IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 6 March 2023, accepted 21 March 2023, date of publication 24 March 2023, date of current version 4 April 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3261459

TOPICAL REVIEW

The Role of Optimal Transmission Switching in Enhancing Grid Flexibility: A Review

MUHAMMAD NUMAN[1], MUHAMMAD FARASAT ABBAS[1], MUHAMMAD YOUSIF[1], SHERIF S. M. GHONEIM[2], (Senior Member, IEEE), ALSHAREF MOHAMMAD[2], (Member, IEEE), AND ABDULFATTAH NOORWALI[3]

[1]Department of Electrical Power Engineering, U.S.-Pakistan Center for Advanced Studies in Energy, National University of Sciences and Technology, Islamabad 44000, Pakistan
[2]Department of Electrical Engineering, College of Engineering, Taif University, Taif 21944, Saudi Arabia
[3]Department of Electrical Engineering, Umm Al-Qura University, Mecca 24382, Saudi Arabia

Corresponding author: Muhammad Numan (numan@uspcase.nust.edu.pk)

This work was supported by the Deanship for Research and Innovation, Ministry of Education, Saudi Arabia, under Project IFP22UQU4290235DSR257.

ABSTRACT The integration of variable renewable energy sources (RES) into power grids has resulted in a more complex operating environment for power system operators (SO), necessitating the need for increased grid flexibility. This is crucial for utilities, as the cost-effective utilization of existing infrastructure is necessary, given the prolonged construction period and high investment costs associated with building new power delivery facilities. Under the umbrella of smart grid, optimal transmission switching (OTS) is a cost-effective transmission technology that can alleviate concerns related to network congestion, limited transmission capacity, and high penetration of renewables. OTS is a concept that is integrated into the optimal power flow (OPF) problem such that it provides SO the choice to temporarily switch one or more lines out of service from the network. OTS is shown in the literature to have economic benefits, reduce operational cost, relieve network congestion, serve as a corrective mechanism for reducing voltage violations, improve system reliability, and minimize system loss. Despite the significant attention given to OTS by researchers over the past decade, no extensive review paper exists on the topic in the literature. Therefore, this paper provides a state-of-the-art overview of the OTS problem. The concept of OTS is explained by approximating the alternating current OPF problem into a linear direct current OPF problem. Various alternative models of the OTS problem proposed in the literature are discussed. The paper also analyzes the interaction between OTS and other flexibility options such as Dynamic thermal rating (DTR), Energy storage systems (ESS), and RES. Furthermore, the paper presents the general framework and impact of the short-term OTS problem on long-term expansion planning problems. Finally, an extensive literature review on the impact of OTS on system reliability is provided.

INDEX TERMS Dynamic thermal rating, energy storage systems, optimal transmission switching, power system reliability, renewable energy sources, transmission expansion planning.

NOMENCLATURE

A. ABBREVIATIONS

OTS	Optimal Transmission Switching.
SO	Service Operator.
RES	Renewable Energy Sources.
ESS	Energy Storage System.
DTR	Dynamic Thermal Rating.
STR	Static Thermal Rating.
TEP	Transmission Expansion Planning.
MILP	Mixed Integer Linear programming.
OPF	Optimal Power Flow.

B. SETS/INDICES

Ω_B	Set of buses: i as an index.
Ω_G	Set of Generators: g as an index.
Ω_L, Ω_L^+	Set of existing and candidate lines: ij as an index.
Ω_T	Time period: t as an index.

The associate editor coordinating the review of this manuscript and approving it for publication was Diego Bellan.

C. PARAMETERS

$\bar{P}, \underline{P}$	Generating unit's capacities.
$\bar{f}_{ij}, \underline{f}_{ij}$	Line capacities.
c_g	Generation cost.
G_{ij}	Line conductance.
B_{ij}	Line susceptance.
D_i	Demand at bus i.
$Z^{\max}$	Maximum line switching actions.
$C_{ij}^{\max}$	Maximum investment cost.
δ^{rec}	Angle reclosing rule.
$\bar{\delta}, \underline{\delta}$	Limits of voltage angle.
J_c, J_r	Convection and radiation terms in the heat balance equation.
J_s, I^2R	Solar radiation and Joule Heating terms in the heat balance equation.
$I_{\max}$	Maximum line ampacity.

D. VARIABLES

P_g	Power dispatched by generator.
f_{ij}	Line flow.
f_{ij}^0, f_{ij}^1	Line flow through existing and candidate lines.
ω_{ij}	Binary variable for line investment indication.
δ_i	Voltage angle at bus i.
N_{ij}^{-1}	N-1 binary variable for contingency analysis.
z_{ij}	Binary variable for line status indication.

I. INTRODUCTION

Maintaining a balance between supply and demand is imperative for the reliable operation of the power system since a supply-demand mismatch can alter the system's frequency. Power system flexibility refers to the system's ability to respond to expected and unexpected supply and demand changes. Traditional power systems are designed to deal with changes only in the system demand, which includes both seasonal and intra-day variability. However, the transition towards a system dominated by renewable energy sources (RES) requires the current power system to harness flexibility.

Power system flexibility can be achieved from all three main elements of the power system: Generation, Distribution, and Transmission. Harnessing grid flexibility from the generation, transmission, and demand sides will be more beneficial for improving economic efficiency and creating a more robust and reliable system. Generation flexibility can be obtained by deploying more reserves into the system from conventional generators to ensure that the power dispatched can withstand RES uncertainty [1]. However, this approach is costly and might reduce the benefits obtained from utilizing cheap and environmentally friendly RES. On the demand side, energy storage and demand response are the two prominent sources that can increase grid flexibility [2], [3]. On the transmission side, flexibility can be obtained from three different aspects of the transmission system. Firstly, system operators (SO) can change the network topology by switching on/off some lines from the network. Another way to add flexibility from the transmission side is to increase the capacity of lines to allow power dispatch from low-cost generators to relieve RES uncertainty [4]. Flexible AC transmission systems (FACTS) devices can also help in controlling transmission assets by changing line impedance [5].

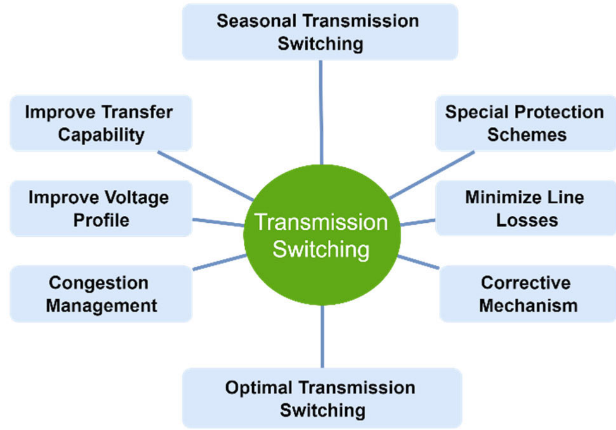

FIGURE 1. **Applications of transmission switching in literature.**

Optimal power flow (OPF) is an optimization problem governed by Kirchhoff's law, which states that changing the impedance of a transmission line alters the power flow through the network. Traditionally, transmission assets in the OPF problem are treated as fixed, and system operators have no ability to control them. However, it is now recognized that to improve transfer capacity, voltage profile, and system reliability, system operators can alter the topology of the grid.

Past research has focused on the use of transmission switching as a control mechanism for different issues, as shown in Figure 1. Transmission switching is mainly used as a corrective mechanism for voltage violations and line overloading [6], [7]. While this aspect of transmission switching acknowledges the use of transmission as a control method providing different benefits, the co-optimization of transmission assets with generation dispatch problems is not explored. A common myth about switching lines off is that it may increase system losses. However, the opposite may be true, and in fact, system losses may reduce with transmission switching. Previous literature has shown that transmission switching can be used to reduce network losses. Limited line capacity may result in network congestion, which might lead to dispatch from expensive generators. Transmission switching is also used as a tool to mitigate congestion. In summary, transmission switching can provide flexibility to power systems and can be used as a tool to co-optimize transmission assets with generation dispatch problems.

A common practice in the industry is to take out lightly loaded transmission lines from service. This is because, during times of low loads, the capacitive part of the transmission lines dominates, while at higher load levels, the reactive component takes over. This can lead to voltage violations. To mitigate these violations, system operators use a common protocol to switch off lines that are not necessary for maintaining reliability [8]. These protocols are listed as possible actions for alleviating voltage violations in PJM, Northeast Power Coordinating Council, and Excelon, among others. Another protocol is to identify transmission lines that can be taken out of service to increase the transfer capability on other lines.

Special protection schemes (SPSs) are integral to enhancing operational efficiency and system reliability. Ad-hoc procedures adopted as SPSs shift the industry from preventive to corrective measures. PJM lists several such SPSs that recommend transmission switching in post-contingency situations. Although alternatives to transmission switching exist, such as re-dispatching generation or choosing a pre-contingency state to avoid overloading, these can increase operating and capital costs as compared to when transmission switching is applied. Load requirements may vary depending on the region and seasonal variability. In one season, the load might be low, and the probability of outages might be high due to storms or rains, while in another season, the load might be high, and the chances of line outages might be low. Therefore, it is useful for utilities to leave some lines in service during seasons when the chances of storms/rains are high, but these lines might be taken out of service during times of low loads. These lines provide system redundancy during line outages and can be switched off from the network when the chances of line outages are low.

Optimal transmission switching (OTS) is a concept that is integrated into the OPF problem, giving system operators the option to temporarily remove one or more transmission lines from the network. This enables co-optimization of the grid topology with the generation dispatch problem, while maintaining system reliability. The notion of OTS was introduced by [9]. The literature has shown that OTS has economic benefits [10], [11], reduce operational cost [12], [13], [14], relieve network congestion [15], [16], [17], [18], [19], [20], alleviate system overloads [21], serve as a corrective mechanism for reducing voltage violations [22], [23], [24], [25], [26], [27], and improve system reliability [28], [29]. However, the problem of OTS is a non-convex combinatorial problem, which is NP-hard and difficult to solve [30], [31], [32], [33], [34]. DC approximated OTS problems are typically solved using mixed integer linear programming (MILP) [35], [36], [37], [38], while AC based OTS problems utilize iterative relaxations and heuristics. Some of these methods include Bender's decomposition [39], [40], [41], [42], [43], [44], genetic algorithms [45], branch-and-bound (B&B) [9], semi-definite programming [46], line ranking [47], interior point search algorithms [48], particle swarm optimization [24], [49], and cutting-plane methods [50], [51]. Stochastic optimization [52], [53], and robust optimization [54], [55], [56] are widely used approaches to address the uncertain variables in the OTS problem combined with RES.

Since the introduction of the OTS concept, a considerable amount of research has been conducted to investigate the operational flexibility that can be achieved through its deployment. OTS has been incorporated into a variety of problems ranging from short-term operating to long-term planning problems. The literature also extensively discusses the role of OTS in facilitating the large-scale integration of renewables. While many papers have highlighted the benefits of OTS, others have focused on the computational complexity associated with solving the OTS problem and proposed different algorithms and heuristics to solve it within a reasonable amount of time. However, no comprehensive overview of the OTS problem has been written to date. Therefore, this paper presents, for the first time, an extensive systematic review of OTS, providing readers with a one-stop article covering all aspects of the problems associated with OTS. The major contributions of the paper are as follows:

- Firstly, a comprehensive state-of-the-art review of the OTS problem is presented, with a primary focus on incorporating the control of transmission elements into the traditional network flow problem. The review paper provides an extensive overview of the key concepts and methodologies that have been developed in this area, highlighting their strengths and limitations.
- Secondly, the paper explores the operational, economic, and reliability implications of the OTS problem when combined with other flexibility options such as DTR, ESS, RES, and transmission expansion planning problem. The paper examines these implications in detail, providing insights into the benefits and challenges of each option.
- Finally, the paper emphasizes the importance of system reliability in achieving optimal power system operation. The study evaluates the impact of switching lines in/out form the network using OTS on system reliability and provides a general framework for system reliability evaluation using OTS, along with relevant literature.

We conducted a systematic search process to gather relevant publications on OTS and its interaction with other smart grid technologies. Figure 2 displays the number of research papers published on this topic from 2008 to 2022. After screening 350 articles, we selected 251 publications for review, categorized in Figure 3 according to their relevance to operation, planning, reliability, or renewables integration. Each category is further subdivided, with the number of publications listed. Finally, Figure 4 illustrates the distribution of journals (IEEE, ELSEVIER, WILEY, IET, etc.) and conference publications for the filtered articles.

The rest of the paper is structured as follows: In Section II, the concept of OTS is explained and an example of the OTS problem in OPF is provided. Section III presents a unified mathematical formulation of the different modifications made to the original OTS problem over the last 14 years. Section IV discusses the interaction between OTS and other flexibility options, such as DTR, ESS, and RES, and explains the impact of short-term OTS on long-term

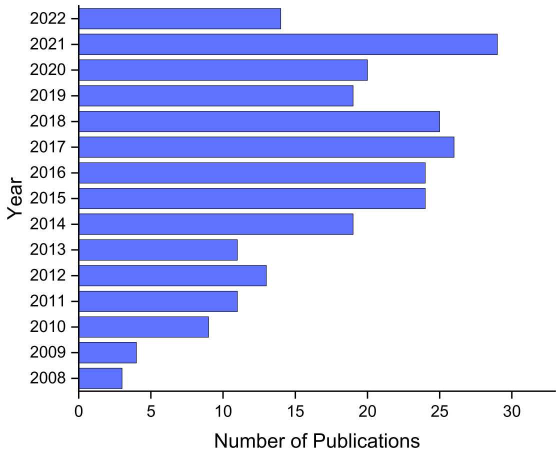

FIGURE 2. Annual publications on optimal transmission switching (OTS).

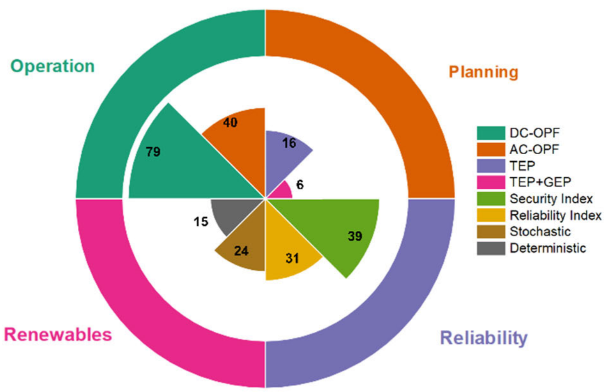

FIGURE 3. Classification and sub-categorization of reviewed articles on OTS.

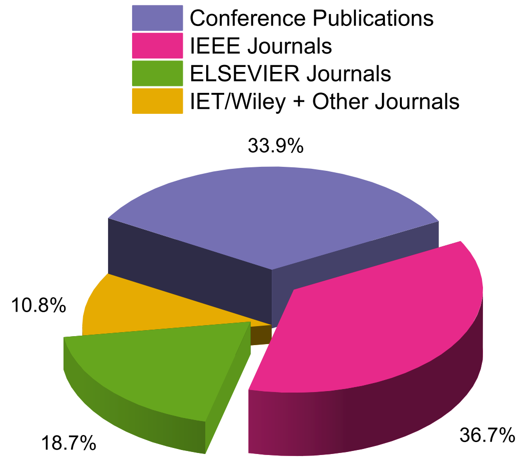

FIGURE 4. Publication and publisher distribution of reviewed papers on OTS.

expansion planning. Section V provides a comprehensive literature review of the impact of OTS on system reliability. Finally, the paper concludes in Section VI.

