^{max}, \forall b \in \Omega_L, \tag{44}$$

where P_{lb} is the active power and P_{lb}^{max} denotes the maximum transmission capacity of line b for the set of all lines; Ω_L is the set of all lines.

4. The system frequency

$$f^{min} \leq f \leq f^{max}. \tag{45}$$

The system frequency f should be between lower frequency limits f^{min} and upper-frequency limits f^{max}.

5. The critical maximum or minimum interval of a generator

$$0 \leq T_{Gi_x}^{t_u} \leq T_{Gi_x}^{max}, \forall i_x \in \Omega_{Gmax} \tag{46}$$

$$T_{Gi_y}^{t_u} \geq T_{Gi_y}^{min}, \forall i_y \in \Omega_{Gmin}, \tag{47}$$

where Ω_{Gmax} and Ω_{Gmin} are the sets of the generators with the critical maximum interval and the critical minimum interval, respectively; $T_{Gi_x}^{t_u}$ is the time when the generator obtains the cranking power between zero and critical maximum interval of generator less than the maximum time $T_{Gi_x}^{max}$ and $T_{Gi_y}^{t_u}$ is the time when the generator should be restarted after the critical minimum interval $T_{Gi_y}^{min}$ is passed.

The summary of objective functions, constraints, and their respective optimization methodologies for generator start-up sequence (GSUS) models are discussed in Figure 2. Besides, the definition of some decision-variables used for the start-up sequence of generation units' optimization models has been discussed in Table 2.

4.2 | Restoration paths models

The goal of the optimization of restoration paths is to maximize the load served at all times, to minimize the restoration time, to minimize the number and magnitude of the control actions to be taken, and eventually to form a skeleton network.[9] The restoration paths from the BS unit to NBS units are built by restoring

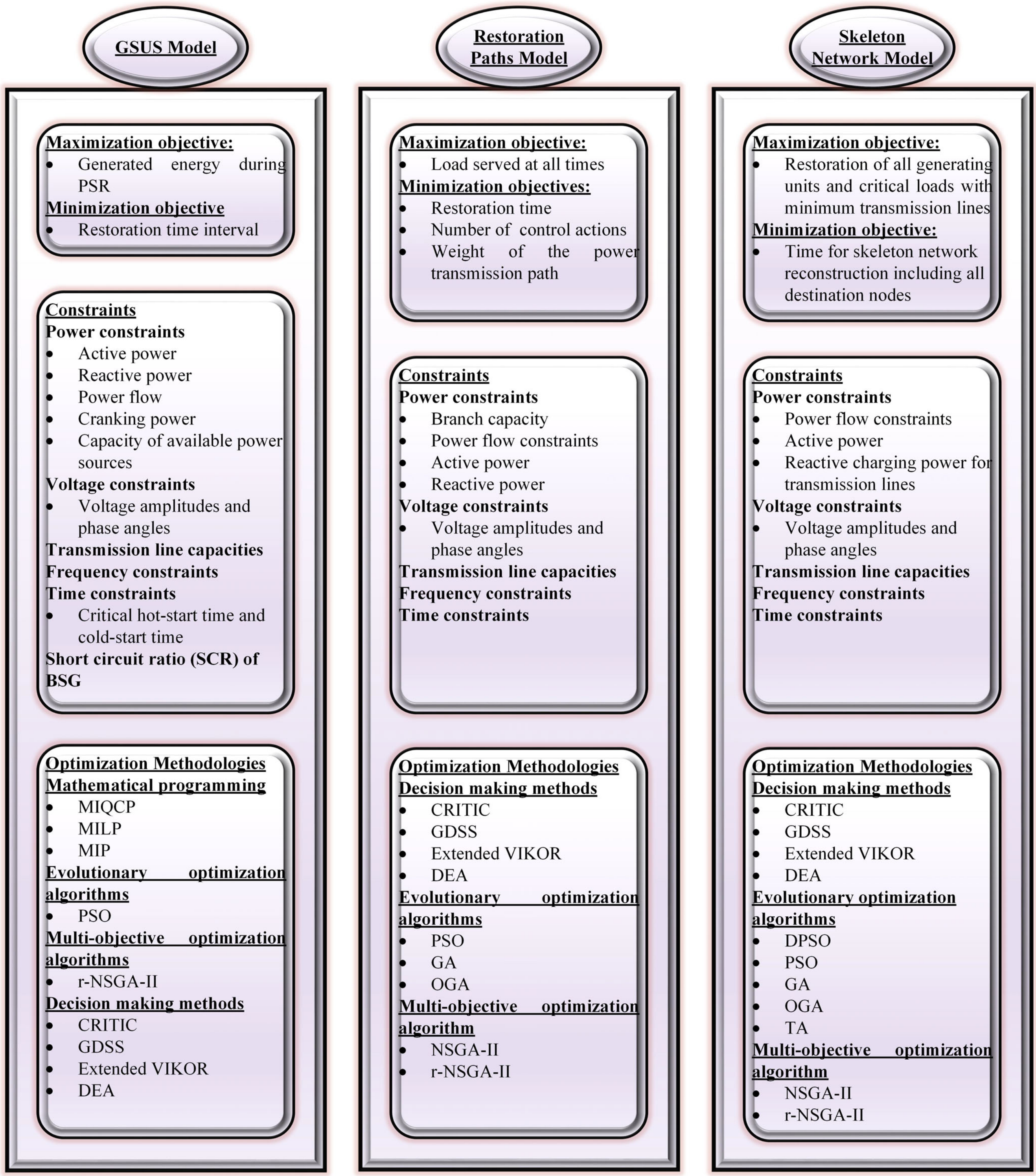

FIGURE 2 Network reconfiguration models (objective functions and constraints) and optimization methodologies

transmission lines one by one to start NBS units.[93-95] The objective of the optimization of the restoration path is to maximize the average importance degree of restoration path and formulated[11] and discussed in Equation (7).

In Reference 22, optimization of power system restoration path is the main objective of network reconfiguration in the power system restoration process. Optimal power system restoration path is proposed to minimize the restored weighted energized paths for the unit's start-up or load recovery by evaluating the shortest path between specified buses in one time-step and formulated as

$$minF_1 = \sum_{i \subseteq U(T)} f(i). \tag{48}$$

The following constraints were considered for the above-discussed optimization model.

1. The limited capacity of available power sources

$$\sum_{i \in F_j} P_i = G_j, \tag{49}$$

where $\sum_{i \in F_j} P_i = G_j$ denotes the limited capacity of available power sources.

2. The power balance between supply and demand

$$\sum_{u \in T_v} P_u - \sum_{u \in F_v} P_u - L_w = 0, \tag{50}$$

where. $\sum_{u \in T_v} P_u - \sum_{u \in F_v} P_u - L_w = 0$ denotes the power balance between supply and demand.

3. Branch capacity constraints

$$P_u \leq C_u, \tag{51}$$

where P_u is the active power and C_u denotes the maximum transmission capacity of the line.

The objective of the network reconfiguration target is to optimize the power system restoration path by considering the lines as the object and each line encoded by a binary number (connected = 1, outage = 0). The objective of this optimization orthogonal GA is to minimize the weight of the power transmission path from one node to the target machine node-set and to obtain uniform distribution line status and formulated as.[22]

$$minF_2 = \sum_{i \in E} f(i).c(i), \tag{52}$$

where i denotes the line between nodes in the network, $f(i)$ denotes the weight of the line and $c(i)$ denotes the status of the line.

In Reference 10, the problem of optimization of restoration paths has been evaluated by applying electrical betweenness, after evaluation for optimization sequence of restoration paths and skeleton network destination. The maximum value of electrical betweenness from restoration paths selected for the non-black start generation or load node in the unrestored region. The optimization objective of the restoration paths and restorative self-healing strategy of power systems is to maximize the electrical betweenness which is formulated as

$$max_{w \in \Omega_{CR}^{t_u}} E_w^{t_u} = \sum_{v \in \Omega_{UR}^{t_u}} \frac{\alpha_1 G_{Pi} + \beta_1 L_{Pi}}{e^{D_{si}-1}}, \tag{53}$$

where t_u denotes the restorative self-healing process time period, $\Omega_{UR}^{t_i}$ is the set of the nodes in the unrestored region of the power grid, $\Omega_{CR}^{t_u}$ denotes the set of candidate restoration paths without redundant paths. G_{Pi} represents the generation capacity of generating unit in node i, L_{Pi} is the active power of important load in node i, α_1 and β_1 are the coefficients for measuring the relative importance of generation nodes and load nodes for the calculation of electrical betweenness of a candidate restoration path, respectively, e is the given coefficient of exponential decay, and $D_{si} = \sum_{a \in l} Z_a$ is the shortest restoration path length.

The following constraints should be respected in the restorative self-healing phase.

1. The power flow constraints

$$P_{Gy}^{t_u} - P_{Ly}^{t_u} - V_y^{t_u} \sum_{z \in \Omega_{NP}^{t_u}} V_z^{t_u} \left(G_{yz} cos\theta_{yz}^{t_u} + B_{yz} sin\, \theta_{yz}^{t_u} \right) = 0,\ \forall y \in \Omega_{NP}^{t_u} = \Omega_N^{t_u} \cup v_{CR} \tag{54}$$

$$Q_{Gy}^{t_u} - Q_{Ly}^{t_u} - V_y^{t_u} \sum_{z \in \Omega_{NP}^{t_u}} V_z^{t_u} \left(G_{yz} cos\theta_{yz}^{t_u} + B_{yz} sin\, \theta_{yz}^{t_u} \right) = 0,\ \forall y \in \Omega_{NP}^{t_u} = \Omega_N^{t_u} \cup v_{CR}, \tag{55}$$

where $\Omega_N^{t_u}$ is the set of the nodes in the restored regions of power systems, v_{CR} denotes the nodes in the unrestored region which connects with the candidate restoration path selected for calculating the electrical betweenness, $\Omega_{NP}^{t_u}$ is the set of the nodes which consists of $\Omega_N^{t_u}$ and v_{CR}; $P_{Gy}^{t_u}$ and $Q_{Gy}^{t_u}$ are the real and reactive power generation, respectively, $P_{Ly}^{t_u}$ and $Q_{Ly}^{t_u}$ are the real and reactive power of important load, respectively, $V_y^{t_u}$ and $V_z^{t_u}$ are the voltage amplitudes, G_{yz} and B_{yz} are the real and imaginary elements in the yth row and zth column of bus admittance matrix, respectively; $\theta_{yz}^{t_u}$ denotes the voltage phase difference between buses.

2. The generation output constraints

$$P_{Gi}^{min} \le P_{Gi}^{t_u} \le P_{Gi}^{max}, \forall i \in \Omega_G^{t_u} \tag{56}$$

$$Q_{Gi}^{min} \le Q_{Gi}^{t_u} \le Q_{Gi}^{max}, \forall i \in \Omega_G^{t_u}, \tag{57}$$

where P_{Gi}^{min} denotes the minimum active power and P_{Gi}^{max} is the maximum active power: Q_{Gi}^{min} is the minimum reactive power of the generator and Q_{Gi}^{max} denotes the maximum reactive power; $\Omega_G^{t_u}$ is the set of the restarted generators in the restored region of the power system at t_u.

3. The constraints of bus voltage amplitudes at nodes

$$V_m^{min} \le V_m^{t_u} \le V_m^{max}, \forall m \in \Omega_N^{t_u} \cup v_{CR}, \tag{58}$$

where $V_m^{t_u}$ is the voltage amplitude of node m at t_u between minimum voltage V_m^{min} and maximum voltage V_m^{max}.

4. The constraints of transmission line capacities

$$P_{lb} \le P_{lb}^{max}, \forall b \in \Omega_L^{t_u} \cup l, \tag{59}$$

where P_{lb} denotes the active power of transmission line b at $t_u$and P_{lb}^{max} denotes the maximum transmission capacity of line b; $\Omega_L^{t_u}$ is the set of the transmission lines in the restored regions of the power system at t_u.

5. The constraints of the system frequency

$$f^{min} \le f^{t_u} \le f^{max}, \tag{60}$$

where f^{t_u} denotes the system frequency at t_u between lower frequency limits f^{min} and upper-frequency limits f^{max}.