II. CONCEPT OF OTS

A. TRADITIONAL OPF PROBLEM

Optimal power flow (OPF) is a problem of optimization used to dispatch power generation to meet load demand, where the electric energy flow is governed by Kirchhoff's laws. The Alternating Current OPF (AC-OPF) network flow problem aims to optimally dispatch generation following network flow and reliability constraints. However, the OPF problem based on AC constraints is a non-convex optimization problem, which becomes difficult to solve due to the presence of trigonometric functions. The active and reactive power flow equations for a transmission line connected between bus i and j (i is *from-bus* and j is *to-bus*) is given by equation (1) and (2). For the AC-OPF problem, additional constraints such as voltage magnitudes, angle differences between connected buses, line flow capacity, and generation limits constraints are also required.

$$f_{ij} = V_i^2 G_{ij} - V_i V_j (G_{ij}\cos(\delta_i - \delta_j) + B_{ij}\sin(\delta_i - \delta_j)) \quad (1)$$

$$f_{ij}^{Q} = -V_i V_j (G_{ij}\sin(\delta_i - \delta_j) - B_{ij}\cos(\delta_i - \delta_j)) - B_{ij}V_i^2 \quad (2)$$

To make the more complex AC-OPF problem easier to solve, a linear approximation is typically used, known as Direct Current OPF (DC-OPF). DC-OPF includes all constraints in linear form and is simpler to solve than AC-OPF. The following approximations are made when transitioning from AC-OPF to DC-OPF formulation: i) voltage variables are assumed to have a per-unit value of one, ii) the voltage angle is assumed to be very small, making the cosine term one and the sine terms negligible. This assumption cancels the $B_{ij}\sin(\delta_i - \delta_j)$ term in (1) and $G_{ij}\sin(\delta_i - \delta_j)$ in (2), iii) the reactive power term in (2) is ignored, iv) the resistance is neglected due to its very small value, and v) a piece-wise linear approximation is used for the generator's cost function. With these assumptions, equation (2) is disregarded and (1) is reduced to the form shown in (3).

$$f_{ij} = B_{ij}(\delta_i - \delta_j) \forall ij \quad (3)$$

The DC-based OPF problem is composed of linear constraints and is formulated as a linear programming (LP) problem. This optimization problem minimizes the cost of generation while taking network constraints into account. The main objective of the OPF is to minimize the total dispatch cost of generators, which is expressed in equation (4). Energy balance at each node is represented by constraint (5), where the total generation is equal to the demand. Constraint (6) indicates the capacity limits of all generators at nodes i, while constraint (7) specifies the phase angle limits of voltages at node i. Constraint (8) represents the DC approximation of Kirchhoff's voltage laws. This approximation is often used instead of AC because it linearizes the problem, reducing its complexity and computational time. Constraint (9) signifies the power flow capacity limits of transmission lines flowing toward node i (positive) or out from node i (negative). This optimization problem yields the optimal output of generators for fixed or variable loads.

$$\min \sum_{g\in\Omega_G} c_g P_g \tag{4}$$

$$\sum_{g\in\Omega_G} P_g + \sum_{ij\in\Omega_L} f_{ij} - \sum_{ji\in\Omega_L} f_{ji} = D_i \, \forall i \in \Omega_B \tag{5}$$

$$\underline{P}_g \leq P_g \leq \bar{P}_g \forall g \in \Omega_G \tag{6}$$

$$\underline{\delta}_i \leq \delta_i \leq \bar{\delta}_i \; \forall i \in \Omega_B \tag{7}$$

$$B_{ij}\left(\delta_i - \delta_j\right) - f_{ij} = 0 \forall ij \in \Omega_L \tag{8}$$

$$\underline{f}_{ij} \leq f_{ij} \leq \bar{f}_{ij} \forall ij \in \Omega_L \tag{9}$$

B. BASIC OTS MODEL

To incorporate OTS into the traditional DC-OPF model, modifications are made by introducing a binary variable, denoted as z_{ij}, which represents the status of each transmission line. A value of one signifies that the line is in service, and circuit breakers are closed, while a zero value indicates that the line from bus i to j is switched, and circuit breakers are opened. When a line is switched, it must be electrically isolated from other lines in the network to ensure that other lines' flow is not affected, and no power flows through that line. If the only objective is to force line flow to zero, then the model will treat this line as a line with very limited capacity, which can severely impact the entire network's flow.

To properly model OTS, certain constraints in the DC-OPF need to be modified. Firstly, the line capacity limit in constraint (9) is multiplied by the binary variable z_{ij}, which forces the flow to zero when a line is switched from the network; otherwise, the flow is restricted by the line's min/max limits. However, this modification alone is not sufficient. When $z_{ij} = 0$ and $f_{ij} = 0$, equation (8) will make the voltage angles of the buses equal, which is not the desired outcome. To avoid this, constraint (8) needs to be modified with what is known as an indicator constraint, which can be achieved using various methods. One way is to break the network flow relationship constraint (8) into two parts using the big-M value constraint. If $z_{ij} = 1$, the product of M in each inequality is zero and yields the same equation as (8). However, if $z_{ij} = 0$, the large value of M allows the voltage angles of the two buses to be different, resulting in the desired output. These modifications to the basic DC-OPF problem result in the OTS problem, as shown in equations (10)-(18).

$$\min \sum_{g\in\Omega_G} c_g P_g \tag{10}$$

$$\sum_{g\in\Omega_G} P_g + \sum_{ij\in\Omega_L} f_{ij} - \sum_{ji\in\Omega_L} f_{ji} = D_i \, \forall i \in \Omega_B \tag{11}$$

$$\underline{P}_g \leq P_g \leq \bar{P}_g \forall g \in \Omega_G \tag{12}$$

$$\delta_{-i} \leq \delta_i \leq \bar{\delta}_i \; \forall i \in \Omega_B \tag{13}$$

$$B_{ij}\left(\delta_i - \delta_j\right) - f_{ij} + (1 - z_{ij})M \geq 0 \forall ij \in \Omega_L \tag{14}$$

$$B_{ij}\left(\delta_i - \delta_j\right) - f_{ij} - (1 - z_{ij})M \leq 0 \forall ij \in \Omega_L \tag{15}$$

$$\left|f_{ij}\right| \leq z_{ij}\bar{f}_{ij} \forall ij \in \Omega_L \tag{16}$$

TABLE 1. Different Big-M values proposed in the literature.

Ref	Big-M Value	OPF	N-1
[4], [9], [35], [56], [59]–[61]	$B_{ij}(\delta^{\max} - \delta^{\min})$	DC	
[10], [40], [62], [63]	$B_{ij}(\delta^{\max} - \delta^{\min})$	DC	■
[64] [65]	$2\bar{\delta}$	DC	
[66]	1.2 Radian	DC	
[67]	$B_{ij}(\delta^{\max} - \delta^{\min})$	AC	■
[30]	$B_{ij} \sum_{ij\in\Omega_L} \bar{f}_{ij} / B_{ij}$	DC	
[68]	$\max\left\{\sum_{ij\in\Omega_L} \left(\bar{f}_{ij} + \Delta f_{ij}^{+}\right)\right\}$	DC	■
[69]	$B_{ij}\bar{\delta}$	DC	
[70]	$2\pi\delta$	DC	■
[71]	$B_{ij} SP_{i-j}$	DC	
[72]	$2\bar{f}_{ij}$	DC	■

$$\sum_{ij} \left(1 - z_{ij}\right) \leq Z^{\max} \forall ij \in \Omega_L \tag{17}$$

$$z_{ij} \in \{0, 1\} \tag{18}$$

C. BIG-M FORMULATION

The OTS formulation employs the big-M value to render the constraints of voltage angles non-binding. However, selecting the appropriate big-M value can be a daunting task, as it impacts both the optimal solution and computation time. If the big-M value is excessively large, it can result in longer solution times dominated by numerical calculations. Conversely, selecting a small big-M value can exclude the optimal solution from the feasible solution space, leading to suboptimal outcomes. Therefore, choosing a big-M value that ensures an optimal solution with reasonable computational complexity is crucial. Various authors propose different values of big-M in the literature. In particular, the authors of [9], [57] suggested using a big-M value greater than or equal to the product of the difference of the voltage angles and the susceptance of the line, i.e., $B_{ij}(\delta_i - \delta_j)$. Table 1 provides detailed information on the different values of big-M recommended by researchers in the literature.

The authors of [58] employed a shortest path algorithm to determine the disjunctive parameter for transmission expansion planning. Their model considered existing lines as static assets and candidate lines for expansion as binary variables. The OTS framework allows modification of the grid topology by switching off some lines, altering the previously connected path between buses. To determine the shortest path for the big-M value in OTS, this disjunctive parameter needs to be modeled as a variable rather than a constant. Therefore, the shortest path for big-M value determination needs to be solved for each possible network configuration, making the problem more complex and increasing computation time.

An approximate OTS model in [69] is used to find the value of this disjunctive big-M parameter by using the $B_{ij}(\delta_i - \delta_j)$ in their formulation, which is auto-tuned by the optimization problem. The authors in [70] suggests a conservative value for this big-M value as to be $2\pi B_{ij}$. Reference [30] proved that finding the suitable value for big-M is Non-polynomial hard (NP-hard). The authors proposed a bound strengthening method for OTS reformulation and showed that it can improve the runtime of the MILP problems significantly. To improve the convergence performance of the network expansion planning problem, [65] used a value of 2δ for the big-M parameter. A constant value of 1.2radian is used in [66] for OTS problem incorporated in investment decision problem. The use of OTS along with dynamic thermal rating (DTR) in an investment model is studied in [68], where the authors suggested a value of max $\left\{\sum_{ij\in\Omega_L}\left(\bar{f}_{ij} + \Delta f_{ij}^{+}\right)\right\}$ for the big-M value. The Δf_{ij}^{+} term represents the additional line capacity brough about by the DTR implementation. It is shown that this value of big-M as compared to the value of $B_{ij}(\delta_i - \delta_j)$ results in a faster convergence of the problem in hand.

D. OTS ILLUSTRATIVE EXAMPLE

The flow of electricity in a network follows the path with the lowest impedances, as dictated by Kirchhoff's law of current. By strategically switching certain lines, the impedance of the network can be modified, potentially enabling the dispatch of more cost-effective generating units and reducing operational costs. This concept of optimal line switching to improve economic dispatch is illustrated using a simple bus system shown in Figure 5 [73]. The network comprises three buses with three transmission corridors and two generating units serving a single load at bus 3. The cost of the two generating units is also provided in Figure 5, where G1 is the cheaper unit compared to G2. The maximum capacity of both units is set to 200MW, which is required to meet a load of 150MW at bus 3. All three lines are assumed to be lossless and have the same reactance. The line capacity of L1 is 30MW, while that of L2 and L3 is 150MW each. The objective is to determine the optimal schedule of the two generating units at minimum cost while meeting the load requirement. The optimal schedule is obtained for the following two scenarios:

a) Transmission lines are assumed to be fixed.
b) OTS is considered.

Given that G1 is more economical than G2, the least-cost dispatch solution would be to deliver all 150MW of load from G1 and leave G2 off. However, in case-a where all lines are connected to the system, this solution is not feasible. To transfer 100MW of the 150MW load, line L2 needs to carry double the power compared to lines L1 and L3, as the series impedance of L1 and L3 is double that of L2. This results in the flow through line L1 exceeding its capacity, rendering the

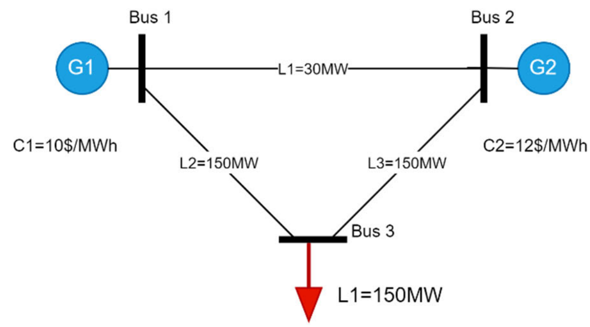

FIGURE 5. System description for the OTS illustrative example.

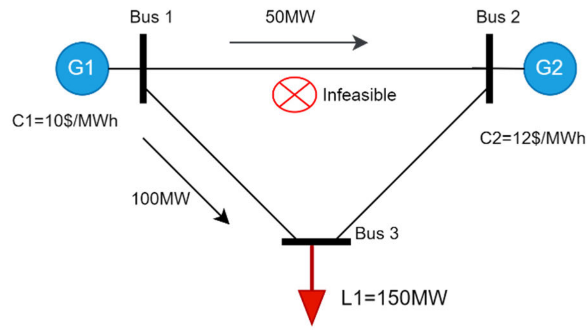

FIGURE 6. Scheduling solution when only G1 is committed and all lines are fixed.

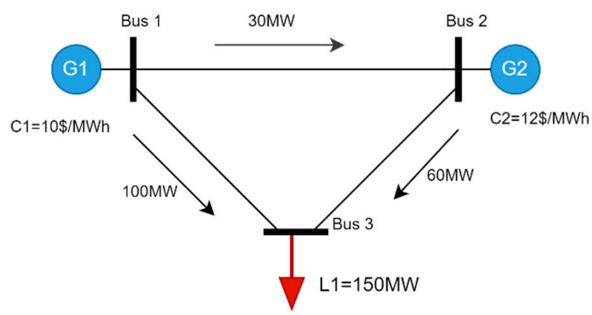

FIGURE 7. Scheduling solution when both G1 and G2 is committed and all lines are fixed.

solution infeasible as shown in Figure 6. To make the solution feasible, G1's power output is reduced, and G2 is turned on to produce counterflow on line L1. The optimal solution now involves generating 120MW of power from G1 and the remaining 30MW from G2, resulting in a flow of 30MW on L1, 90MW on L2, and 60MW on L3, as depicted in Figure 7. The total operating cost in case-a is 120MW*10/MWh + 30MW$120/MWh=$1560.

When OTS is applied in case-b, we can switch either L1 or L3 to achieve a more economical schedule. In either situation, power from G1 alone can satisfy the load through a single path. The line between bus1 and bus2 (L2) shown in Figure 8 is switched off, as it has enough capacity to deliver the power. In this case, the total operating cost is 150*$10/MWh=$1500. Incorporating OTS resulted in a cost

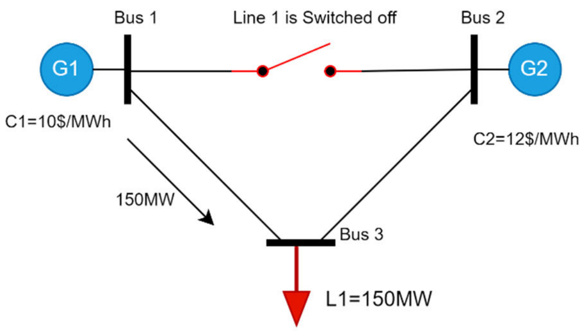

FIGURE 8. Scheduling solution when only G1 is committed and OTS is applied.

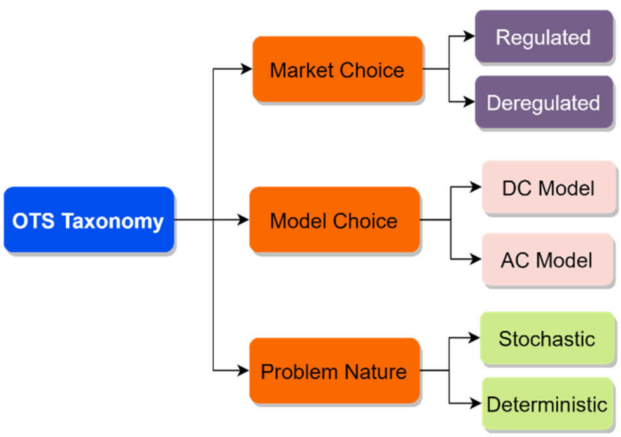

FIGURE 9. OTS classification based on market choice, model choice and nature of the problem.

saving of 3.8% compared to the base case, where all transmission lines are fixed.

III. EXTENDED OTS MODELS

The solution to the OTS problem involves the use of general network techniques and the relaxed mathematical models making use of the voltage angles and active/reactive power of the network. Current network topology is required as the needed data for the OTS problem. Classical simplified OTS models mostly used by the researchers in the literature as shown in Figure 9, are the DC-OPF and AC-OPF based model, deterministic and stochastic models. DC-OPF neglects bus voltages and power losses in OTS model. On the other hand, AC model of OTS considers reactive power and voltage magnitudes, so when feasible solution is not found, it means transmission switching isnot satisfying voltage security requirements. The deterministic approach assumes fixed values for the parameters associated with uncertainty, while the stochastic approach considers the random nature of the uncertainty to provide more realistic information about the system. This section explores the different modifications made to the OTS problem since its inception. To improve readability, all extended models are presented using a consistent mathematical representation for coherence.

A. ALTERNATIVE OTS MODEL

An alternative way to model OTS formulation in a DC-OPF based framework is to introduce an additional variable to allow the line flow f_{ij} be replaced by the term $B_{ij}(\gamma_{ij} - \delta_i)$ where the voltage angle corresponds to the bus (*from-bus*) [13]. If the line is in service, then equation (8) is modified into constraints (23) and (24), which enforces γ_{ij} to equal δ_j. If the line is switched off from the network, then γ_{ij} and δ_j are not equal by (23) and (24). The inclusion of constraint (22) will force γ_{ij} equal δ_i. This means that when the line is in service the variable γ_{ij} will equal δ_j(*to-bus*) and when the line is removed it will equal to δ_i(*from-bus*) angle. In this alternative model, big-M value is replaced with the δ^{rec}.

$$\min \sum_{g\in\Omega_G} c_g P_g \tag{19}$$

$$\underline{P}_g \leq P_g \leq \bar{P}_g \forall g \in \Omega_G \tag{20}$$

$$\sum_{g\in\Omega_G} P_g + \sum_{j\in\Omega_L} B_{ij}(\gamma_{ij} - \delta_i) - \sum_{i\in\Omega_L} B_{ij}(\gamma_{ij} - \delta_i) = D_i \,\forall i \tag{21}$$

$$\bar{f}_{ij} z_{ij} \leq B_{ij}(\gamma_{ij} - \delta_i) \leq f_{ij} z_{ij} \forall ij \tag{22}$$

$$\delta_j - \gamma_{ij} + (1 - z_{ij})\delta^{rec} \geq 0 \forall ij \tag{23}$$

$$\delta_j - \gamma_{ij} - (1 - z_{ij})\delta^{rec} \leq 0 \forall ij \tag{24}$$

and equations (13),(17),(18).