6. The critical maximum or minimum interval of a generator

$$0 \le T_{Gi_x}^{t_u} \le T_{Gi_x}^{max}, \forall i_x \in \Omega_{Gmax} \tag{61}$$

$$T_{Gi_y}^{t_u} \ge T_{Gi_y}^{min}, \forall i_y \in \Omega_{Gmin}, \tag{62}$$

where Ω_{Gmax} and Ω_{Gmin} are the sets of the generators with the critical maximum interval and the critical minimum interval, respectively; $T_{Gi_x}^{t_u}$ is the time when the generator obtains the cranking power between zero and critical maximum interval of generator less than the maximum time $T_{Gi_x}^{max}$ and $T_{Gi_y}^{t_u}$ is the time when the generator should be restarted after the critical minimum interval $T_{Gi_y}^{min}$ is passed.[10]

In Reference 52, the weight coefficient was used to resolve the network reconfiguration problem for the transmission line, and the weight coefficient is evaluated by combining the data envelopment analysis (DEA) method with preference information. The efficiency of multiple inputs and multiple outputs with peer decision-making units (DMUs) resolved by DEA, super-efficiency DEA model formulated as

$$max\eta_k = \sum_{r=1}^{s} a_r c_{rk}. \tag{63}$$

The following constraints should be respected in the network reconfiguration model.

$$\sum_{i=1}^{m} b_i d_{ik} = 1 \tag{64}$$

$$\sum_{r=1}^{s} a_r c_{rj} - \sum_{i=1}^{m} b_i d_{ij} \le 0, j = 1,2,...,n, j \ne k, a_r, b_i \ge \epsilon > 0 a_r > b_i, r = 1,2,...,s, i = 1,2,...,m \tag{65}$$

$$a_r > b_i, r = 1,2,...,s, i = 1,2,...,m, \tag{66}$$

where d_{ik} and c_{rj} are the ith input and rth output of the kth DMU; b_i and a_r are weight parameters relative to d_{ik} and c_{rj} respectively.

The summary of objective functions, constraints, and their respective optimization methodologies for restoration path models are discussed in Figure 2. Furthermore, the definition of some decision-variables used for the restoration paths optimization models has been discussed in Table 2.

4.3 | Skeleton network models

The objective of the skeleton network is to obtain the network consisting of vital nodes because the number of nodes in the skeleton network is far less than the original network. The backbone network reconfiguration plays a vital role in power system restoration, and it is important for skeleton network reconstruction and load restoration.[19] The burden of network reconfiguration can be reduced after obtaining the skeleton network. The main requirements to establish the skeleton network are these, the network contains vital power sources and loads and second transmission lines are used to organize and allocate the power reasonably.[23]

In Reference 96, NSGA-II has been proposed to solve the multi-objective reconstruction problem, there are three objectives of the proposed model. The first objective is to maximize the restoration generating capacity in a limited time $F_3 = -\sum_{i=1}^{n} P_{i\,max}$ and the second to maximize parallel restoration time through power system sub-area $F_4 = t_{max}$ and last one is to minimize the time for skeleton network reconstruction including all destination nodes $F_5 = \sum_{i=1}^{n} t_i$ and formulated as

$$min(F_3, F_4, F_5) \tag{67}$$

The following constraints should be respected in the network reconstruction phase.

1. Time constraint

$$0 < t_j < t_{jm}, j = 1,2,...,N_{sg}, \tag{68}$$

where t_j denotes the time which non-black-start generator waits for AC power from black-start sources and t_{jm} is the limited time for generator hot start constraint; N_{sg} is the sum of generators in the s-th subarea.

2. The generation output constraints

$$P_{Gi}^{min} \le P_{Gi} \le P_{Gi}^{max}, \forall i = 1, 2, ..., N_{sg} \tag{69}$$

$$Q_{Gi}^{min} \le Q_{Gi} \le Q_{Gi}^{max}, \forall i = 1, 2, ..., N_{sg}, \tag{70}$$

where P_{Gi}^{min} denotes the minimum active power and P_{Gi}^{max} is the maximum active power: Q_{Gi}^{min} is the minimum reactive power of the generator and Q_{Gi}^{max} denotes the maximum reactive power.

3. The constraints of bus voltage amplitudes at nodes

$$V_i^{min} \le V_i \le V_i^{max}, \forall i = 1, 2, ..., N_{sn}, \tag{71}$$

where V_i is the voltage amplitude of node i between the minimum voltage V_i^{min} and maximum voltage V_i^{max}; N_{sn} is the sum of nodes in the s-th subarea.

4. The constraints of transmission line capacities

$$P_{lb} \le P_{lb}^{max}, \forall i = 1, 2, ..., b, \tag{72}$$

where P_{lb} denotes the active power of transmission line b and P_{lb}^{max} denotes the maximum transmission capacity of line b.

5. Generator excitation constraint

$$kS > q_c \tag{73}$$

where S denotes the capacity of black is start generator, k denotes the short circuit ratio (SCR) of black start generator and q_c is the reactive charging power for transmission lines.

In Reference 11, the objective of the proposed optimization model for the skeleton network is to restore all generating units and significant buses with minimum transmission lines. This model uses node importance evaluation based on the concept of regret. To maximize the average importance of the skeleton network is the main objective of this model formulated as

$$max \alpha_s = \sum_{i \in V_s} \frac{\gamma_i}{N_{ns}}, \tag{74}$$

where α_s is the average importance degree of the skeleton network represented by s, V_s and N_{ns} are the set and number of the unrestored nodes in the skeleton network, respectively. Importance degree of a node is denoted by $D_m = P_m + \mu C_m$, which is the combination of average regret value of losing topological connectivity and average regret value of increased restoration cost. $P_{\alpha s} = \sum_{i \in V_s} P_i / N_{ns}$ is the average regret value of losing topological connectivity and $C_{\alpha s} = \sum_{i \in V_s} C_i / N_{ns}$ denotes the average regret value of increased restoration cost, u is the ratio coefficient between them.

In Reference 25, the skeleton network optimal configuration model based on the chance-contained programming (CCP) is constructed considering the restoration time and restoration successful rate as trapezoidal fuzzy variables. The CCP model constructed, units can only be allowed to be restored one by one by considering dispatching rules constraint of the power system. The objective function of the shortest restoration time and the highest reliability of network skeleton formulated as

$$max_Q max_f \bar{f}_7 \tag{75}$$

where $R = \sum_{u=1}^{N} \prod_{v=1}^{N_u} R_{uv}/N$ is the restoration reliability of the skeleton network, R_{uv} denotes the restoration successful rate of the transmission line or transformer v in restoration path u, and N_u is the number of transmission lines and transformers in the restoration path.

The following constraints should be respected in the network reconstruction phase.

1. Confidence level constraints

$$Pos\left\{\frac{\varrho}{\tau} \geq \bar{f}_7\right\} \geq \beta. \tag{76}$$

This constraint ensures the objective function value $\bar{f}$ at least at confidence level β.

$$Pos\left\{\tau_i \geq \sum_{j=1}^{N_1} t_{ij}\right\} \geq \alpha. \tag{77}$$

This constraint ensures that units can start-up at least at confidence level α, τ_i is the critical maximum interval of the unit. t_{ij} denotes the fuzzy restoration time of transmission line or transformer j in restoration path i which provides power supply to unit i and it is a trapezoidal fuzzy variable, N is the number of units needed to be restored. $\tau = \sum_{k=1}^{N_2} t_k$ is the total restoration time of the network skeleton, t_k is restoration time of the transmission line or transformer k, which is a trapezoidal fuzzy variable, N_2 is the number of transmission lines or transformers in the skeleton network.