B. DC-OPF BASED OTS WITH N-1

The network is constructed to meet various conditions like load, generation levels and contingencies. But all these situations do not co-exist simultaneously. A line which needs to be in service for N-1 security in one situation might not be needed to meet N-1 standard in another network condition. Thus, transmission switching might be possible even meeting the N-1 requirements. N-1 DCOPF means system will be able to endure the loss of a single line or generator unit. The objective function is to minimize total expected cost while satisfying physical constraints of the system. In DC-OPF, we consider a lossless system however, in AC system, losses increase or decreases with use of transmission switching. When losses increase, we must increase generation capacity. In some cases, total system cost is reduced with increase in losses which is one of the beneficial aspects of transmission switching. The optimization problem for OTS with N-1 DC-OPF formulation is presented by different authors considering different objective function and constraints. A generalized form of the N-1 DC-OPF based OTS framework is given in equations (25)-(31).

In order to represent element contingency and their states, a binary variable N_{ec}^{-1} is included for state c and element e, where $N_{ij,c}^{-1}$ =0 represents the contingency of line ij while the loss of generator unit is given by $N_{g,c}^{-1}$ =0. In case of transmission line contingency, (29) will force the line flow to zero. Similarly, power from generator in contingency state is forced to zero by (28). To make the bus voltage angles irrelevant from each other, constraints (30) and (31) are used, which make them unbinding. A transmission line is considered to be switched off from the network when the binary variable $z_{ij} = 0$, while a line is considered to be in state of contingency when $N_{ij,c}^{-1}$ =0. So that these two terms cannot be confused with each other. The N-1 DC-OPF solutions resulting from the OTS implementation must satisfy the requirements of the N-1 criteria.

$$\min \sum_{g\in\Omega_G} c_g P_{g,0} \tag{25}$$

$$\sum_{g\in\Omega_G} P_{g,0} + \sum_{ij\in\Omega_L} f_{ij,c} - \sum_{ji\in\Omega_L} f_{ji,c} = D_i \,\forall i, N_{ij,c}^{-1} \tag{26}$$

$$\delta_{-i} \leq \delta_{i,c} \leq \bar{\delta}_i \;\forall i \in \Omega_B, c \tag{27}$$

$$P_{-g} N_{g,c}^{-1} \leq P_{g,c} \leq \bar{P}_g N_{g,c}^{-1} \forall g \in \Omega_G \tag{28}$$

$$f_{-ij,c} z_{ij} N_{ij,c}^{-1} \leq f_{ij,c} \leq \bar{f}_{ij,c} z_{ij} N_{ij,c}^{-1} \forall ij, N_{ij,c}^{-1} \tag{29}$$

$$B_{ij}\left(\delta_{i,c} - \delta_{j,c}\right) - f_{ij,c} + (2 - z_{ij} - N_{ij,c}^{-1})M \geq 0 \forall ij, N_{ij,c}^{-1} \tag{30}$$

$$B_{ij}\left(\delta_{i,c} - \delta_{j,c}\right) - f_{ij,c} - (2 - z_{ij} - N_{ij,c}^{-1})M \leq 0 \forall ij, N_{ij,c}^{-1} \tag{31}$$

and equations (17) and (18).

C. AC-OPF BASED OTS

The AC-OPF based OTS formulation for cost minimization objective function involves voltage magnitude (approximated to one in DC-OPF) and reactive power in its constraints. DC-OPF neglects bus voltages and power losses in OTS model. Thus, it is vital to consider losses for cost minimization. AC model of OTS considers voltage magnitudes and reactive power of generators, so when feasible solution is not found, it means transmission switching is not satisfying voltage security requirements. DC-OTS provides total cost reduction due to efficient switching decisions, but it requires more research mainly due to the fact that DC-OTS may cause system security to be threaten as switching decisions of DC-OTS cannot ensure the AC feasibility. Secondly, when ACOPF is performed before and after switching lines, DC-OTS will not provide accurate results in some instances, it will either causes increase in cost or underestimate cost savings. Thirdly, DC-OTS is not applicable for illustrating some other benefits of transmission switching like eliminating temporary voltage violations. Thus, these issues can be resolved by performing AC-OTS. In the literature, the problem of AC-OTS is also extensively studied by different researchers from different perspectives [23], [74], [75], [76], [77], [78], [79], [80]. A generalized form of the AC-OPF based OTS formulation is presented in equations (32)-(39). The active and reactive power balance is achieved using (33) and (34) respectively. The active and reactive power flows are governed by constraints (35) and (36) respectively. The magnitude of the apparent power flow considering both active and reactive power is constrained by (38), while the voltage limits are constrained by (39).

$$\min \sum_{g\in\Omega_G} c_g P_g \tag{32}$$

$$\sum_{g\in\Omega_G} P_g - (1 - z_{ij}) f_{ij} = D_i \;\forall g, ij \tag{33}$$

$$\sum_{g\in\Omega_G} Q_g - (1 - z_{ij}) f_{ij}^Q = D_i \forall g, ij \tag{34}$$

$$f_{ij} = V_i V_j (G_{ij} \cos(\delta_{ij}) + B_{ij} \sin(\delta_{ij})) - G_{ij} V_j^2 \forall ij \tag{35}$$

$$f_{ij}^Q = V_i V_j (G_{ij} \sin(\delta_{ij}) - B_{ij} \cos(\delta_{ij})) + V_j^2 (B_{ij} - b_{ij}) \forall ij \tag{36}$$

$$((1 - z_{ij}) f_{ij})^2 + ((1 - z_{ij}) f_{ij}^Q)^2 \leq ((1 - z_{ij}) \bar{S}_{ij})^2 \forall ij \tag{37}$$

$$\underline{Q}_g \leq Q_g \leq \bar{Q}_g \forall g \tag{38}$$

$$\underline{V}_i \leq V_i \leq \bar{V}_i \forall i \tag{39}$$

and equations (12),(13),(17),(18).

D. APPROXIMATE OTS MODEL

Frequently switching off lines from the network may have undesirable impact on system reliability and security. The basic OTS model results in switching off too many lines for big power system if there is no restriction on the number of switchable actions. For example, in [81] a total of 24 lines need to be switched for IEEE 118-bus system, when the $z_{ij} = \infty$. This might pose a security risk for power system and undermine the benefits obtained from OTS. An approximate OTS model is presented in [69] that provides better solution quality and less computational time. This approximate model provides same cost of generation dispatch but reduces the number of switching actions while maintaining the computation time almost the same. The approximate OTS model is given in equations (40)-(42). An additional term is added to the base case OTS model in the objective function where the term ζ_{ij} is a variable and C' is a constant number. The optimal value of C' is found to be αP_1^0 where $\alpha = 0.1\%$ and P_1^0 is the dispatch solution for the base case DC-OPF when no line is switched. It is concluded by the authors that the number of switched transmission lines using approximate OTS model is reduced to half and in some situations even less. The computation time using approximate OTS model is also reduced as compared to the base case OTS model.

$$\min \sum_{g\in\Omega_G} c_g P_g + C' \sum_{ij\in\Omega_L} \frac{\zeta_{ij}}{M_{ij}} \tag{40}$$

$$-\zeta_{ij} \leq f_{ij} - B_{ij}(\delta_i - \delta_j) \leq \zeta_{ij} \forall ij \tag{41}$$

$$0 \leq \zeta_{ij} \leq (1 - z_{ij}) M_{ij} \forall ij \tag{42}$$

and equations (11),(12),(13),(16)-(18).

E. OTS MODEL THAT AVOIDS SWITCHING UNNECESSARY LINES

Another modification to the basic OTS problem is made in [82]. This model is used to only switch lines that produces a profit greater than a certain threshold, thereby avoiding switching of unnecessary lines from the network. The model is modified by introducing a new term in the objective function given in (43). The term C^{prof} in the objective function is used to switch only those lines which produces a minimum specified profit. In other words, only those lines need to be switched from the system which provides profit greater than or equal to C^{prof}. The value of C^{prof} can be defined by the system operator according to the savings he is willing from switching one line from the network. The introduction of the new term in the objective function produces two changes in the optimization process: i) lines which lead to a small reduction in the operation cost should not be switched and ii) the computational complexity of the problem for large power system may be reduced significantly.

$$\min \sum_{g \in \Omega_G} c_g P_g + C^{prof} \sum_{ij \in \Omega_L} (1 - z_{ij}) \tag{43}$$

and equations (11)-(18).

F. OTS MODEL THAT AVOIDS ISLANDING

Switching lines in the network may result in islanding, which occurs when some buses become disconnected from other buses. This issue has been addressed in a modified OTS model proposed by [82], which prevents islanding during the switching process. This OTS model avoids unconnected partial solutions that can cause convergence issues in the solver. It does this by utilizing graph theory, which states that if a bus is linked to each of the other buses, the graph is connected. This concept is applied in the mathematical model of the OTS that avoids islanding, as shown in the equations (44)-(48).

Constraints (45)-(48) represent artificial flows in network which consist of artificial generation bus and all other buses will be demand bus, which will have a unity artificial power. A reference bus is used to provide this unity artificial demand to remaining buses of the system such that a path from the reference bus is always provided to other buses in the network, which makes the network connected.H_i represents the artificial power produced at bus i, h_{ij} denotes the artificial flow on line ij, and the cardinality of the buses is given by $|\Psi_b|$. The energy balance equation (45) is used to make sure the unity artificial demand is satisfied. Constraint (46) ensures that if at least one line of branch ij is connected, then the maximum artificial flow through this branch is limited to $|\Psi_b| - 1$. The artificial generation is only limited to the reference bus using the constraints (47) and (48). This model provides same generation cost obtained by traditional OTS model (DC-OPF).

$$\min \sum_{g \in \Omega_G} c_g P_g + C^{prof} \sum_{ij \in \Omega_L} (1 - z_{ij}) \tag{44}$$

$$\sum_{ij \in \Omega_L} h_{ij} - \sum_{ji \in \Omega_L} h_{ji} + H_i = 1 \forall i \in \Omega_N \tag{45}$$

$$\left|h_{ji}\right| \leq (|\Psi_b| - 1) z_{ij} \ \forall ij \in \Omega_L \tag{46}$$

$$H_i = 0 \forall i \in \Omega_b | i \neq \text{ref} \tag{47}$$

$$H_{ref} = |\Psi_b| \tag{48}$$

and equations (12)-(18).

G. BILEVEL MODEL FOR OTS

The number of lines which are required to be switched is limited by constraint (17). If value of $Z^{\max}$ is too small then effect of transmission switching is not apparent however, if value of $Z^{\max}$ is too large then it involves too many switching actions. To take this issue into consideration, authors in [83] introduces a bilevel OTS model which consists of an outer and inner optimization. Outer optimization aims to reduce the number of switching actions to make generation cost less or equal to the value specified by SO. The objective function of the inner optimization is to reduce system generation cost determined by outer optimization. This model is based on DCOPF, however, AC-OPF formulation is also possible with the expense of computational complexity. The objective function and constraints of the bilevel model are presented in equations (49)-(53).

$$\min \sum_{ij \in \Omega_L} \left| z_{ij} - z_{ij}^0 \right| \tag{49}$$

$$TC \leq TC_{desired} \tag{50}$$

$$TC = \min \sum_{g \in \Omega_G} c_g P_g \tag{51}$$

$$f_{ij} = z_{ij} B_{ij} \sum_{i \in \Omega_N} \Lambda_{ij} \delta_i \forall ij \tag{52}$$

$$\sum_{g \in \Omega_G} P_g + \sum_{ij \in \Omega_L} \Lambda_{ij} f_{ij} - \sum_{ji \in \Omega_L} \Lambda_{ij} f_{ji} = D_i \ \forall i \in \Omega_B \tag{53}$$

and equations (12)-(18).

Where z_{ij}^0 represents the initial status of line ij (open, z_{ij} =0; closed, z_{ij} =1); TC denotes the objective value of the inner optimization problem; $TC_{desired}$ denotes the desired system generation cost specified by system operators; Λ_{ij} denotes the element of the network incidence matrix. The decision variable of the outer optimization is the vector of z_{ij}. The outer optimization of the model is given by (49) and (50), while inner optimization is governed by equations (51)-(53). The line flows are restricted by the constraints of bus voltage angles and line operating status in (52). Power balance equation is given by the constraint (53). Rest of the constraints on generation and voltage limits are similar to the basic OTS model.

IV. OTS WITH OTHER FLEXIBILITY OPTIONS

World is moving towards renewable energy owing to the population growth, increasing demand, sustainable policies, and greenhouse effect. Indeed, the deployment of hydropower, solar, and wind power has been remarkable and it goes on increasing. However, the integration of such massive amount of RES into the grid imposes economical and technical challenges. The intermittent nature of these resources makes it difficult to predict and deliver fluctuating power, which adds

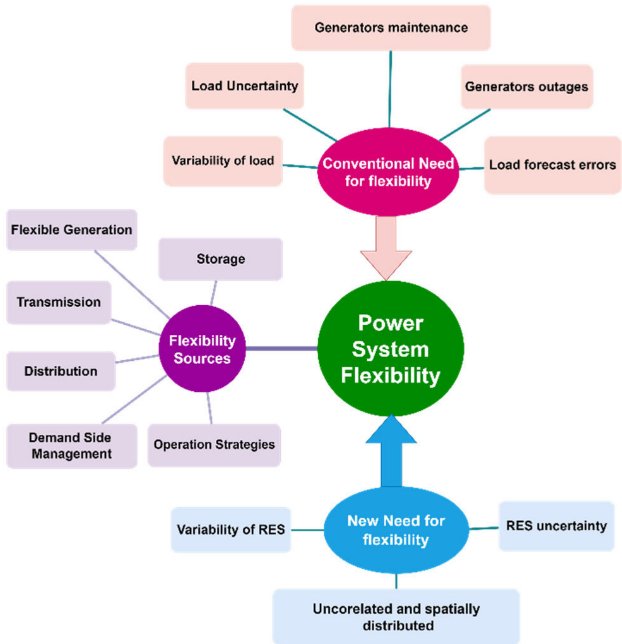

FIGURE 10. Need for flexibility in power system and sources to achieve such flexibility.

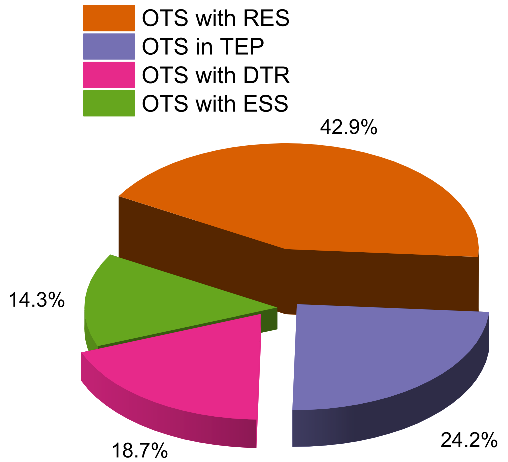

FIGURE 11. Articles classification based on the interaction of OTS with other flexibility options.

variability and uncertainty to the operation and planning of power system. These properties of RES make the power systems adequacy in terms of energy balance, voltage, and frequency regulation. Therefore, to successfully integrate large-scale RES into the grid, the operation and planning of the power system ought to be more flexible than what is today. Flexibility in power system can be provided through different approaches as shown in Figure 10. Integrating both conventional and flexible resources efficiently need new methods and control schemes, which can cope with the uncertainty in the power system operation and planning problem without compromising the reliability of power system.

Power system flexibility can be achieved from all the three sectors of the power system i.e., Generation, transmission, and distribution [84], [85]. From the generation side, the flexibility can be achieved by allotting more reserves from the conventional power plants to cope with the uncertainty posed by the RES. From the load side, demand side management and storage options can be deployed to make the system more flexible. However, such technologies are expensive at the current stage. The flexibility from transmission side can be achieved by changing the network topology using OTS, the benefits of which are explained in the earlier sections. This section focuses on the interaction of the OTS with such other flexibility options to make the system more reliable, efficient, and cost effective. Figure 11 demonstrates the classification of articles based on the interaction of OTS with other such technologies.