2. The power balance constraints must meet the following conditions

$$P_y = V_y \sum_{z=1}^{N_3} V_z\left(G_{yz}\cos\theta_{yz} + B_{yz}\sin\theta_{yz}\right) \tag{78}$$

$$Q_y = V_y \sum_{z=1}^{N_3} V_z(G_{yz}\cos\theta_{yz} - B_{yz}\sin\theta_{yz}, \tag{79}$$

where P_y, and Q_y are the active power and reactive power at node y: G_{yz}, B_{yz}, θ_{yz} are corresponding electrical parameters of transmission lines in the power system: where V_u, V_u^{min}, V_u^{max} are the safe ranges of bus steady-state voltage amplitude, minimum voltage, and the maximum voltage of node u, respectively.

3. The generation output constraints

$$P_{Gi}^{min} < P_{Gi} < P_{Gi}^{max}, \forall i \in \Omega_G \tag{80}$$

$$Q_{Gi}^{min} < Q_{Gi} < Q_{Gi}^{max}, \forall i \in \Omega_G, \tag{81}$$

where P_{Gi}^{min} denotes the minimum active power and P_{Gi}^{max} is the maximum active power: Q_{Gi}^{min} is the minimum reactive power of the generator and Q_{Gi}^{max} denotes the maximum reactive power; Ω_G is the set of all the generators.

4. The voltage amplitudes at nodes

$$V_u^{\min} \leq V_u \leq V_u^{\max}, \forall u \in \Omega_N, \tag{82}$$

where V_u is the voltage amplitude of node u between the minimum voltage V_u^{min} and maximum voltage V_u^{max}; Ω_N is the set of all nodes.

5. Transmission line capacities

$$P_{lb} \le P_{lb}^{max}, \forall b \in \Omega_L, \tag{83}$$

where P_{lb} is the active power and P_{lb}^{max} denotes the maximum transmission capacity of line b for the set of all lines; Ω_L is the set of all lines.

Network reconfiguration efficiency has been proposed to obtain the restoration target instead of switching sequences. The efficiency ξ_1 is defined as the ratio of average node importance degree of load nodes selected and average clustering coefficient, of all nodes selected such as source nodes and load nodes,[9] network reconfiguration efficiency for skeleton networks is formulated as Equation (16).

In Reference 13, network reconfiguration consisting of two consecutive phases such as the determination of a target system and the construction of a feasible operation sequence leading to the target system. Skeleton network has been proposed to determine the target system efficiently[9] that consists of power sources and important loads, but the betweenness index was ignored to obtain important transmission lines. Transmission lines are capable of coordinating and distributing the power reasonably. Network reconfiguration efficiency index has been proposed considering three parameters such as line betweenness, node importance degree, and clustering coefficient. The objective of efficiency index is to identify key nodes and lines as well as keeping its sparseness in order to alleviate the burden of reconfiguration, efficiency ξ_2 index is formulated as

$$\xi_2 = \frac{\alpha_2 + \mu\delta}{\beta_2} \tag{84}$$

s.t. $L_b < L_{b.\ max}$

$$\Gamma_u < \Gamma_{u.max}$$

$$\Gamma_p < \Gamma_{p.max}, \tag{85}$$

where $L_b < L_{b.\ max}$ denotes that the selected length of transmission line which must be limited corresponding to a different voltage level in order to maintain the prescribed over-voltage limit. The other two unequal constraints are represented by $\Gamma_u < \Gamma_{u.\ max}$ and $\Gamma_p < \Gamma_{p.\ max}$ for operation performance when power flow analysis is made with regard to network reconfiguration. Inequality operation constraints make network reconfiguration more feasible in practice. The average node importance degree $\alpha_2 = \sum_{u=1}^{m_{KC}} A_u / m_{KC}$ of total m_{KC} load nodes selected in the target network. The value of A_u is normalized in terms of maximum A_u for all nodes m_{KC} with consideration of load nodes only. Average line betweenness $\delta = \sum_{k=1}^{m_{kC}} B_k / m_{kC}$ of total transmission lines m_{kC} in network reconfiguration network reconfiguration. The value of B_k is that normalized in terms of maximum B_k of all lines. Average clustering coefficient $\beta_2 = \sum_{k=1}^{m_C} G_k / m_C$ of total nodes m_C in reconfiguration network considered both power source nodes and loads for the target network. Regulatory factor μ (value will affect the selection of key lines), $\Gamma_u = m_u / m_C$is the total number of nodes m_u breaking voltage limits concerning power flow of reconfiguration network, $\Gamma_P = m_P / m_{kC}$ denotes the total number of transmission lines m_p breaking transmission capacity constraints concerning the power flow of the reconfiguration network.[13]

In Reference 84, the principle reason for network reconfiguration is to assemble a path and to make a steady or stable network for rapidly restarting generators that do not have the black-start competence. Effectively supplying loads with power through the optimized path with maximize the restored loads as well as minimizing switching activity to diminish restoration time.[97] The objective function efficiency ξ_3 in Reference 84 is formulated as

$$max\xi_3 = \frac{1}{\sum_{i=1}^{N-1} (p^i . d_i)}, \ p \succ 1, \tag{86}$$

where ξ_3 is the efficiency score for the network reconfiguration, restoration step i, total number of the restoration steps allowed N and p^i penalty at the i-th step. Total number of switching d_i operations remaining to restore the entire system at the i-th step and it serves as the important factor to define the efficiency of network reconfiguration.

The following constraints should be respected in the network reconstruction phase.

1. The power balance between supply and demand

$$\sum_{u=1}^{U} L_u^i = \sum_{u=1}^{U} G_u^i, \tag{87}$$

where G_u^i is the electric power supply in the total network must be equal to the total power demand L_u^i.

2. The limited capacity of the restorative-available power

$$\sum_{u=1}^{U} X_u^i \le \sum_{u=1}^{U} \left(G_u^{i-1} - L_u^{i-1}\right). \tag{88}$$

The limited capacity of the restorative-available power does not exceed the limit is supplied to the collapsed nodes, available power X_u^i is calculated with the power supply factor G_u^{i-1} and power demand factor L_u^{i-1} from the last step.

3. Limits on branch power flow

$$|P_v| - U_v \le 0\,(v \in V). \tag{89}$$

The power flow on a branch P_v is less than power capacity U_v of that branch.