A. OTS WITH DYNAMIC THERMAL RATING

The thermal rating of transmission lines is an important property in the power dispatch problem, which needs to be carefully considered. Conventional way of assigning ratings to transmission lines is based on the worst case scenarios and is known as static thermal rating (STR) [86]. Environmental conditions, however, are not constant and continuously vary. So, the actual capacity of a line in real time can be different than STR. Dynamic thermal rating (DTR) enhances system flexibility by increasing the capacity of transmission lines and facilitates wind power integration [87], [88]. DTR system uses sensors to record real time weather parameters from which real-time ratings are determined. Different international organizations have developed models for the determination of the line ratings according to the DTR. All these models lead to almost the same result, the only difference is in their calculation method. These standards include the IEEE Standard 738 [89], CIGRE Technical Brochure 601 [90], and IEC TR61597 [91]. All these standards follow the first law of thermodynamics in the form of heat balance equation, a general formulation of which is given in Figure 12. For detailed understanding the reader is suggested to consult these standards for in-depth knowledge of the DTR calculation method.

Previous research has shown that using DTR, the transmission capacity can be increased from 15-50% and in some cases it could be up to 150% of the STR ratings [92]. In literature, DTR is utilized to increase transmission line capacity, which leads to improved RES integration [93], relieve network congestion [94], enhance system reliability [88], and can help postpone the need for building new transmission infrastructure [61]. The cost of DTR deployment is comparatively less (approx. 2% of the cost for building new line), which makes it a promising solution to add flexibility in the current system. Therefore, it is natural that OTS along with DTR, if implemented in coordination can help improve system flexibility as compared to their implementation alone.

OTS along with DTR has been studied in the literature from different perspectives ranging from power system dispatch problems to network expansion planning problems.

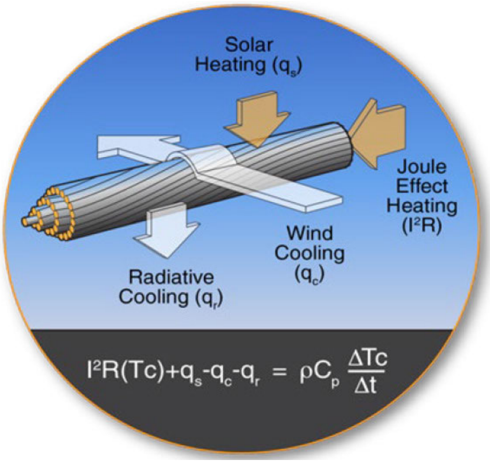

FIGURE 12. Heat balance equation demonstration for the DTR calculation [95].

OTS and DTR are simultaneously optimized in a two-stage SUC framework to study their impact on system performance. This model exploits changing network topology (OTS) along with real time thermal ratings of lines (DTR) to observe their impact on total system cost, utilization of wind power, and network congestion [59]. The authors showed that co-optimization of OTS and DTR can considerably reduce total system dispatch cost by up to 23%, reduce congestion by around 44%, and can utilize RES up to 97%. The congestion mitigation property of the OTS and DTR are studied in a day-ahead model in [96], where the authors modeled OTS and DTR simultaneously in a network constrained UC problem to show that the combined interaction of OTS and DTR can help reduce wind power curtailment and system cost. To tackle the uncertainty linked with the RES, a stochastic formulation is presented in [4] to determine the optimal candidate lines for transmission switching and at the same time decide which line should adopt real-time ratings using DTR. Results indicate that deploying network reconfiguration and DTR simultaneously can have a significant impact on reducing system cost and more wind power penetration.

A stochastic framework is used to combine OTS with flexible line ratings, which will determine the lines to adopt DTR ratings and lines for switching operations in the recourse actions. It is showed that incorporating OTS and flexible DTR ratings help improve the first stage decisions in the optimization problem. The test results on the IEEE 118-bus system and Central European system showed a cost reduction of 19% and 4.5% respectively. A more flexible model incorporating OTS with DTR is presented in [97], where the authors instead of using real time ratings for DTR, assumed a predetermined increased capacity i.e., 10% of the normal ratings. The combination of OTS with DTR in reducing carbon dioxide emissions is presented in [98]. In addition to the constraints on the system dispatch and transmission constraints, emission reduction constraints are included in the MILP. Numerical results proved effective in reducing CO_2 emissions.

To maintain system reliability, the literature also showed that only a small fraction of the total transmission lines needs to switch and adopt real-time ratings. A congestion management method is proposed in [99] where the authors used a multi-objective probabilistic problem using transmission switching and deploying real-time ratings. The results conducted on the RTS-96 proved that implementing DTR with OTS can reduce system cost by 6.78% as compared to when SLR ratings are used. The enforcement of OTS along with DTR is shown to effective in improving system reliability [100]. Transmission lines cover a long distance and weather parameters along the route may not be the same, which could affect the calculation of DTR accurately. This issue is addressed in [101] by proposing a multi-regional network constrained UC model utilizing both OTS and DTR. The multi-regional model is shown to be effective in reducing system cost and accommodating more wind power.

The combination of OTS with DTR is also studied in the power system network expansion planning problems. The main objective in including these short-term problems in the long-term problem network expansion is to exploit the operational flexibility of these two technologies, which could help in efficient utilization of the transmission infrastructure and could help in postpone/reduce additional investment in these assets. A co-optimized expansion planning model is proposed in [61] to add new generating units and transmission lines in the current network for the next 20 years. The model is used to decide the size, number, and location of the generating plants and lines for the said planning horizon. OTS and DTR are included in the operational constraints of the model to add flexibility to the network.

B. OTS WITH ENERGY STORAGE SYSTEMS

Energy storage systems (ESS) offer a more intelligent solution for mitigating power output fluctuations, maintaining frequency, providing voltage stability, and improving the quality of power supply [102]. Typically, an ESS consists of four components: a storage medium for converting electrical energy into a specific form, a charging unit that allows the flow of energy from the electrical system to the storage medium, a discharging unit that releases the stored energy for various applications, and a control system that manages the entire charging and discharging processes. With the rapid advancement in technology, various types of ESS technologies exist, which are further classified based on the storage medium, response time, and their functions. The most widely used classification is based on the stored energy, which can be in the form of chemical, electrical, mechanical, thermal, or electrochemical. The battery energy storage system (BESS) is commonly used due to its quick response time, geographical independence, and adjustable size. BESS facilitates the integration of renewable energy from wind farms or photovoltaics into the power system, thus enhancing the reliability and flexibility of the system [103].

The integration of renewable energy sources (RES) has highlighted the importance of energy storage systems (ESS), which can help smooth the output power of RES or time-shift generation. However, network congestion often leads to a significant amount of wind power curtailment. To efficiently utilize the benefits of optimal transmission switching (OTS) for congestion mitigation and ESS for storing excess generated wind power, a co-optimized model is proposed in [104]. The authors suggest that implementing OTS effectively can increase ESS capability, leading to less wind power curtailment. In [105], the uncertainty associated with RES is addressed in a security-constrained unit commitment (UC) problem using the flexibility offered by OTS and energy storage. A robust optimization problem based on the information gap decision theory is used and solved using the benders decomposition technique. The efficacy of the proposed model in managing uncertainties in large-scale wind power integration is demonstrated using two test systems: IEEE 6-bus and 118-bus. However, the benefits of ESS may not always be fully utilized due to limited transmission capacity, and network congestion hinders its full utilization. To address this issue, [106] proposes a stochastic security-constrained unit commitment (SCUC) problem in a day-ahead framework that uses OTS as a corrective action for line flexibility to enhance ESS utilization. Results show that network reconfiguration using OTS can not only reduce system costs but also enhance ESS utilization for better impact in both normal and post-contingency scenarios.

To increase the realism of the model, rather than using the traditional DC-OPF based problem, the authors in [107] proposed an intelligent parallel scheduling AC-OPF based OTS problem, combined with batteries, to alleviate network congestion and reduce operational costs. To solve the non-linear problem, they proposed a two-stage optimization approach where the master and sub-problems are created and solved in parallel. In [108], the authors also proposed a multi-stage problem that combines OTS with battery energy storage systems in an AC-OPF based formulation to minimize system costs. During contingencies, it's important to reconfigure the network to minimize the impact of outages in the distribution network such as power losses and network overloads. The contingency assessment of a combined ESS and RES integration is proposed in a stochastic programming model to determine the optimal network topology by switching the optimal set of lines during contingencies [109], to demonstrate that wind penetration with ESS can improve system reliability. Another concept of mobile BESS, which involves transporting battery energy storage systems using OTS, is presented in an NCUC model [110]. The model was tested to evaluate the impact of ESS transportation followed by network reconfiguration and compared with the traditional static BESS model. Results showed that the model not only reduces system operational costs but also enhances grid flexibility by reducing wind curtailment.

The impact of OTS in energy storage investments is also analyzed by [111]. A two-stage stochastic model is presented in which the objective is to find the optimal location and size of the ESS units subject to constraints on the wind curtailment and loadshedding. OTS is incorporated in the operational constraints of the model and it is found that including these constraints the model can reduce the investment cost by 17% and reduce the investment in ESS capacity by 50%. Another work that also considers OTS in the investment decision model of ESS size and location is given in [112]. The authors consider the expansion of generation units, lines, and bulk ESS units in their model subject to constraints on the renewable portfolio standards (RPS) i.e., a limit on the maximum amount of energy served from RES. The stochastic MILP problem also incorporates OTS in the second stage of the model as operational constraints. The authors observed that up to \$180M/yr can be saved in cost by co-optimizing OTS, ESS and RPS requirements. Major savings is achieved by investment deferrals while only a small savings in the operational cost. Another important result that is presented by the authors is that if these investments are made sequentially instead of co-optimizing all these assets will result in \$3M/yr more than the co-optimized case.

To maximum utilize the transmission infrastructure, authors in [113] proposed a network topology optimization-based model which also incorporate ESS and DTR simultaneously. Battery energy storage is deployed to time-shift RES power and reduce wind curtailment. OTS is used to relieve network congestion while DTR is implemented to increase the transmission capacity thus allowing more wind power to be penetrated the system. It is validated that the benefits obtained from coordinating these three technologies is more than any other fewer combination of them or deploying each method in isolation. Table 2 demonstrates a detailed breakdown and brief explanation of the articles containing the incorporation of OTS along with other flexibility options.

C. OTS AND RES INTEGRATION

Renewable energy sources such as wind, solar, and hydro power are rapidly growing technologies that contribute significantly to the world's electricity portfolio. However, their uncertain characteristics pose economic and technical challenges for system operators. A large amount of renewable energy is curtailed to maintain system security, while ample reserves must be available to cover the uncertainty of RES generation in real time. To ensure safe and reliable system operation, these resources must be distributed carefully and efficiently utilizing existing infrastructure. The flexibility offered by OTS in reconfiguring network topology and enabling a more feasible dispatch solution can help optimize the use of these resources. Extensive research has been conducted in the literature [114], [115], [116], [117], [118] to address the challenges posed by wind uncertainties using OTS.

A dynamic dispatch model incorporating OTS is proposed by [119] to reduce system operation cost as well as improve wind power penetration. To accommodate more wind power into the network, a high performance computing framework using a parallel implementation of stochastic UC and Lagrangian relaxion is given in [120]. Another parallel

TABLE 2. Summary of articles containing combination of OTS with other flexibility options.

Ref	Flexibility Options			Model			Findings
	DTR	ESS	RES	Nature	OPF	Method	
[59]	■		■	Stochastic	DC	MILP	The two-stage SUC model integrating OTS and DTR reduced system cost by 22.28%, accommodate more wind power and relieved network congestion.
[96]	■		■	Deterministic	DC	MILP	The coordinated NCUC NTO based model with DTR is shown to be effective in reducing system cost and wind power curtailment.
[4]	■		■	Stochastic	DC	MILP	The SUC model co-optimizing OTS and DTR exploited the inherent network flexibility by reducing system cost and wind power curtailment.
[99]	■		■	Stochastic	AC	MINLP	The probabilistic multi-objective congestion management utilizing both OTS and DTR is proved to perform better than STR by 6.78%.
[97]	■		■	Stochastic	DC	MILP	The SUC model utilizing inherent flexibility of lines based on DTR and OTS proved to be cost effective without degrading system reliability.
[98]	■		■	Deterministic	DC	MILP	The model is used to reduce CO_2 emissions by jointly utilizing OTS and DTR in an investment decision framework.
[61]	■			Deterministic	DC	MILP	The joint optimization of DTR and OTS is applied to minimize investment cost of building new lines and generating units.
[100]	■		■	Deterministic	DC	Monte Carlo Simulation	The reliability assessment model utilizing both OTS and DTR is shown to improve the system reliability along with cost reduction.
[101]	■		■	Deterministic	DC	MILP	The NCUC model co-optimizing OTS and DTR with multi-area information reduced cost and wind curtailment.
[107]		■	■	Deterministic	AC	MINLP	The intelligent parallel scheduling method combining OTS and BSS with ac constraints proved to be effective in cost reduction and congestion management.
[108]		■	■	Stochastic	AC	Approximate method	The Stochastic AC-OPF problem based on OTS and ESS provided more savings in operational cost.
[104]		■	■	Deterministic	DC	MILP	The co-optimized OTS-ESS model is used to enhance the performance of ESS to reduce renewable curtailment.
[105]		■	■	Stochastic	DC	IGDT	The information gap decision theory based robust optimization model is used to accommodate large-scale wind power into the network.
[106]		■	■	Stochastic	DC	MILP	The incorporation of OTS as a preventive and corrective action along with ESS is presented for reducing total system cost, RES curtailment, and improved ESS utilization.
[109]		■	■	Stochastic	AC	MILP	The two-stage stochastic model developed for contingency assessment by deploying OTS and ESS proved to improve system reliability, reduce power losses, and wind curtailment.
[111]		■	■	Stochastic	DC	MILP	The model decreased the system cost by 17% and capacity of ESS by 50%
[112]		■	■	Stochastic	DC	MILP	The Co-optimized model with RPS targets, OTS, and ESS can save up to $180M per year
[110]		■	■	Deterministic	DC	MILP	The NCUC model incorporating OTS and transportable ESS provided more grid flexibility, reduce system cost, and mitigate network congestion
[113]	■	■	■	Deterministic	DC	MILP	The combined model consisting of OTS, DTR, and ESS resulted in lower cost, less wind and load curtailment as compared to any other combination of these technologies.

implementation of OTS along with ESS in an intelligent scheduling method using AC-OPF to reduce network congestion for power system with large RES integration is presented in [107]. The MINLP is solved using a two-stage optimization method. OTS is included in a SCUC model to manage the RES uncertainty while taking into account line/unit failures in [121]. The authors in [35] presented a stochastic model using OTS to mobilize grid flexibility for power system with large share of RES integration. Network topology reconfiguration is used in [122] with focus on maximizing RES injection. The MINLP problem is solved using binary particle swarm optimization (PSO) algorithm. The optimal topology obtained from OTS is used to assess its impact on high shares of renewables as well as grid flexibility for reducing total system cost is proposed in [123].

Renewable energy sources, such as wind and solar power, are often located far from areas of high electricity demand, which can cause network congestion due to limited transmission capacity. Poorly scheduled generation may result in high curtailments of wind power, making it difficult to integrate renewable energy into the grid. To address this issue, researchers have proposed several approaches using OTS. For instance, a DC-OPF based formulation in [124] enforces line switching to reduce network congestion and improve wind power integration. In [125], a linearized AC-OPF formulation is used with OTS to consider the impact of network losses and reactive power consideration. The linearized model is solved using a benders decomposition technique. In a day-ahead scheduling, [126] suggests using OTS as a corrective action to reduce wind curtailments and network congestion, leading to a more economical schedule and less emissions. OTS can also be used in post-contingency situations to reduce network congestion and wind power curtailments [127]. A two-stage stochastic security-constrained unit commitment model using OTS is proposed in [128] to facilitate wind power utilization. The role of OTS in accommodating renewable energy and considering deep peak regulation is presented in [129]. In [130], the steady-state security region model using OTS is proposed and solved by a decomposition approach. Additionally, [131] discusses the impact of OTS on a hybrid wind/PV generation, where the AC-OPF model is solved using a combination of a genetic algorithm and a non-linear primal-dual interior point algorithm. Lastly, [132] proposes a stochastic OTS model that considers the uncertainty associated with both wind and PV to minimize grid vulnerability and reduce generation cost. Table 3 summarizes the articles utilizing OTS for improved wind power integration.

D. OTS AND TRANSMISSION EXPANSION PLANNING

In the coming years, significant changes are expected in the power sector as renewable energy resources become more prevalent in the power system network. This shift will likely lead to the shutdown of some conventional power plants and the establishment of new market structures to balance flexible demand requirements. As a result, the flow in transmission lines will be altered, and there will be a need to increase transmission line capacity. The primary objective of transmission expansion planning (TEP) is to determine the optimal plan for expanding the existing infrastructure in the network to enable more feasible system operation at the lowest possible cost. TEP involves identifying the timing, location, and number of new circuits to be installed in the network.

The literature has extensively explored TEP from different angles [140], with most studies proposing new planning models or optimization methods to address the complex TEP problem. Optimization methods can be broadly classified into three groups: exact, approximate, and mathematical programming. Exact methods rely on branch-and-bound, dynamic programming, game theory, and benders decomposition algorithms. Approximate methods, on the other hand, employ heuristic and metaheuristic techniques such as genetic algorithms, ant colony optimization, differential evolution, fuzzy logic, and artificial neural networks. An alternative approach is to combine mathematical formulations with optimization procedures, which formulate the TEN as a mathematical optimization problem to determine the optimal location and number of new transmission lines while minimizing cost. While ideally, TEP should use an AC-OPF model, using the AC equations leads to a MINLP model that can be difficult to solve and may not guarantee the optimized solution. Hence, linearized and relaxed models that utilize the active power and phase angle of the system are often used to solve the TEP problem [141].

Transmission lines are typically viewed as fixed assets and the possibility of switching some lines is often disregarded because all lines are assumed to be necessary for proper system operation. However, there is a possibility that some of the existing lines can lead to network congestion that may be not eliminated by simply expanding the network. This arise the need that base system topology needs to be modified while the system is being upgraded. Besides, even candidate transmission lines may result in congestion, which also need modification of the network topology in each scenario. This will lead to decrease in investment costs significantly, allowing greater efficiency. It should be noted that the decrease in investment cost by integrating transmission switching does not mean that the existing network was not optimally planned. This can be explained by the fact that the generation and demand of the base year may be different from the one that is considered in the expansion planning problem. Also, the redundancy in the current network is incorporated to maintain the reliability of the system in case of contingencies. While TEP is a long-term problem that is solved over an extended duration, the problem of OTS is a short-term problem related to operating conditions. The challenge lies in how to link these two problems to assess the impact of OTS on the expansion plan. A general formulation for incorporating OTS into a TEP problem is presented in equations (54)-(66).

$$\min \sum_{ij\in\Omega_L} c_{ij}\omega_{ij} \tag{54}$$

$$\sum_{g\in\Omega_G} P_{g,t} - \sum_{ij}\left(f^0_{ij,t} + f^1_{ij,t}\right) = D_{i,t} - L_{i,t} \forall i \in \Omega_B \tag{55}$$

$$\sum_{ij\in\Omega_L^+} \omega_{ij} \leq \Gamma^{\max} \forall ij \in \Omega_L^+ \tag{56}$$

TABLE 3. Summary of articles incorporating OTS for improved RES integration.

Ref	Nature	WC	LS	CM	N-1	OPF	Method	Contribution
[115]	Stochastic		■	■	■	DC	MILP	A two-stage stochastic model is proposed to model network topology control using OTS for power system with large RES integration.
[128]	Stochastic	■	■	■	■	DC	Benders Decomposition	The stochastic SCUC model incorporating OTS is used to facilitate wind power integration by reducing the WC and LS costs.
[35]	Stochastic	■	■	■		DC	MILP	A two-stage SUC model based on OTS is used to mobilize grid flexibility by efficiently utilizing renewable energy resources
[107]	Deterministic			■		AC	MINLP	Intelligent parallel scheduling method utilizing OTS and BESS is proposed to alleviate transmission congestion and operational cost
[120]	Stochastic	■	■			DC	Lagrange Relaxation	Proposed parallel implementation of Lagrange relaxation method for solving SUC problem considering uncertainty in renewable energy and failures of transmission lines and generators
[112]	Stochastic	■	■			DC	MILP	Co-optimization of network expansion considering both generation and transmission investments along with ESS investments to assess the economic interaction between planning decisions for achieving high wind integration
[133]	Deterministic	■	■			DC	MILP	Transmission switching model is proposed for minimizing the cost of conventional units and integrating a highly amount of wind power.
[4]	Stochastic	■	■	■		DC	MILP	To analyze the combined impact of OTS and DTR on wind power utilization and network congestion, a two-stage SUC problem is presented.
[2]	Stochastic	■	■		■	DC	Decomposition Algorithm	An investment model is proposed incorporating ESS, wind farm installation, and transmission network for promoting investments in RES and alleviating network congestion.
[119]	Deterministic	■	■			DC	MILP	Proposed dynamic economic dispatch utilizing OTS for wind integrated power systems to improve wind power penetration and reduce system operating costs
[104]	Deterministic	■		■		DC	MILP	OTS is used to optimize the optimal size and location of ESS units in a UC framework for mitigating network congestion and enhancing system efficiency.
[131]	Deterministic			■		AC	GA	AN AC-OPF based model utilizing OTS is presented to improve voltage security and power system flexibility for improved penetration of RES.
[106]	Stochastic			■		DC	Big-M	OTS is introduced as means of network reconfiguration for preventive and corrective actions to add transmission flexibility in a day-ahead formulation with large scale renewables.
[121]	Stochastic		■			AC	MILP	A stochastic security constrained model is used to utilize OTS in order to manage the wind uncertainty and failures of equipment.
[134]	Stochastic		■			DC	Lagrange relaxation method	A decision-making approach working in parallel with OTS in a day-ahead scheduling framework is presented for loadshedding reduction and improving wind power utilization.
[59]	Stochastic	■	■	■		DC	MILP	Co-optimized model of DTR and OTS is deployed to mitigate congestion and increase wind generation in the network.
[125]	Stochastic		■			AC	MILP	Efficient power flow model is presented by implementing stochastic security constrained unit commitment with transmission switching.
[124]	Stochastic		■	■		DC	MILP	Transmission Switching is deployed with mixed integer programs to increase capacity of transmission networks and to reduce operational cost.
[122]	Deterministic			■		AC	PSO	In order to maximize renewable energy integration, optimal topological configurations in transmission networks are considered.

TABLE 3. ***(Continued.)*** **Summary of articles incorporating OTS for improved RES integration.**

[127]	Stochastic			■	■	DC	Big-M	Stochastic optimal power flow is presented to relieve network congestion and increase renewable injection.
[132]	Stochastic		■		■	AC	MILP	Considered generation from renewable sources by developing a stochastic optimal transmission switching model.
[114]	Stochastic			■		AC	Point estimation method (PEM)	In order to deal with uncertainties of renewable energy, OTS model is presented with point estimation method. A novel method using point estimation method (PEM) is proposed for solving the stochastic optimization problem.
[135]	Deterministic	■	■		■	DC	Fast heuristics, decomposition	Implementation of optimal topology control is presented due to increase renewable sources of energy in the conventional grid.
[126]	Stochastic			■	■	DC	Big-M	Modeled stochastic N-1 security-constrained unit-commitment with corrective network reconfiguration for reducing RE integrations and minimizing network congestion
[130]	Stochastic			■		DC	MILP	Proposed modeling of robust novel OTS that includes system robust domain (SRD) for describing uncertainty of nodal power injections
[136]	Stochastic	■	■			DC	Decomposition algorithm and MILP	A combined ESS and transmission expansion model along with OTS is proposed to reduce investment cost as well as operational costs while reducing wind power curtailments and loadshedding.
[137]	Deterministic			■	■	DC	MILP	Analyzed the effect of active transmission line switching operation by utilizing TCSC and BESS for resolving stability issues, reducing network congestion which increases integration of RE
[116]	Stochastic		■			DC	Big-M	Proposed a tractable linear decision rule (LDR) based approximation solution for reducing uncertain variables and utilize real time optimal transmission switching for finding generation dispatch
[3]	Stochastic	■	■			DC	Benders Decomposition	Proposed a stochastic model to increase the grid flexibility by combining OTS, demand response, and energy storage to deal with wind power uncertainty and failures of equipment
[138]	Stochastic	■	■		■	DC	MILP	A two-stage stochastic model is proposed along with OTS to determine the risk level of the load shed
[139]	Deterministic	■		■	■	AC	Genetic Algorithm	A congestion management method with OTS is proposed in a security constrained AC-OPF based formulation and is solved using genetic algorithm for improved RES penetration.
[105]	Stochastic	■				DC	Benders Decomposition	A security constrained SUC model incorporating OTS and ESS are used for managing the uncertainty associated with wind power. The robust optimization model is solved using information gap decision theory.

*WC=Wind Curtailment, LS=Load-shedding, CM=Congestion Management

$$\sum_{ij\in\Omega_L^+} c_{ij}\omega_{ij} \leq C_{ij}^{\max} \forall ij \in \Omega_L^+ \quad (57)$$

$$P_{-g} \leq P_{g,t} \leq \bar{P}_g \forall g, t \quad (58)$$

$$f_{ij,t}^0 - B_{ij}(\delta_{i,t}^0 - \delta_{j,t}^0) + M(1 - z_{ij,t}) \geq 0 \forall ij \in \Omega_L, t \quad (59)$$

$$f_{ij,t}^0 - B_{ij}(\delta_{i,t}^0 - \delta_{j,t}^0) - M(1 - z_{ij,t}) \leq 0 \forall ij \in \Omega_L, t \quad (60)$$

$$f_{-ij} z_{ij} \leq f_{ij,t}^0 \leq \bar{f}_{ij} z_{ij} \forall ij \in \Omega_L, t \quad (61)$$

$$\left| f_{ij,t}^1 - B_{ij}(\delta_{i,t}^1 - \delta_{j,t}^1) \right| \leq M(1 - \omega_{ij,t}) \forall ij \in \Omega_L^+, t \quad (62)$$

$$\left| f_{ij,t}^1 \right| \leq \bar{f}_{ij}\omega_{ij} \forall ij \in \Omega_L^+, t \quad (63)$$

$$\delta \leq \delta_i \leq \bar{\delta} \forall i \in \Omega_B \quad (64)$$

$$\sum_{ij} \left(1 - z_{ij,t}\right) \leq Z^{\max} \; \forall ij \in \Omega_L, t \quad (65)$$

$$z_{ij} \in \{0, 1\}, \omega_{ij} \in \{0, 1\} \quad (66)$$

The objective function of the TEP is to minimize total investment cost of building new lines into the network satisfying both planning and operational constraints. Energy balance is guaranteed in (55) by taking both the existing and candidate lines into account. The number of maximum candidate lines that can be built is imposed by (56) while the capital budget constraint is given by (57). The power from generating units is limited to min/max amounts by constraint (58). Network flow constraints for the existing lines and candidate lines along with the option of switching existing lines is enforced in constraints (59)-(63). Voltage angle limits is given by (64) and the maximum number of switchable lines is restricted by constraint (65). The solution of the TEP planning problem will identify the installation of candidate lines in the planning horizon, and identification of lines to be switched off from the network in the operating scenarios.

While considering OTS in TEP, the role of uncertain outages can be more prominent. In order to fully utilize the network, TS change the topology by switching one or more lines from the network, which enhances system utilization, prevents overloading transmission line, and decrease total system cost [63]. The reliability and investment plan of the power system can be affected during the contingency states by changing the network topology. For power system having flexible generators, when a line or generating unit fails, corrective actions can be taken by changing the network topology using OTS and flexible generators. This will help in avoiding over investment (building additional generating units or lines) by fully utilizing the existing infrastructure. This issue is addressed in [70], where the authors proposed a contingency based TS concept in a two-stage stochastic formulation. A scenario-based reduction technique is proposed which utilizes a filtering technique is used to reduce the computational burden of solving the problem. The model is tested on three different networks including the IEEE reliability test system, IEEE 11-bus System, and a 380-KV Turkish transmission network. The authors showed that altering network topology using OTS can change the expansion plans significantly and can reduce the system cost up to 10.13%. Table 4 presents summary of the publications considering the problem of OTS in the expansion planning problem for adding flexibility into the grid. The optimal placement of phaser measurement units (PMS) using OTS in a two-stage process is presented in [142], wherein the first stage the PMU are installed to check the observability while the second stage ensures the compliance with N-1 security criteria.

To add flexibility in the generation and transmission expansion planning, [72] introduced OTS in the NEP problem. The proposed model is decomposed into a master and two subproblems. The investment plan is executed in the master problem to find optimal candidate units and lines for the expansion horizon. The sub-problems then use this investment plan and apply OTS to mitigate any violations in transmission flows and execute optimal dispatch of generation units. OTS along with network repowering is introduced in [65] as a non-conventional candidate solutions in the TEP problem. The model is linearized into a MILP so that commercial solvers can be used to solve the problem. The inclusion of network reconfiguration and repowering allows for a more wider search space and can find better solution than the conventional candidates only. Garver, IEEE 24-Bus and a reduced Columbian test systems are utilized to demonstrate that the non-conventional solution can reduce the overall cost of investment in the TEP problem significantly.

To solve the stochastic TEP problem for large power system, [66] presented a decomposition method that involves transmission switching. The authors proposed a Dantzig-Wolfe reformulation of the problem which is solved using a column-generation technique. Computational performance of the model is tested in the IEEE 73-Bus and 118-Bus systems. The authors in [71] showed that the incorporation of OTS in TEP is an NP-hard problem, and switching some lines from the network may lead to a more efficient expansion planning. The emphasis is on finding the optimal value of the big-M formulation. It is showed that minimum value for big-M can be computed by finding the shortest and longest route between two buses. The authors in [61] presented a co-optimized network expansion planning model to simultaneously incorporate OTS and dynamic line rating to exploit the transmission network inherent flexibility. The model is formulated as a MILP and solved using CPLEX. In addition to the investment plan, the model determine which line should be switched off from the network and which line should adapt real-time ratings in the operation stage of the problem. Their results demonstrate that the practice of DLR and OTS in the NEP is complementary and can reduce the investment cost up to 20%. The modification of network topology using OTS in an expansion planning is also studied by [64] where the switching of lines is considered in the operation stage of the problem. Only those lines are switched which can degrade the system performance. This helps in relieving the network congestion thereby enhancing existing network performance along with the candidate lines and results in a lower investment cost. The model is tested on the IEEE reliability test system and IEEE 46-Bus networks.

Almost all countries have set renewable portfolio standards target for the next 30 years. In this context the authors in [124] considers the case of Denmark and propose a TEP problem to integrate 50% of the RES in the system, while reducing the investment cost for generating units and lines. A two-stage stochastic formulation is presented using Dantzig-Wolfe reformulation, which is solved using column-generation approach. OTS is utilized in the problem to relieve network congestion caused by the Kirchhoff's voltage law. It is showed that the incorporation of OTS in the TEP problem results in better utilization of the system with large-scale wind power integration. The results also demonstrate that optimal investment plan is affected by the OTS approach, which can help reduce the wind curtailment. The increased penetration of RES into the grid imposes further challenges to the TEP problem. To cater the intermittence and randomness of the RES, the authors in [143] proposed a novel combines GEP and TEP problem with mixed integer second order cone programming framework. Their results demonstrate that the proposed mode not only accommodate wind power efficiently but also reduce the total investment cost.

Generally, wind power and load demands have negative correlation i.e., the production of wind power is high when the load demand is low and vice versa. This results in curtailment of the extra generated wind power. A proficient way

TABLE 4. Summary of the articles combining the problem of OTS in the expansion planning.

Ref	GEP	TEP	OPF	RES	Nature	Model	N-1	Test System
[70]	■	■	DC		Stochastic	Scenario reduction based	■	24-Bus, 118-Bus, Turkish System
[72]	■	■	DC		Deterministic	Benders Decomposition	■	6-Bus, 118-Bus, 1168-Bus
[65]		■	DC		Deterministic	MILP		Garver, 24-Bus, Columbian System
[143]	■	■	AC	■	Stochastic	Second Order Cone Programming		6-Bus, 24-Bus
[66]		■	DC		Stochastic	Dantzig-Wolfe Decomposition		73-Bus, 118-Bus
[124]		■	DC	■	Stochastic	Dantzig-Wolfe Decomposition		6-Bus, 118-Bus, Danish Network
[136]		■	DC	■	Stochastic	Robust Optimization		24-Bus, 73-Bus
[71]		■	DC		Deterministic	Big-M Formulation	■	Garver, 24-Bus, Brazil Network
[64]		■	DC		Deterministic	MILP		24-Bus, Brazilian System
[144]		■	DC	■	Deterministic	Benders Decomposition	■	30-Bus
[61]	■	■	DC		Deterministic	MILP		24-Bus, 118-Bus
[2]		■	DC	■	Stochastic	Analytical Target Cascading		48-Bus
[68]		■	DC		Deterministic	Benders Decomposition	■	Garver, 118-Bus
[145]		■	DC	■	Stochastic	Reduced Disjunctive Model		24-Bus

to mitigate wind power curtailment is to utilize utility scale energy storage systems (ESS). The synergistic impact of OTS in combined ESS and TEP expansion is studied in [136], where the authors proposed a two-stage stochastic min-max-min problem to characterize the variability related to wind power production and load demands. A decomposition algorithm is presented to solve the min-max-min problem. A co-planning model of transmission, energy storage and wind farm is proposed in [2]. To facilitate wind power integration into the network, OTS and unit commitment model are also integrated into the model. A decomposition algorithm using analytical target cascading (ATC) approach is used to solve the problem. The results show that in the co-planning model OTS helps in congestion mitigation, UC improves conventional generators flexibility, and ESS assist in satisfying RPS targets. The impact of incorporating OTS in the expansion planning considering contingencies along with renewables uncertainty is studied in [144]. The authors presented a three level N-1 contingency compliant expansion planning problem, which is solved using benders decomposition. Their work demonstrated that the optimal plan is affected by the uncertainty sets, OTS can help reduce overall cost, and the decomposition method can solve the problem efficiently.