In Reference 61, the objective of the proposed network reconfiguration model is to minimize the voltage sag indices in the buses of the network by applying the power flow study to obtain pre faulted voltage values. The analytical method is used to calculate the voltage sag number or indices. The voltage sag of the calculated value must be greater than the reference value. $f_{c,v}$ denotes the calculated sag value and $f_{r,v}$ is the reference sag value and formulated as

$$min\left(f_{c,v} - f_{r,v}\right)\forall v \tag{90}$$

The following constraints should be respected in the network reconfiguration problem.

1. The voltage amplitudes at nodes

$$V_u^{\min} \le V_u \le V_u^{\max}, \forall u \in \Omega_N, \tag{91}$$

where V_u is the voltage amplitude of node u between the minimum voltage V_u^{min} and maximum voltage V_u^{max}; Ω_N is the set of all nodes.

2. The generation output constraints

$$P_{Gi}^{min} < P_{Gi} < P_{Gi}^{max}, \forall i \in \Omega_G \tag{92}$$

$$Q_{Gi}^{min} < Q_{Gi} < Q_{Gi}^{max}, \forall i \in \Omega_G, \tag{93}$$

where P_{Gi}^{min} denotes the minimum active power and P_{Gi}^{max} is the maximum active power: Q_{Gi}^{min} is the minimum reactive power of the generator and Q_{Gi}^{max} denotes the maximum reactive power; Ω_G is the set of all the generators.

The summary of objective functions, constraints, and their respective optimization methodologies for skeleton network models are discussed in Figure 2. Moreover, the definition of some decision-variables used for the skeleton network optimization models has been discussed in Table 2.

TABLE 3 Merits and demerits of optimization methodologies

Algorithms	Merits	Demerits
DPSO[9,13,23]	• Several reconfiguration schemes can be obtained[9,23] • The evolved strategy will not choose transmission lines randomly but select them into the target network according to their priority[13] • Suitable for large scale power systems	• This method can only get one solution on a single run[9,23] • Many control parameters such as population size, number of generations, inertia parameter, cognitive parameter, social parameter, and the stopping criterion
PSO[25,95]	• One by one restoration units by considering dispatching rules constraint of power system • Fewer parameters than DPSO[25]	• Not suitable for large power systems • Trapped in local optimum
GA[26-29,31,32]	• *N* and *N*−1 security criteria considered • It can handle discrete or integer variables	• The increase of chromosome length causes an increase in computation time
GA/Expert system[28]	• Expert System is used to lead and direct the GA's toward practical areas in the solution space in the shortest possible time	• Makes it difficult for GA to explore due to the huge solution space
(R-NSGA-II)[53]	• Number of solutions can be controlled, and decision-makers preference also reflected	• N/A
NSGA-II[96]	• Obtain the overall Pareto solutions, better convergence, and lower computational complexity compared to other power system reconstruction methods based on genetic algorithms,[64]	• Number of solutions cannot be controlled, and decision-makers preference cannot be reflected
Tabu Search[44,89]	• Can avoid entrapment in local optimal solutions • Fast convergence	• Difficult coding due to many parameters
Decision making[11]	• Used for real-time analysis	• This method can only get one solution on a single run
CRITIC[17]	• Fewer restoration times • Allow decision-makers to weight coefficients and compare alternatives with relative ease	• Need to combine many indices for obtaining obtain good results
GDSS[20]	• Speed up network reconfiguration considering security constraints	• slow communication means it takes more time to make decisions
VIKOR[18,19]	• Ranking and selecting from a set of alternatives in case of conflicting criteria	• By changing the weight of these solutions, the ranking order is also changed
DEA[14,52]	• Handling multiple inputs and outputs.	• Does not deal with imprecise data and assumes that all input and output data are exactly known
MILP[21,22,98]	• Provides rigorous lower and upper bounds on the solution, which in turn provide information regarding the optimality of the solution	• Computational complexity
MIP[26,27]	• Security criteria problem against actions including line outages and change over operations[26]	• Computational complexity

4.4 | Optimization methodologies used for transmission network reconfiguration

There are three phases of optimization of network reconfiguration, (a) to obtain the start-up sequence of generating units, (b) to build the skeleton network, and (c) to optimize the restoration paths,[12] with the satisfaction of all restoration constraints as shown in Figure 2. Optimization of start-up units' sequence can be determined by two methods such as decision-making methods and multi-objective optimization methods also discussed in Figure 2. In Reference 11, the decision-making method is used to evaluate the start-up sequence. A two-stage optimization method has been proposed, the first one to maximize the restored generation capacity and then optimal restoration path selected for restoring generating nodes. In Reference 17, criteria importance through inter-criteria correlation CRITIC-based multi-index decision-making method has been proposed for skeleton network reconfiguration. The objective of the proposed method is to evaluate the objective weights of relative importance degrees. In Reference 20, a group decision support system (GDSS) has been proposed to speed up network reconfiguration considering security constraints and it can resolve the semi-structured decision problem of network reconfiguration efficiently. In References 18,19, extended VIKOR method proposed for backbone-network reconfiguration and can be utilized after blackouts as well as in restoration after local outages. The objective of the proposed method is to evaluate and rank the candidate restoration schemes. DEA model is proposed to evaluate the weight coefficient for weighted energized paths,[14] to minimize the restored weighted paths.[52] The objective of the proposed multi-agent system method is to make the priority for the reallocation of loads based on power system status dynamically.[51] Decision-making methods have some advantages and disadvantages, which are discussed in Table 3.

Non-linear programming also has been applied to optimize the network reconfiguration problem as shown in Figure 2. Mixed-integer quadratically constrained program has been proposed in[99] to solve the start-up sequence of the generators for each time step. Mixed-integer linear programming (MILP) proposed for the start-up sequence of generators[21] is proposed to find optimal load tap switching and transmission line charging considering security constraints and to obtain the optimal solution of pick-up and charging the predetermined loads and transmission lines by finding system frequency.[4] The objective of MILP is to optimize the lines (restoration paths) for network reconfiguration.[22,98] Mixed integer programming (MIP) is used for optimal substation reconfiguration model, the objective is to minimize the cost by satisfying parameters such as direct current (DC) power flow and phase angle,[26] to minimize the sum of branch overloads with consideration of line switching performing cost.[27] Non-linear programming has some merits and demerits, which are discussed in Table 3.

In Reference 47, multi-objective optimization has been proposed to solve network reconfiguration problem for three optimization subproblems, the objective of the network unit layer is to restart those plants with larger capacity (MWh output), to maximize the total weighted MWh output that the system can provide during the network-reconfiguration period objective of plant-layer unit restarting and to maximize the total weighted load amount is the objective of load restoration. The lexicographic method is used to obtain the optimal value by the ranking of all objectives according to descending order, it helps to optimize the objective function on the basis of reserved previous optimization results.[100] In Reference 96, the main objective of the proposed method is to maximize restoration generating capacity in the limited time of the skeleton network. In Reference 101, the objective of the minimization of active and reactive power losses for improving the voltage profile at each bus in the power system network reconfiguration and solved by the Newton-Raphson load flow technique.