V. OTS AND SYSTEM RELIABILITY

There is often a misconception that taking a line out of service may result in degrading reliability of power system. The concept of OTS does not ignore the importance of system reliability standards and that the co-optimization of generation dispatch along with network topology is not done at the expense of system reliability [36]. In fact, there is no guarantee that switching a line out of service may lead to a less reliable system because network topology is not the sole factor which affects system reliability but it also depends on the load and optimal generation dispatch solutions. Power system is a complex network and taking one element out of it one cannot judge that the said topology is best regarding reliability for every possible operational scenario that may exist. On the contrary, it is also possible that switching lines out of service can improve the system reliability under certain conditions. System reliability depends on the flexibility of the load, generation dispatch, ramping capabilities of generators, available power capacity, and network topology etc. In practice all these conditions are constantly changing and there is no guarantee that a single network topology is more reliable for all the possible conditions [13].

Proper system reliability is determined in two stages: micro and macro stages. The engineering feasibility viewpoint is

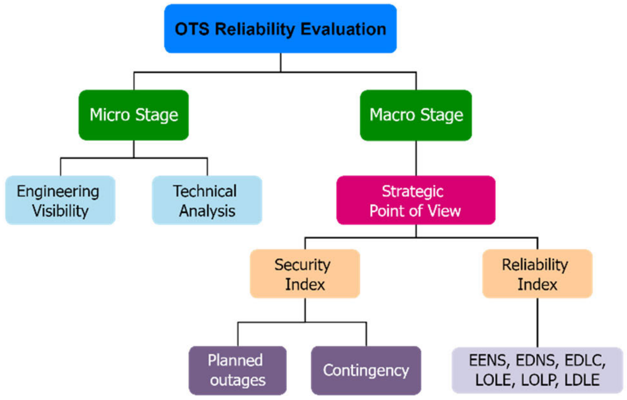

FIGURE 13. **OTS evaluation in relation to security and reliability constraints.**

studied in micro stage while the macro stage studies the strategic point of view. Usually, micro stage is linked to the technical analysis of the system, whereas the macro stage includes the reliability analysis, security, and adequacy as is shown in Figure 13. The security and reliability of the network under consideration can be included in the problem formulation as part of the objective function or as constraints. Commonly used reliability indices are expected energy not served (EENS), expected demand not supplied (EDNS), loss of load probability (LOLP), loss of load expectation (LOLE), load level expectation (LDLE), and expected duration of load curtailment (EDLC) etc. In the problem formulation, the security aspect considers the planned outages and contingencies as part of the performance requirements.

Although OTS have economic benefits, current system states might change by switching off some lines with different reliability levels. In the literature, reliability of OTS is studied from two broader perspectives i.e., N-1 criteria and reliability indicators [146], [147], [148], [149], [150], [151], [152]. The N-1 contingency analysis is carried out to assess whether a system is capable of withstanding failure of every single element in the network or not. This approach mostly neglects the probability of failure of different components and does not take into consideration the possible multiple contingencies, which might result in cascaded contingencies leading to blackout [153]. The more general probabilistic reliability analysis is the use of reliability indices which are evaluated for different OTS solutions to provide service operator with the support information that is needed for the implementation of OTS actions. These analyses help the operator to decide whether the optimized network topology can be adopted and to decide which amongst the different possible switching solutions can be implemented, which will help in maintaining a balance between the technical system reliability and economic savings obtained from the OTS. The general framework of the OTS reliability evaluation using probabilistic method is given in Figure 14 and the flowchart is explained using the Algorithm 1.

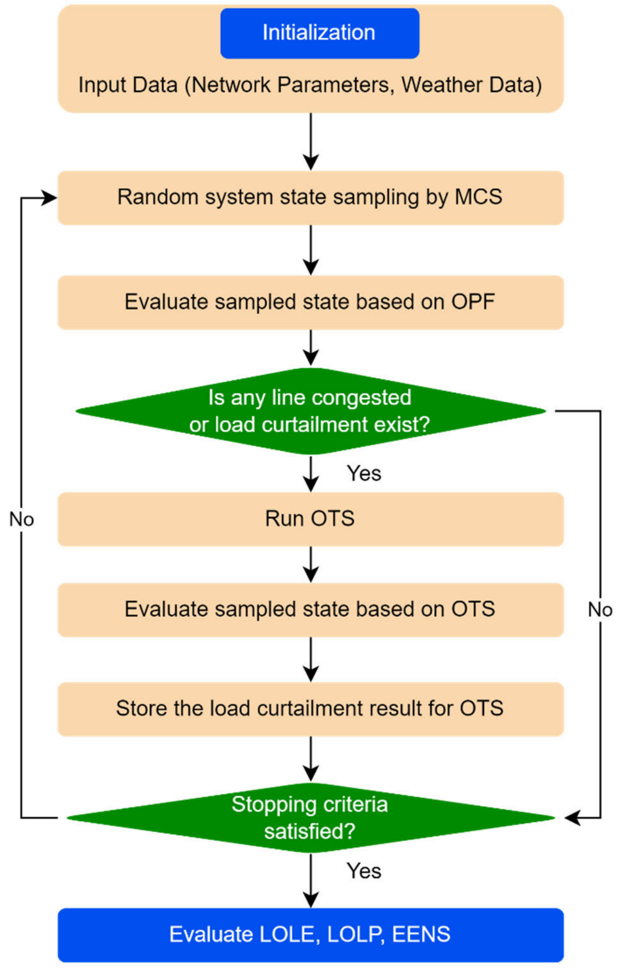

FIGURE 14. **Flowchart for reliability evaluation of OTS.**

The authors in [63] demonstrated that including OTS in the system dispatch problem can still satisfy the N-1 criteria while switching off some lines from the network. The savings obtained from the N-1 DC-OPF problem using OTS is about 15%. An important point in the results is that the percent saving obtained from the N-1 DC-OPF is more than that in the standard DC-OPF formulation. The co-optimization of generation unit commitment and OTS with contingency analysis is studied in [62] where it is shown that including OTS can change the optimal generator schedule. The authors in [154] studied OTS in both pre and post-contingency in a SCUC model in the context of electricity market applications and showed that power imbalance and system cost can be reduced with the proposed model. The impact of OTS in terms of voltage angles and loadability is carried out in [155] where the authors modeled OTS in a DC-OPF framework along with contingency requirements. The authors concluded that OTS is beneficial both in terms of voltage angles and loadability even in case of contingencies. Security-constrained OTS problem considering network connectedness is addressed in [156], where the authors propose two criteria for maintain the network connectedness in reasonable amount of time. To further analyze the impact of OTS in cascaded events, the authors in [22] presented an N-1-1 reliability model in a day-ahead market structure to use OTS as a corrective action. Results demonstrated that OTS could help obtain a reliable N-1-1 solution without making the system to return to N-1 reliability. The use of OTS as a remedial action to improve system resilience in case of extreme weather impacts is studied in [157] to reduce the amount of loadshedding by optimally switching lines to counter any contingency caused by the extreme weather conditions. Another work [158] relates the use of corrective OTS in cases of terrorist actions to reduce loadshedding after the attack. To improve power system resilience, a controlled islanding using OTS is provided in [159] to reduce the amount of loadshedding in case of islanding.

To achieve maximum probabilistic reliability and minimum cost using OTS, [29] proposed a multi-objective optimization approach and solved the problem using Monte Carlo simulations and evolutionary algorithm. It is noted that model can provide insights into the trade-off between the system reliability and cost using OTS. The role of OTS in sub-transmission lines on system reliability is modeled using a multi-objective optimization problem in terms of energy loss, in addition to using load and generation information [160]. The multi-objective optimization is solved using a non-dominated genetic classification algorithm (NSGA-II) in the first phase while for the second phase a simulation-based method is adopted for reliability evaluation. The model is tested on an Ecuadorian power utility and it is concluded that the concept of sub-transmission meshed networks can help in decision for policy makers. Short and medium-term reliability assessment of OTS using time variant reliability models is studied in [161]. The probabilistic security assessment of OTS considering both socio-economic disruptions and generation cost is presented in [40]. Results from the test cases demonstrate that it is important to perform the probabilistic security analysis before OTS solution is implemented. An emergency damping control strategy adopting the concept of OTS to reduce inter-area oscillations is presented in [162].

The impact of OTS on power system reliability with AC-OPF based formulation considering N-1 criteria is also studied by different authors [163], [164]. An AC-OPF based OTS reliability assessment with N-1 standards is studied on the Tennessee Valley Authority (TVA) network in [165] to show that OTS can help relive voltage and thermal violations in post-contingency situations. A dynamic programming approach is used to model OTS in an AC-OPF based formulation considering the N-1 security analysis to reduce the computational time of solving the problem [166]. On the contrary, the authors in [100] argue that system reliability using AC-OPF based formulation remains unchanged while DC based model can help improve system reliability. This may not be regarded as a general conclusion though as network topology may vary by switching different lines from service. The

Algorithm 1 *Reliability Evaluation of OTS*

Input: Load profile, generation data, weather data, wind turbine data and transmission line ratings
Output: Reliability indices EENS, LOLE & LOLP
Step 1: Initialize weather data and network parameters related to load profile, generation data, wind farm data and lines capacities.
Step 2: Apply SMC simulations to randomly sample system's component states and run DCOPF to evaluate these sampled states.
Step 3: If load curtailment or line congestion exists, switch-off some lines to relieve network congestion so as to enhance power transfer capacity, otherwise go to step 5.
Step 4: Evaluate sampled states based on OTS and record load curtailment results for OTS.
Step 5: If No load curtailment exists after applying OTS, proceed to step 6.
Step 6: Calculate Reliability indices if convergence criteria is satisfied otherwise again sample system states by SMC simulations and repeat step 3-4.

composite reliability of OTS with AC-OPF based formulation considering failure mitigation and disturbances reduction is presented in [167]. The impact of OTS on system reliability using reliability indices is studied in [67] for both DC and AC-OPF based formations. The reliability indices calculated are expected energy not served (EENS), loss of load probability (LOLP), and customer interruption costs (CIC). The two-part paper from [168] developed an AC-OPF based OTS model with real time contingency analysis, which can handle large practical power system with tractable computational time. The model is tested on the Tennessee Valley Authority (TVA) and snapshots from an actual EMS system from Pennsylvania New Jersey Maryland (PJM) and ERCOT. Results indicated that OTS as a corrective action can reduce the post-contingency violations significantly. The power engineering letter in [169] also studied real-time contingency analysis using an AC-OPF based framework on the networks of TVA, PJM, and ERCOT. The impact of geomagnetically induced currents (GIC) is reduced in an AC-OPF based formulation using correcting switching of lines using OTS and generation redispatch [170].

Following a contingency, the concept of corrective transmission switching may be used to regain system security without rescheduling generation or loadshedding. This issue is addressed in [171] where a DC-OPF based model is used to check the feasibility of OTS in an N-1 and N-2 criteria. The model is solved using constraint programming to reduce the computational time of solving. To counter cascaded failures, a corrective OTS concept is utilized to block the cascading of failures considering the correction time [172]. A two-part paper in [173] and [174] incorporates corrective-OTS in the energy management system by proposing a real-time SCUC formulation for the economic dispatch problem while the second part aims at real-time contingency analysis. The proposed method with EMS is shown to improve system reliability with significant cost savings economic dispatch, reduce network congestion, and can leverage pos-contingency violations. The corrective switching actions of OTS is further discussed in [175], where a robust corrective OTS model is presented, which can be solved offline to indicate line switching actions that can be enforced in assessment tools in real-time. The corrective action of OTS considering N-k contingency assessment is proposed in [176] using a robust model. The authors argue that this model may result in conservative findings because the optimal solution that is obtained need to satisfy all the N-k contingencies. The security and economic benefits of OTS is discussed in [177], which presents a joint reserve and energy scheduling model that uses OTS as a corrective action to improve system ability to circumvent post-contingency events. The authors noticed that with only fewer corrective OTS actions, the system operator can control different contingencies resulting in lower operation and reserve costs. The reliability impact of OTS as a remedial action is modeled in a MILP formulation to minimize damage caused by loadshedding [178]. Reliability indices are calculated and it is found that system reliability is enhanced when OTS is incorporated as remedial actions. The benefits of OTS in reducing overload in post-contingency situation using a real time contingency analysis is performed in [179] to identify the vulnerable overloads. Another work in [180] presented OTS as a congestion management tool to find potential candidate lines for line switching actions to relieve network congestion without violating constraints on the voltage angles. The problem is modeled as a MINLP problem and Bender's decomposition is applied to solve it. The authors concluded that DC-OPF based OTS may jeopardize system security and in some instances can result in voltage collapse, while the AC-OPF based OTS can help ensure the voltage security.

The increasing integration of RES along with the transmission aging and load growth pose excessive stress on the reliable operation of the grid. Utilities are in dire need of alternatives that can efficiently utilize existing infrastructure. Smart grid technologies like dynamic thermal rating (DTR), energy storage systems (ESS), and demand side management (DSM) have the potential to leverage capacity of transmission network and provide flexibility to the power system operation reliability. The impact of incorporating OTS with other flexible smart grid technologies is also studied from reliability perspectives. In [100], the authors proved that the enforcement of OTS with dynamic thermal rating can help improve power system reliability as compared to the case when none or only one of these technologies is implemented. In [101], OTS and DTR are incorporated in a network-constrained UC formulation considering multi-area information. Their results demonstrated that the combined effect of OTS and DTR can help reduce wind curtailment and generation cost. The coordinated impact of OTS and DTR are incorporated into power system reliability assessment in [181], where it shown showed that the combination of these two smart grid technologies can improve system reliability, especially for network which have low transmission capacities. To tackle the uncertainties associated with wind/solar and load, [132] proposes a stochastic OTS model to minimize the grid vulnerability. A scenario-reduction technique is adapted which helps reduce the computational complexity of the model. Another paper also discusses the stochastic nature of wind farms, which is modeled as a two-level multi-scenario based stochastic model [182]. It also includes the N-1 security constraints and is solved using the affinity propagation (AP) clustering algorithm.

VI. CONCLUSION

OTS has been shown in the literature to have economic benefits, reduce operational costs, relieve network congestion, serve as a corrective mechanism for reducing voltage violations, improve system reliability, and minimize system loss. This paper presents, for the very first time, a comprehensive overview of the OTS problem in the traditional network flow problem. The basic formulation of the OTS problem in the traditional OPF is explained in detail. Since the introduction of the OTS, different variations of the basic OTS models have become available. These models are discussed in detail with consistent mathematical formulations to make the readers' flow easy to understand. The different alternative models of OTS explained are the alternative model of OTS, the N-1 DC-OPF based model, the AC-OPF based OTS model, the approximate OTS model, the OTS model that avoids islanding and switching unnecessary lines, and the bi-level OTS model. The basic OTS formulation involves a disjunctive parameter called the big-M value, which is used to make the voltage angle constraints non-binding. The proper selection of the big-M value is a challenging task regarding both the optimal solution and computation time. This paper provides detailed information on the different values of the big-M value suggested by researchers in the literature.

The interaction of OTS with other flexibility options such as dynamic thermal rating (DTR), energy storage systems (ESS), and renewable energy sources (RES) are discussed in detail. It is shown that the coordination of OTS with these technologies further improves system flexibility while maintaining system reliability with minimum operation cost. Later, the paper provides the impact of the short-term OTS problem on the long-term expansion planning problems. Although both problems differ in nature, the operational flexibility of OTS can help utilize the existing infrastructure more efficiently and, in some cases, can postpone the need for adding new transmission elements. The concept of OTS does not ignore the importance of system reliability standards, and the co-optimization of generation dispatch along with network topology is not done at the expense of system reliability.

It is observed that the incorporation of OTS into the dispatch problem can further increase the system reliability.