In this section, some optimization algorithms used for power system network reconfiguration are discussed. A discrete particle swarm optimization algorithm has been proposed to restore the concerned backbone network, subsystems interconnection, and build a stable skeleton network are three objectives of network reconfiguration.[9] DPSO proposed to obtain main network and quick load restoration,[13] to determine the skeleton network and also many optimal schemes for power system restoration instead of restoration paths sequence by using efficiency index[23] as shown in Figure 2. In Reference 25, the objective of the particle swarm optimization algorithm is to find the optimal restoration sequence of the units and loads to be restored and the objective of the fuzzy simulation is to check fuzzy constraints.

The GA has also been proposed to solve the network reconfiguration problem. The objective of the proposed GA is to minimize the sum of branch overloads with consideration of line switching performing cost,[27] to obtain optimized skeleton networks for power systems is the main objective of GA with the expert system,[28] to maximize the reconstruction efficiency,[102] to detect the congestion with less real power losses[26,103] as shown in Figure 2. The objective of the proposed GA is to minimize the power transfer distribution factor PTDF (parallel flows),[31] to find an optimal path for the skeleton network,[29] to minimize the L-index value.[32] The objective of the GA is to optimize the restoration sequence of target nodes and the objective of the Dijkstra algorithm is to obtain the shortest path from the black start units to target nodes[30] as shown in Figure 2. In Reference 26, GA and deterministic-based approaches are proposed to solve best topological network arrangement with security criteria problem against actions including line outages and change over operations. Moreover, GA has some advantages and disadvantages, which are discussed in Table 3.

In Reference 53, a non-r-dominance sorting GA II (r-NSGA-II) is used to solve the model for both the generator start-up sequence and the restoration paths. The objective of the proposed multi-objective optimization algorithm is to maximize the generation capability for a limited time and to maximize the average importance node and line in the restoration path. In Reference 96, a fast and elitist non-dominated sorting GA (NSGA-II) is proposed, and the main objectives of the proposed method are to maximize restoration generating capacity in limited time as shown in Figure 2, parallel restoration through power sub-area, and minimize the time for the reconstruction of the skeleton network. In References 22,104, an orthogonal GA proposed to optimize the lines (restoration paths) as an objective for network reconfiguration, which plays a vital for power system restoration after a major blackout. The objective of the proposed algorithm is to minimize the weight of the power transmission path from the vertex set run through the targeted vertex as shown in Figure 2.

The objective of the Tabu search (TS) algorithm is to obtain optimal network topology that minimizes the voltage sag indices is the system average RMS frequency index to improve the power quality in electrical networks,[61] to improve the voltage sag indices during faults system for obtaining maximum performance or efficiency.[89] Furthermore, the TS algorithm has some advantages and disadvantages, which are discussed in Table 3.

Transmission network reconfiguration strategy has been proposed by many researchers for reliable, secure, and efficient operation because transmission networks serve as connecting links between generators and load centers. The transmission network system is a source of feeding sub-transmission networks and is used to interconnect the many power grids of the country, and there is a bulk supply system used for the parallel configuration between extra-high voltage EHV and high voltage sub-transmission networks. The studied methodology for network planning based on the reconfiguration of transmission network proposed for reliable against normal and emergency cases and also transmission network expansion, these issues are resolved by for network planning.[105] Transmission network reconfiguration strategy proposed to power re-route power through the weakest bus of a network for minimization of the impact of critical outages and causes minimum losses and enhanced security margin.[106,107] Transmission Network reconfiguration algorithm proposed, fast voltage stability index to limit high short circuit current in transmission system,[108] network reconfiguration has been proposed to enhance the voltage stability by reducing power losses such as real and reactive power losses of transmission line.[109]

5 | PRACTICAL CHALLENGES, ISSUES, AND INDUSTRY PRACTICES

Power system blackout may occur due to overloading, voltage violations, cascading failures, or even loss of stability, and force system operators to take appropriate counteractive control actions. Several major types of challenges and technical issues are shown in Figures 3 and 4, respectively. The main challenges like transient security such as voltage stability and compensation in energizing long-distance transmission lines with light or no load, tie-line phase angles of synchronization, switching surge, and so on. Moreover, steady-state security challenges such as active power balance, reactive power balance, thermal stability, voltage stability, generation selection, line re-routing, and reliability, and so on. These challenges and issues need to be considered and managed in terms of power engineering during the power system restoration after the blackout. The restoration process can be quick against partial outage, but it may be a significant barrier itself against extensive outages.[2]

The challenges of network reconfiguration can be subdivided into three areas: regulatory, economic, and technical issues. In this review article, only a brief overview of the regulatory and economic challenges will be summarized. This review article emphasizes the technical issues (transient overvoltage issues) related to the transmission network reconfiguration. Thus, the key issue is to handle transient issues in network reconfiguration for grid resilience and protection against the influence of weather events.[110,111]