REFERENCES

[1] J. Ma, Y. Liu, S. Zhang, L. Wu, and Z. Yang, "Comprehensive probabilistic assessment on capacity adequacy and flexibility of generation resources," *Int. J. Electr. Power Energy Syst.*, vol. 145, Feb. 2023, Art. no. 108677, doi: 10.1016/j.ijepes.2022.108677.

[2] C. Zhang, H. Cheng, L. Liu, H. Zhang, X. Zhang, and G. Li, "Coordination planning of wind farm, energy storage and transmission network with high-penetration renewable energy," *Int. J. Electr. Power Energy Syst.*, vol. 120, Sep. 2020, Art. no. 105944, doi: 10.1016/j.ijepes.2020.105944.

[3] J. Aghaei, A. Nikoobakht, M. Mardaneh, M. Shafie-khah, and J. P. S. Catalão, "Transmission switching, demand response and energy storage systems in an innovative integrated scheme for managing the uncertainty of wind power generation," *Int. J. Electr. Power Energy Syst.*, vol. 98, pp. 72–84, Jun. 2018, doi: 10.1016/j.ijepes.2017.11.044.

[4] M. Numan, D. Feng, F. Abbas, S. Habib, and S. Hao, "Coordinated operation of reconfigurable networks with dynamic line rating for optimal utilization of renewable generation," *Int. J. Electr. Power Energy Syst.*, vol. 125, Feb. 2021, Art. no. 106473, doi: 10.1016/j.ijepes.2020.106473.

[5] L. You, H. Ma, T. K. Saha, and G. Liu, "Security-constrained economic dispatch exploiting the operational flexibility of transmission networks," *Int. J. Electr. Power Energy Syst.*, vol. 138, Jun. 2022, Art. no. 107914, doi: 10.1016/j.ijepes.2021.107914.

[6] A. A. Mazi, B. F. Wollenberg, and M. H. Hesse, "Corrective control of power system flows by line and bus-bar switching," *IEEE Trans. Power Syst.*, vol. PS-1, no. 3, pp. 258–264, Aug. 1986, doi: 10.1109/TPWRS.1986.4334990.

[7] W. Shao and V. Vittal, "Corrective switching algorithm for relieving overloads and voltage violations," *IEEE Trans. Power Syst.*, vol. 20, no. 4, pp. 1877–1885, Nov. 2005.

[8] K. W. Hedman, S. S. Oren, and R. P. O'Neill, "A review of transmission switching and network topology optimization," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2011, pp. 1–7, doi: 10.1109/PES.2011.6039857.

[9] E. B. Fisher, R. P. O'Neill, and M. C. Ferris, "Optimal transmission switching," *IEEE Trans. Power Syst.*, vol. 23, no. 3, pp. 1346–1355, Aug. 2008.

[10] E. B. Fisher, K. W. Hedman, R. P. O. Neill, M. C. Ferris, and S. S. Oren, "Optimal transmission switching in electric networks for improved economic operations," in *Proc. Infraday Conf.*, 2008, pp. 1–24.

[11] Y. Tohidi, M. R. Hesamzadeh, R. Baldick, and D. R. Biggar, "Transmission network switching for reducing market power cost in generation sector: A Nash-equilibrium approach," *Electric Power Syst. Res.*, vol. 146, pp. 71–79, May 2017, doi: 10.1016/j.epsr.2016.12.031.

[12] K. W. Hedman, S. S. Oren, and R. P. O. Neill, "Optimal transmission switching: Economic efficiency and market implications," *J. Regulatory Econ.*, vol. 40, pp. 111–140, Oct. 2011, doi: 10.1007/s11149-011-9158-z.

[13] K. W. Hedman, S. S. Oren, and R. P. O'Neill, "Flexible transmission in the smart grid: Optimal transmission switching," in *Handbook of Networks in Power Systems*, P. M. Pardalos, Ed. Springer, 2012, pp. 523–555.

[14] C. Barrows and S. Blumsack, "Transmission switching in the RTS-96 test system," *IEEE Trans. Power Syst.*, vol. 27, no. 2, pp. 1134–1135, May 2012, doi: 10.1109/TPWRS.2011.2170771.

[15] S. R. Salkuti, "Congestion management using optimal transmission switching," *IEEE Syst. J.*, vol. 12, no. 4, pp. 3555–3564, Dec. 2018, doi: 10.1109/JSYST.2018.2808260.

[16] M. Khanabadi, Y. Fu, and C. Liu, "Decentralized transmission line switching for congestion management of interconnected power systems," *IEEE Trans. Power Syst.*, vol. 33, no. 6, pp. 5902–5912, Nov. 2018, doi: 10.1109/TPWRS.2018.2838046.

[17] M. Khanabadi and H. Ghasemi, "Transmission congestion management through optimal transmission switching," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2011, pp. 1–5, doi: 10.1109/PES.2011.6039357.

[18] P. A. Ruiz, J. M. Foster, A. Rudkevich, and M. C. Caramanis, "Tractable transmission topology control using sensitivity analysis," *IEEE Trans. Power Syst.*, vol. 27, no. 3, pp. 1550–1559, Aug. 2012, doi: 10.1109/TPWRS.2012.2184777.

[19] Y. Sang and M. Sahraei-Ardakani, "The interdependence between transmission switching and variable-impedance series FACTS devices," *IEEE Trans. Power Syst.*, vol. 33, no. 3, pp. 2792–2803, May 2018, doi: 10.1109/TPWRS.2017.2756074.

[20] H. Ahmadi and H. Lesani, "Transmission congestion management through LMP difference minimization: A renewable energy placement case study," *Arabian J. Sci. Eng.*, vol. 39, no. 3, pp. 1963–1969, Mar. 2014, doi: 10.1007/s13369-013-0744-5.

[21] Z. Shen, H.-D. Chiang, Y. Tang, and N. Zhou, "An online line switching methodology with look-ahead capability to alleviate power system overloads based on a three-stage strategy," *Int. J. Electr. Power Energy Syst.*, vol. 115, Feb. 2020, Art. no. 105500, doi: 10.1016/j.ijepes.2019.105500.

[22] M. Abdi-Khorsand, M. Sahraei-Ardakani, and Y. M. Al-Abdullah, "Corrective transmission switching for N-1–1 contingency analysis," *IEEE Trans. Sustain. Energy*, vol. 32, no. 2, pp. 1606–1615, Mar. 2017, doi: 10.1109/TPWRS.2016.2614520.

[23] M. Zarghami, M. Sheikh, J. Aghaei, T. Niknam, R. Sadooghi, N. Javidtash, S. Shahriari, F. Wang, and J. P. S. Catalao, "Voltage security constrained optimal power flow considering smart transmission switching maneuvers," in *Proc. IEEE Ind. Appl. Soc. Annu. Meeting (IAS)*, Oct. 2021, pp. 1–7, doi: 10.1109/IAS48185.2021.9677199.

[24] M. Nojavan, H. Seyedi, and B. Mohammadi-Ivatloo, "Voltage stability margin improvement using hybrid non-linear programming and modified binary particle swarm optimisation algorithm considering optimal transmission line switching," *IET Gener., Transmiss. Distrib.*, vol. 12, no. 4, pp. 815–823, Feb. 2018, doi: 10.1049/iet-gtd.2016.1895.

[25] J. Belanger, L. A. Dessaint, and I. Kamwa, "An extended optimal transmission switching algorithm adapted for large networks and hydro-electric context," *IEEE Access*, vol. 8, pp. 87762–87774, 2020.

[26] H. Seyedi and S. Tanhaeidilmaghani, "New controlled switching approach for limitation of transmission line switching overvoltages," *IET Gener., Transmiss. Distrib.*, vol. 7, no. 3, pp. 218–225, Mar. 2013, doi: 10.1049/iet-gtd.2012.0285.

[27] P. Balasubramanian, M. Sahraei-Ardakani, X. Li, and K. W. Hedman, "Towards smart corrective switching: Analysis and advancement of PJM's switching solutions," *IET Gener., Transmiss. Distrib.*, vol. 10, no. 8, pp. 1984–1992, May 2016, doi: 10.1049/iet-gtd.2015.1362.

[28] S. A. T. Khorram, M. Fotuhi-Firuzabad, and A. Safdarian, "Optimal transmission switching as a remedial action to enhance power system reliability," in *Proc. Smart Grids Conf. (SGC)*, Dec. 2016, pp. 7–12, doi: 10.1109/SGC.2016.7882944.

[29] C. Zhang and J. Wang, "Optimal transmission switching considering probabilistic reliability," *IEEE Trans. Power Syst.*, vol. 29, no. 2, pp. 974–975, Mar. 2014, doi: 10.1109/TPWRS.2013.2287999.

[30] S. Fattahi, J. Lavaei, and A. Atamturk, "A bound strengthening method for optimal transmission switching in power systems," *IEEE Trans. Power Syst.*, vol. 34, no. 1, pp. 280–291, Jan. 2019.

[31] C. Barrows, S. Blumsack, and R. Bent, "Using network metrics to achieve computationally efficient optimal transmission switching," in *Proc. 46th Hawaii Int. Conf. Syst. Sci.*, Jan. 2013, pp. 2187–2196, doi: 10.1109/HICSS.2013.590.

[32] C. Crozier, K. Baker, and B. Toomey, "Feasible region-based heuristics for optimal transmission switching," *Sustain. Energy, Grids Netw.*, vol. 30, Jun. 2022, Art. no. 100628, doi: 10.1016/j.segan.2022.100628.

[33] X. Liu, Y. Wen, and Z. Li, "Multiple solutions of transmission line switching in power systems," *IEEE Trans. Power Syst.*, vol. 33, no. 1, pp. 1118–1120, Jan. 2018, doi: 10.1109/TPWRS.2017.2770019.

[34] T. Leveringhaus, L. Klu, I. Bekker, and L. Hofmann, "Solving combined optimal transmission switching and optimal power flow sequentially as convexificated quadratically constrained quadratic program," *Electr. Power Syst. Res.*, vol. 212, pp. 1–7, Oct. 2022, doi: 10.1016/j.epsr.2022.108534.

[35] M. Numan, D. Feng, F. Abbas, S. Habib, and A. Rasool, "Mobilizing grid flexibility through optimal transmission switching for power systems with large-scale renewable integration," *Int. Trans. Electr. Energy Syst.*, vol. 30, no. 3, pp. 1–15, Mar. 2020, doi: 10.1002/2050-7038.12211.

[36] R. P. O'Neill, K. W. Hedman, E. A. Krall, A. Papavasiliou, and S. S. Oren, "Economic analysis of the N-1 reliable unit commitment and transmission switching problem using duality concepts," *Energy Syst.*, vol. 1, no. 2, pp. 165–195, Jan. 2010, doi: 10.1007/s12667-009-0005-6.

[37] P. Li, X. Huang, J. Qi, H. Wei, and X. Bai, "A connectivity constrained MILP model for optimal transmission switching," *IEEE Trans. Power Syst.*, vol. 36, no. 5, pp. 4820–4823, Sep. 2021, doi: 10.1109/TPWRS.2021.3089029.

[38] H. Behnia and M. Akhbari, "Integrated generation and transmission maintenance scheduling by considering transmission switching," *Int. Trans. Electr. Energy Syst.*, vol. 29, no. 4, p. e2792, 2019, doi: 10.1002/etep.2792.

[39] T. Lan, Z. Zhou, W. Wang, and G. M. Huang, "Stochastic optimization for AC optimal transmission switching with generalized Benders decomposition," *Int. J. Electr. Power Energy Syst.*, vol. 133, pp. 1–10, Nov. 2021, doi: 10.1016/j.ijepes.2021.107140.

[40] M. Jabarnejad, J. Wang, and J. Valenzuela, "A decomposition approach for solving seasonal transmission switching," *IEEE Trans. Power Syst.*, vol. 30, no. 3, pp. 1203–1211, May 2015, doi: 10.1109/tpwrs.2014.2343944.

[41] B. Zhao, Z. Hu, Q. Zhou, H. Zhang, and Y. Song, "Optimal transmission switching to eliminate voltage violations during light-load periods using decomposition approach," *J. Modern Power Syst. Clean Energy*, vol. 7, no. 2, pp. 297–308, Mar. 2019, doi: 10.1007/s40565-018-0422-4.

[42] J. Lin, Y. Hou, G. Zhu, S. Luo, P. Li, L. Qin, and L. Wang, "Co-optimization of unit commitment and transmission switching with short-circuit current constraints," *Int. J. Electr. Power Energy Syst.*, vol. 110, pp. 309–317, Sep. 2019, doi: 10.1016/j.ijepes.2019.03.019.

[43] H. Haghighat, "Loading margin calculation with line switching: A decomposition method," *Int. J. Electr. Power Energy Syst.*, vol. 64, pp. 104–111, Jan. 2015, doi: 10.1016/j.ijepes.2014.07.019.

[44] R. Saavedra, A. Street, and J. M. Arroyo, "Unlocking reserves with smart transmission switching," *Electric Power Syst. Res.*, vol. 195, Jun. 2021, Art. no. 106805, doi: 10.1016/j.epsr.2020.106805.

[45] G. Granelli, M. Montagna, F. Zanellini, P. Bresesti, R. Vailati, and M. Innorta, "Optimal network reconfiguration for congestion management by deterministic and genetic algorithms," *Electric Power Syst. Res.*, vol. 76, nos. 6–7, pp. 549–556, Apr. 2006, doi: 10.1016/j.epsr.2005.09.014.

[46] C.-Y. Chang, S. Martinez, and J. Cortes, "Virtual-voltage partition-based approach to optimal transmission switching," *IEEE Trans. Control Syst. Technol.*, vol. 29, no. 3, pp. 1246–1256, May 2021, doi: 10.1109/TCST.2020.3004704.

[47] C. Coffrin, H. L. Hijazi, K. Lehmann, and P. Van Hentenryck, "Primal and dual bounds for optimal transmission switching," in *Proc. Power Syst. Comput. Conf.*, Aug. 2014, pp. 1–5.

[48] S. S. Dey, B. Kocuk, and N. Redder, "Node-based valid inequalities for the optimal transmission switching problem," *Discrete Optim.*, vol. 43, Feb. 2022, Art. no. 100683, doi: 10.1016/j.disopt.2021.100683.

[49] S. Pal, S. Sen, J. Bera, and S. Sengupta, "Regenerative and combinatorial random variable based particle swarm optimization towards optimal transmission switching," *Appl. Soft Comput.*, vol. 95, Oct. 2020, Art. no. 106529, doi: 10.1016/j.asoc.2020.106529.

[50] J. Ostrowski, J. Wang, and C. Liu, "Exploiting symmetry in transmission lines for transmission switching," *IEEE Trans. Power Syst.*, vol. 27, no. 3, pp. 1708–1709, Aug. 2012, doi: 10.1109/TPWRS.2012.2187121.

[51] J. Ostrowski, J. Wang, and C. Liu, "Transmission switching with connectivity-ensuring constraints," *IEEE Trans. Power Syst.*, vol. 29, no. 6, pp. 2621–2627, Nov. 2014, doi: 10.1109/TPWRS.2014.2315434.

[52] R. Aazami, M. R. Haghifam, and K. Aflaki, "Stochastic energy and spinning reserve market with considering smart transmission switching action," in *Proc. IEEE PES Innov. Smart Grid Technol. (ISGT)*, Jan. 2012, pp. 1–6, doi: 10.1109/ISGT.2012.6175692.

[53] D. Liu, C. Zhang, G. Chen, Y. Xu, and Z. Y. Dong, "Stochastic security-constrained optimal power flow for a microgrid considering tie-line switching," *Int. J. Electr. Power Energy Syst.*, vol. 134, Jan. 2022, Art. no. 107357, doi: 10.1016/j.ijepes.2021.107357.

[54] Q. Lete and A. Papavasiliou, "Impacts of transmission switching in zonal electricity markets—Part I," *IEEE Trans. Power Syst.*, vol. 36, no. 2, pp. 902–913, Mar. 2021, doi: 10.1109/TPWRS.2020.3015033.

[55] Q. Lete and A. Papavasiliou, "Impacts of transmission switching in zonal electricity markets—Part II," *IEEE Trans. Power Syst.*, vol. 36, no. 2, pp. 914–922, Mar. 2021, doi: 10.1109/TPWRS.2020.3015012.

[56] M. H. Taheri, S. Dehghan, M. Heidarifar, and H. Ghasemi, "Adaptive robust optimal transmission switching considering the uncertainty of net nodal electricity demands," *IEEE Syst. J.*, vol. 11, no. 4, pp. 2872–2881, Dec. 2017.

[57] K. Hedman, R. O'Neill, E. Fisher, and S. Oren, "Optimal transmission switching—Sensitivity analysis and extensions," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2009, pp. 1–11, doi: 10.1109/PES.2009.5275884.

[58] S. Binato, M. V. F. Pereira, and S. Granville, "A new Benders decomposition approach to solve power transmission network design problems," *IEEE Trans. Power Syst.*, vol. 16, no. 2, pp. 235–240, May 2001, doi: 10.1109/59.918292.