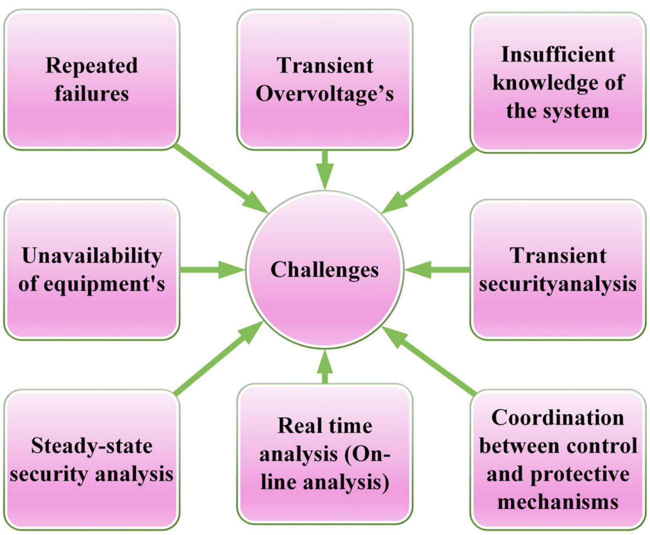

FIGURE 3 Challenges during power system restoration

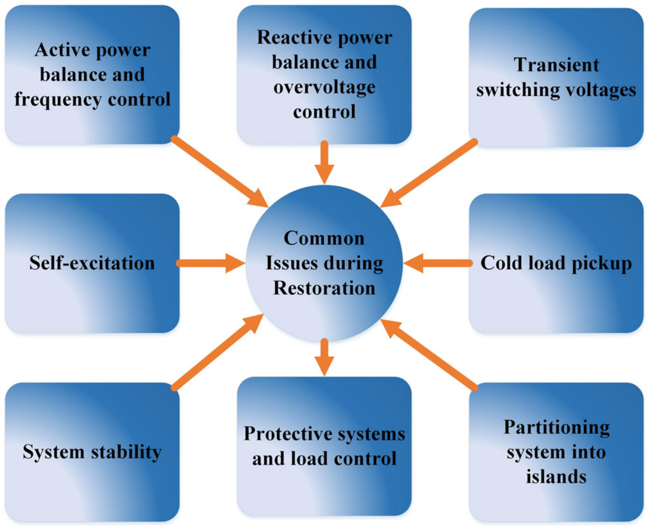

FIGURE 4 Technical issues during power system restoration

Regulatory issues are controlled by the directives from the authorities in charge of deciding the specified level of service reliability to be provided by the utilities to end-users. Service reliability can be affected by the in-appropriate restoration actions such as repeated failures, insufficient knowledge of the system, too fast restoration. This review article gives a brief overview of the regulatory issues faced during the power system restoration, that is, (a) most in-appropriate restoration actions such as repeated failures due to unexplained strategy or direction, that is, lack of awareness for such emergency at substation level in the network reconfiguration phase. This issue can be encountered by proactive mobilization of staff and adequate replacement equipment inventory to minimize downtime. (b) Transient overvoltage due to over-excitation of transformers, lightly loaded transmission lines, energizing large segments of the transmission system. This issue can be encountered by increasing transmission system resilience. (c) Service reliability due to the insufficient information on failure circumstances. This issue can be improved by the pro-active mobilization of staff. (d) Misunderstandings between control centers (ie, GENCO, TRANSCO, and DISCO). These issues can be handled by mobilizing/dispatching staff to critical stations and backup control centers. Regulatory authorities generally establish the standards, criteria, and requirements for power system network reconfiguration. Each country has different criteria and standards to overcome these regulatory issues. For example, these standards and criteria are established by the North American Electric Reliability Corporation, and regional transmission operator.

Economic issues are handled differently in different countries or regions of the world. In a market-based system, coordination among many companies (ie, GENCO, TRANSCO, and DISCO) is required due to different owners and operators. Companies' owners are responsible for offering many services, such as participating in the testing and training to implement them successfully. Economic issues can be encountered by integrating new equipment and deploying new resources to enhance the observability and controllability of SCADA, EMS, and emerging WAMS to improve steady-state security, transient security, and real-time analysis. Furthermore, frequent operator training, online equipment diagnostic systems and environment monitoring information systems, and adequate replacement equipment inventory minimize downtime to encounter economic issues. Moreover, the emphasis of this article is discussed as the technical issues that affect power system restoration. In this section, the transient issues are discussed in detail with current research publications and some industry practices during network reconfiguration of the transmission system.

5.1 | Transient overvoltage issues

The network reconfiguration process starts after the energization of black start generators, which means more generators are engaged as well as meshed transmission lines and dispatchable resources. Due to this, more options are available to deal with transient instabilities along the way.

The major transient issues that occur in the transmission system reconfiguration are classified as: sustained power frequency overvoltages, switching transients, and harmonic resonance voltages as shown in Figure 5. Firstly, sustained

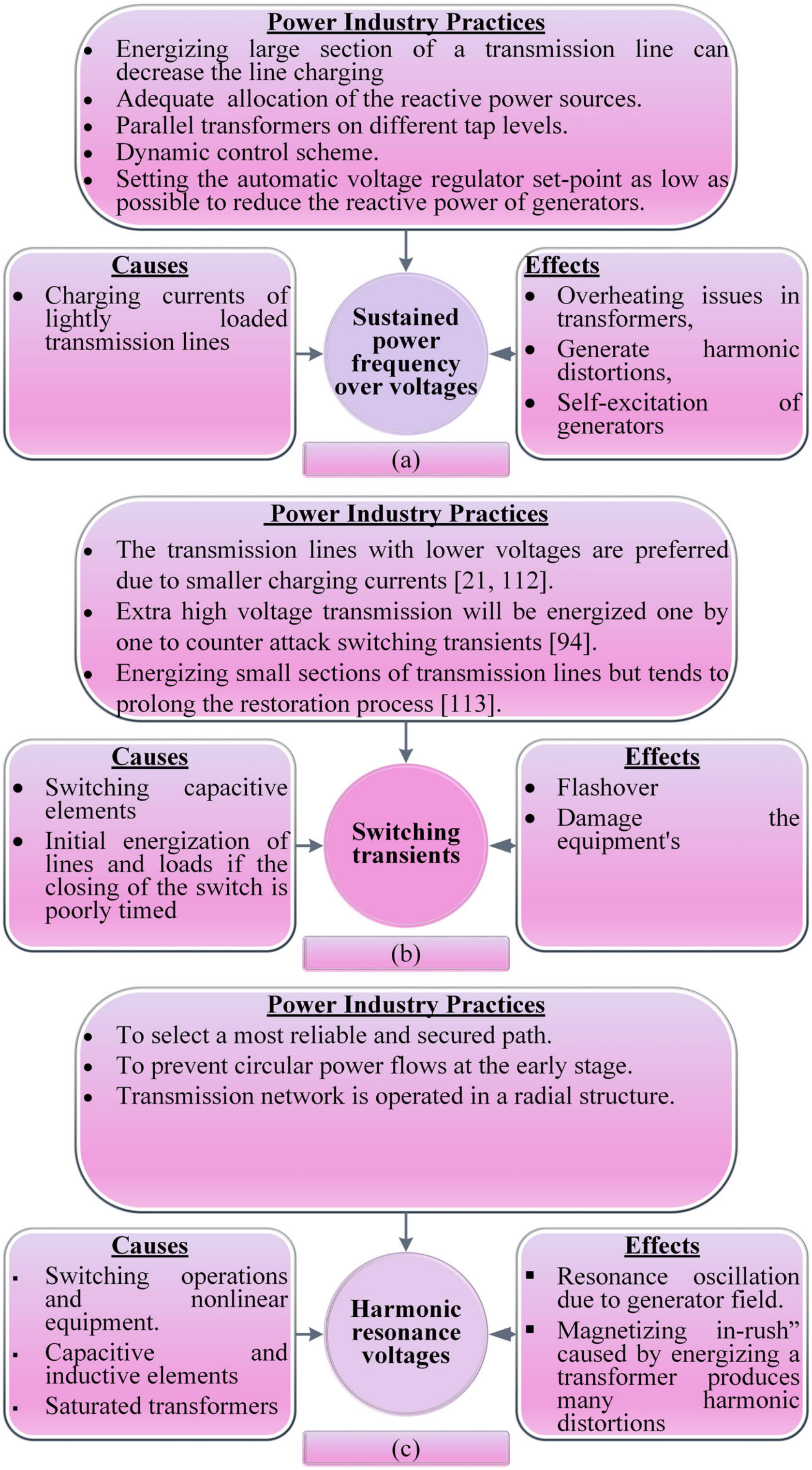

FIGURE 5 Transient overvoltage issues: A, sustained power frequency over voltages, B, switching transients and C, harmonic resonance voltages

power frequency overvoltages are caused by charging currents of lightly loaded transmission lines. Secondly, overvoltages and switching transients are caused by energizing large segments of the transmission system or due to switching capacitive elements.[21,94,112,113] Thirdly, harmonic resonance voltages are caused by switching operations and non-linear equipment.[113,114] Voltage security is a critical issue during the early stage of restoration because the restarting of NBSGs and load pickup are done by transmission path. To overcome these issues, power industry practices are discussed in Figure 5.

Furthermore, many researchers' work to handle transient issues during transmission network reconfiguration.[27,32,106,108] Transient issues can be handled using offline simulation tools (power flow, electromagnetic transients) as well as decision-making tools. Decision-making based on situation awareness from supervisory control and data acquisition systems (SCADA) and WAMS[115] will be realized soon with the effective application of fast-developing artificial intelligence technologies.

5.2 | Power industry practices

For many decades, power generation, transmission, and distribution companies follow some restoration planning practices such as the availability of BSG units which can energize lightly loaded transmission lines for other NBSG. This NBSG should be capable of quick returns to services and can rebuild the transmission system through automation facilities. Both power and utility companies have different restoration planning, training, and testing. Only a few companies maintain the updated restoration plan and perform comprehensive transient and steady-state tests, but most of them follow the simplified structures. To add this, most GENCO companies focus on the periodic test on the capability of BSG to restore NBSG, and when talking about transmission companies they focus on the rebuilding of the grid based on the steady-state analysis. Some companies rely on the participation in the table-top drills (simulation of the actual processes) called by regional transmission organization. As pointed in restoration planning requires close collaboration between GENCO, TRANSCO, and DISCO.[116]

The power industry uses both offline and real-time simulations to assess both offline reliability data, online fault diagnosis, and weather data.[117] The offline simulation method is only applicable to solve small-scale transient issues with a more detailed dynamic model. To resolve problems of the large-scale power systems, a simplified model is analyzed but this method is less reliable. So, many power industries work on the steady-state analysis to find the overall performance of the power system. The on-line dynamic analysis could be conducted based on the most recent system information as data, statuses, and topology structures. The security of the system could anticipate failures of more than one critical component and simulations will be available to prevent actions or correct situations. The investment in communication is really a big issue for true feedback control. The measurements can come from several sources: SCADA, EMS applications, PMU, and PDC. The secure region is constrained by the limits of relay settings, transient voltage dip/rise, voltage, and frequency limit.[118] Industrial practices have already shown that the PMU could support these two tasks significantly[119,120]: island information and generator black start.

In the power industry, transmission system operators are legally instructed to ensure the peak level of reliability and quality of electricity supply for industrial as well as domestic consumers without breaking any system security constraints such as voltage limits, lines thermal limits, and stability limits. The advantages of planning methodology are to increase the reliability, to develop technical plans/options/projects required to connect new generating units and new extra-high voltage substations, and to minimize operational issues such as reduce short circuit levels in substations and overloading during contingencies and emergencies cases.[105]

If the transmission network violates the system security constraints, this causes transmission congestion. In the power industry, system operators should be capable of managing transmission congestion to minimize the total operating costs,[29,121] for obtaining their marking goals with security and stability.[122] Voltage stability analysis can be applied to mitigate transient issues in both the power transmission system and the distribution system.[123-125]

6 | CONCLUSION AND FUTURE WORK

After a complete power system blackout, network reconfiguration has more attention and made great improvements recently. State-of-the-art research progress of the network reconfiguration for transmission networks are reviewed in this article, including start-up sequences of units, restoration path, and skeleton network. CNT-based indices, optimization models, and optimization techniques are presented and discussed. Furthermore, practical challenges, technical issues (transient issues) during network reconfiguration of the transmission system, and industry practices are presented and discussed in detail. There is a long way to go to achieve quick restoration of the power grid after a blackout. Grid resilience would involve a quick dynamic reconfiguration of the power system to minimize the propagation of attack influences on the grid. In the future, decision-making methods like SCADA and WAMS will be applied in the network reconfiguration of the power system for grid resilience.

Despite the vast previous works on this transmission network reconfiguration problem, many stimulating and vital issues are still open. In the subsequent discussions of crucial issues among existing models, methodologies for transmission network reconfiguration problem will be addressed. Possible directions for future research are also highlighted as follows:

1. In the future, the co-simulation of the transmission and distribution networks model can be used to obtain the optimal resilience performance of a power system.
2. In the previous work, most of the optimization problems have been modeled as MILP, MINLP, or MISCOP problems. A significant number of authors have linearized the nonlinear optimization problem without considering the accuracy of the methods for the network reconfiguration problem. These problems are very complicated and computationally exhaustive. To overcome this problem, integrated machine learning, stochastic approach, and proper decomposition algorithm could be a good approach to tackle these challenges and simplify and efficiently solve them. Commonly used solution algorithms to solve the optimization problems are column and constraints generation (C&CG), nested C&CG, Bender's decomposition, greedy search algorithm, dual decomposition algorithm, scenario-based decomposition, and progressive hedging algorithm. These algorithms have been implemented in various mathematical programming tools such as GAMES and MATLAB and solved by such as IBM ILOG CPLEX Optimization Studio, Gurobi, interior-point optimizer (IPOPT).
3. RES can improve system resilience by supplying critical loads and isolated areas at the transmission level. RES may improve the ability of power systems to recover from disturbances and blackouts. The integration of RESs into power grids creates various technical challenges due to high penetration, which have not been previously studied. In the future, further investigations are essential.
4. Dynamical models for transmission network reconfiguration are still unsolved yet. The advantage of the dynamical models is that they can capture vital dynamical behaviors of the power system. In the future, further investigations are essential.

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DATA AVAILABILITY STATEMENT

Data sharing not applicable - no new data generated, or the article describes entirely theoretical research Data sharing not applicable to this article as no datasets were generated or analysed during the current study

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