[59] M. Numan, A. Z. Khan, M. Asif, S. M. Malik, and K. Imran, "Exploiting the inherent flexibility in transmission network for optimal scheduling, wind power utilization, and network congestion management," *IEEE Access*, vol. 9, pp. 88746–88758, 2021, doi: 10.1109/ACCESS.2021.3090089.

[60] Z. Yang, H. Zhong, and Q. Xia, "Optimal transmission switching based on auxiliary induce function," in *Proc. IEEE PES Gen. Meeting Conf. Expo.*, Jul. 2014, pp. 1–5, doi: 10.1109/PESGM.2014.6938949.

[61] M. Numan, D. Feng, F. Abbas, U. Rahman, and W. A. Wattoo, "Impact assessment of a co-optimized dynamic line rating and transmission switching topology on network expansion planning," *Int. Trans. Electr. Energy Syst.*, vol. 30, no. 8, pp. 1–24, Aug. 2020, doi: 10.1002/2050-7038.12457.

[62] K. W. Hedman, M. C. Ferris, R. P. O'Neill, E. B. Fisher, and S. S. Oren, "Co-optimization of generation unit commitment and transmission switching with N-1 reliability," *IEEE Trans. Power Syst.*, vol. 25, no. 2, pp. 1052–1063, May 2010, doi: 10.1109/TPWRS.2009.2037232.

[63] K. W. Hedman, R. P. O'Neill, E. B. Fisher, and S. S. Oren, "Optimal transmission switching with contingency analysis," *IEEE Trans. Power Syst.*, vol. 24, no. 3, pp. 1577–1586, Aug. 2009, doi: 10.1109/TPWRS.2009.2020530.

[64] M. Meneses, E. Nascimento, L. H. Macedo, R. Romero, and S. Member, "Transmission network expansion planning considering line switching," *IEEE Access*, vol. 8, pp. 115148–115158, 2020, doi: 10.1109/ACCESS.2020.3003973.

[65] D. Tejada, J. M. López-Lezama, M. J. Rider, and G. Vinasco, "Transmission network expansion planning considering repowering and reconfiguration," *Int. J. Electr. Power Energy Syst.*, vol. 69, pp. 213–221, Jul. 2015, doi: 10.1016/j.ijepes.2015.01.008.

[66] J. C. Villumsen and A. B. Philpott, "Investment in electricity networks with transmission switching," *Eur. J. Oper. Res.*, vol. 222, no. 2, pp. 377–385, Oct. 2012, doi: 10.1016/j.ejor.2012.05.002.

[67] P. Dehghanian and M. Kezunovic, "Impact assessment of transmission line switching on system reliability performance," in *Proc. 18th Int. Conf. Intell. Syst. Appl. Power Syst. (ISAP)*, Sep. 2015, pp. 1–6, doi: 10.1109/ISAP.2015.7325581.

[68] M. Jabarnejad and J. Valenzuela, "Optimal investment plan for dynamic thermal rating using benders decomposition," *Eur. J. Oper. Res.*, vol. 248, no. 3, pp. 917–929, Feb. 2016, doi: 10.1016/j.ejor.2015.08.010.

[69] M. Jabarnejad, "Approximate optimal transmission switching," *Electr. Power Syst. Res.*, vol. 161, pp. 1–7, Aug. 2018, doi: 10.1016/j.epsr.2018.03.021.

[70] M. Peker, A. S. Kocaman, and B. Y. Kara, "A two-stage stochastic programming approach for reliability constrained power system expansion planning," *Int. J. Electr. Power Energy Syst.*, vol. 103, pp. 458–469, Dec. 2018, doi: 10.1016/j.ijepes.2018.06.013.

[71] L. S. Moulin, M. Poss, and C. Sagastizábal, "Transmission expansion planning with re-design," *Energy Syst.*, vol. 1, no. 2, pp. 113–139, May 2010, doi: 10.1007/s12667-010-0010-9.

[72] A. Khodaei, M. Shahidehpour, and S. Kamalinia, "Transmission switching in expansion planning," *IEEE Trans. Power Syst.*, vol. 25, no. 3, pp. 1722–1733, Aug. 2010, doi: 10.1109/TPWRS.2009.2039946.

[73] A. Khodaei, "Optimal transmission switching in power system operation and planning," Ph.D. dissertation, Dept. Elect. Comput. Eng., Illinois Inst. Technol., Chicago, IL, USA, Dec. 2010.

[74] Y. Bai, H. Zhong, Q. Xia, and Y. Wang, "A conic programming approach to optimal transmission switching considering reactive power and voltage security," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2015, pp. 1–5, doi: 10.1109/PESGM.2015.7285833.

[75] M. Soroush and J. D. Fuller, "Accuracies of optimal transmission switching heuristics based on DCOPF and ACOPF," *IEEE Trans. Power Syst.*, vol. 29, no. 2, pp. 924–932, Mar. 2014, doi: 10.1109/TPWRS.2013.2283542.

[76] C. Barrows, S. Blumsack, and P. Hines, "Correcting optimal transmission switching for AC power flows," in *Proc. 47th Hawaii Int. Conf. Syst. Sci.*, Jan. 2014, pp. 2374–2379, doi: 10.1109/HICSS.2014.642.

[77] D. Bienstock and G. Munoz, "Approximate method for AC transmission switching based on a simple relaxation for ACOPF problems," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2015, pp. 1–5, doi: 10.1109/PESGM.2015.7286321.

[78] B. Kocuk, S. S. Dey, and X. A. Sun, "New formulation and strong MISOCP relaxations for AC optimal transmission switching problem," *IEEE Trans. Power Syst.*, vol. 32, no. 6, pp. 4161–4170, Nov. 2017.

[79] W. M. Guo, Q. Wei, G. J. Liu, M. Yang, and X. K. Zhang, "Transmission swtiching to relieve voltage violations in low load period," in *Proc. IEEE Int. Conf. (TENCON)*, Oct. 2013, pp. 1–5, doi: 10.1109/TENCON.2013.6718480.

[80] T. Potluri and K. W. Hedman, "Impacts of topology control on the ACOPF," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2012, pp. 1–7.

[81] J. Shi and S. S. Oren, "Wind power integration through stochastic unit commitment with topology control recourse," in *Proc. Power Syst. Comput. Conf. (PSCC)*, Jun. 2016, pp. 1–7.

[82] M. Flores, L. H. Macedo, and R. Romero, "Alternative mathematical models for the optimal transmission switching problem," *IEEE Syst. J.*, vol. 15, no. 1, pp. 1245–1255, Mar. 2021, doi: 10.1109/JSYST.2020.3000978.

[83] W. Q. Li, W. M. Guo, G. J. Liu, M. Yang, X. S. Han, and X. K. Zhang, "A bilevel approach to transmission switching," in *Proc. IEEE Int. Conf. (TENCON)*, Oct. 2013, p. 3, doi: 10.1109/TENCON.2013.6718479.

[84] M. Numan, Z. Ming, J. B. Brima, I. J. Sowe, and M. K. Bodla, "Requirements driven implementation of smart grid applications and technology," in *Proc. IEEE 11th Conf. Ind. Electron. Appl. (ICIEA)*, Jun. 2016, pp. 2305–2310, doi: 10.1109/ICIEA.2016.7603976.

[85] I. Transactions and O. N. Power, "Editorial: Special section on harnessing flexible transmission assets for power system optimization," *IEEE Trans. Power Syst.*, vol. 32, no. 2, pp. 1595–1596, Mar. 2017.

[86] E. Fernadez, I. Albizu, M. T. Bedialauneta, A. J. Mazon, and P. T. Leite, "Review of dynamic line rating systems for wind power integration," *Renew. Sustain. Energy Rev.*, vol. 53, pp. 80–92, Jan. 2016, doi: 10.1016/j.rser.2015.07.149.

[87] C. Lai and J. Teh, "Comprehensive review of the dynamic thermal rating system for sustainable electrical power systems," *Energy Rep.*, vol. 8, pp. 3263–3289, Nov. 2022, doi: 10.1016/j.egyr.2022.02.085.

[88] J. Teh and C.-M. Lai, "Reliability impacts of the dynamic thermal rating system on smart grids considering wireless communications," *IEEE Access*, vol. 7, pp. 41625–41635, 2019, doi: 10.1109/ACCESS.2019.2907980.

[89] *IEEE Standard for Calculating the Current-Temperature Relationship of Bare Overhead Conductors*, IEEE Standard 738, 2012, doi: 10.1109/IEEESTD.2013.6692858.

[90] "Guide for thermal rating calculation of overhead lines," CIGRE, Tech. Brochure 601, Dec. 2014.

[91] *Overhead Electrical Conductors—Calculation Methods for Staranded Bare Conductors*, Standard IEC Tr61597, 2005.

[92] D. Douglass, W. Chisholm, G. Davidson, I. Grant, K. Lindsey, M. Lancaster, D. Lawry, T. McCarthy, C. Nascimento, M. Pasha, J. Reding, T. Seppa, J. Toth, and P. Waltz, "Real-time overhead transmission-line monitoring for dynamic rating," *IEEE Trans. Power Del.*, vol. 31, no. 3, pp. 921–927, Jun. 2016, doi: 10.1109/TPWRD.2014.2383915.

[93] M. Numan, M. Asif, M. W. Khan, S. M. Malik, and F. U. Khilji, "Impact of dynamic thermal rating on optimal siting and sizing of energy storage systems under renewable portfolio standards requirements," *Sustain. Energy, Grids Netw.*, vol. 32, Dec. 2022, Art. no. 100881, doi: 10.1016/j.segan.2022.100881.

[94] M. M. Esfahani and G. R. Yousefi, "Real time congestion management in power systems considering quasi-dynamic thermal rating and congestion clearing time," *IEEE Trans. Ind. Informat.*, vol. 12, no. 2, pp. 745–754, Apr. 2016, doi: 10.1109/TII.2016.2530402.

[95] S. Bossart and R. Staubly. (2014). *Dynamic Line Rating Systems for Transmission Lines*. [Online]. Available: https://www.smartgrid.gov/files/SGDP_Transmission_DLR_Topical_Report_04-25-14_FINAL.pdf

[96] Y. Li, B. Hu, K. Xie, L. Wang, Y. Xiang, R. Xiao, and D. Kong, "Day-ahead scheduling of power system incorporating network topology optimization and dynamic thermal rating," *IEEE Access*, vol. 7, pp. 35287–35301, 2019, doi: 10.1109/ACCESS.2019.2904877.

[97] J. Shi and S. S. Oren, "Flexible line ratings in stochastic unit commitment for power systems with large-scale renewable generation," *Energy Syst.*, vol. 11, no. 1, pp. 1–19, Feb. 2020, doi: 10.1007/s12667-018-0306-8.

[98] M. Jabarnejad, "Facilitating emission reduction using the dynamic line switching and rating," *Electric Power Syst. Res.*, vol. 189, Dec. 2020, Art. no. 106600, doi: 10.1016/j.epsr.2020.106600.

[99] M. El-Azab, W. A. Omran, S. F. Mekhamer, and H. E. A. Talaat, "Congestion management of power systems by optimizing grid topology and using dynamic thermal rating," *Electric Power Syst. Res.*, vol. 199, Oct. 2021, Art. no. 107433, doi: 10.1016/j.epsr.2021.107433.

[100] R. Xiao, Y. Xiang, L. Wang, and K. Xie, "Bulk power system reliability evaluation considering optimal transmission switching and dynamic line thermal rating," in *Proc. Int. Conf. Probabilistic Methods Appl. Power Syst. (PMAPS)*, Oct. 2016, pp. 1–5, doi: 10.1109/PMAPS.2016.7764210.

[101] Y. Li, K. Xie, R. Xiao, B. Hu, H. Chao, and D. Kong, "Network-constrained unit commitment incorporating dynamic thermal rating and transmission line switching," in *Proc. 2nd IEEE Conf. Energy Internet Energy Syst. Integr. (EI)*, Oct. 2018, pp. 1–6, doi: 10.1109/EI2.2018.8582182.

[102] M. Shterjova, D. Minovski, and V. Sarac, "Battery energy storage systems and technologies: A review," *Etima*, vol. 1, no. 1, pp. 95–104, Mar. 2021.

[103] U. Datta, A. Kalam, and J. Shi, "A review of key functionalities of battery energy storage system in renewable energy integrated power systems," *Energy Storage*, vol. 3, no. 5, Oct. 2021, doi: 10.1002/est2.224.

[104] Y. Sang and M. Sahraei-Ardakani, "Enhancing wind energy integration by co-optimizing energy storage systems and transmission switching," in *Proc. IEEE Power Energy Soc. Gen. Meeting (PESGM)*, Aug. 2019, pp. 1–5, doi: 10.1109/PESGM40551.2019.8973447.

[105] A. Nikoobakht, J. Aghaei, and M. Mardaneh, "Managing the risk of uncertain wind power generation in flexible power systems using information gap decision theory," *Energy*, vol. 114, pp. 846–861, Nov. 2016, doi: 10.1016/j.energy.2016.08.070.

[106] A. V. Ramesh and X. Li, "Network reconfiguration impact on renewable energy system and energy storage system in day-ahead scheduling," in *Proc. IEEE Power Energy Soc. Gen. Meeting (PESGM)*, Jul. 2021, pp. 1–5, doi: 10.1109/PESGM46819.2021.9638033.

[107] T. Lan and G. M. Huang, "An intelligent parallel scheduling method for optimal transmission switching in power systems with batteries," in *Proc. 19th Int. Conf. Intell. Syst. Appl. Power Syst. (ISAP)*, Sep. 2017, pp. 1–6, doi: 10.1109/ISAP.2017.8071398.

[108] T. Lan, Z. Zhou, and G. M. Huang, "An approximation for parallelism in ACOPF based stochastic optimal transmission switching with battery energy storage systems," in *Proc. IEEE 12th Int. Conf. Compat., Power Electron. Power Eng. (CPE-POWERENG)*, Apr. 2018, pp. 1–7, doi: 10.1109/CPE.2018.8372607.

[109] P. M. De Quevedo, J. Contreras, M. J. Rider, and J. Allahdadian, "Contingency assessment and network reconfiguration in distribution grids including wind power and energy storage," *IEEE Trans. Sustain. Energy*, vol. 6, no. 4, pp. 1524–1533, Oct. 2015, doi: 10.1109/TSTE.2015.2453368.

[110] H. He, E. Du, N. Zhang, C. Kang, and X. Wang, "Enhancing the power grid flexibility with battery energy storage transportation and transmission switching," *Appl. Energy*, vol. 290, May 2021, Art. no. 116692, doi: 10.1016/j.apenergy.2021.116692.

[111] M. Peker, A. S. Kocaman, and B. Y. Kara, "Benefits of transmission switching and energy storage in power systems with high renewable energy penetration," *Appl. Energy*, vol. 228, pp. 1182–1197, Oct. 2018, doi: 10.1016/j.apenergy.2018.07.008.

[112] R. S. Go, F. D. Munoz, and J.-P. Watson, "Assessing the economic value of co-optimized grid-scale energy storage investments in supporting high renewable portfolio standards," *Appl. Energy*, vol. 183, pp. 902–913, Dec. 2016, doi: 10.1016/j.apenergy.2016.08.134.

[113] C.-M. Lai and J. Teh, "Network topology optimisation based on dynamic thermal rating and battery storage systems for improved wind penetration and reliability," *Appl. Energy*, vol. 305, Jan. 2022, Art. no. 117837, doi: 10.1016/j.apenergy.2021.117837.

[114] H. Zhang, H. Cheng, and S. Zhang, "Stochastic optimal transmission switching considering the correlated wind power," *IET Gener., Transmiss. Distrib.*, vol. 13, no. 13, pp. 2664–2672, Jul. 2019, doi: 10.1049/iet-gtd.2018.5043.

[115] J. Shi and S. S. Oren, "Stochastic unit commitment with topology control recourse for power systems with large-scale renewable integration," *IEEE Trans. Power Syst.*, vol. 33, no. 3, pp. 3315–3324, May 2018, doi: 10.1109/TPWRS.2017.2772168.

[116] Y. Zhou, H. Zhu, and G. A. Hanasusanto, "Transmission switching under wind uncertainty using linear decision rules," in *Proc. IEEE Power Energy Soc. Gen. Meeting (PESGM)*, Aug. 2020, pp. 1–5, doi: 10.1109/PESGM41954.2020.9281999.

[117] X. Zhang, Y. Liu, J. Zhao, J. Liu, M. Korkali, and X. Chen, "Short-circuit current constrained unit commitment and transmission switching model for improving renewable integration: An MILP formulation," *IET Gener., Transmiss. Distrib.*, vol. 16, no. 9, pp. 1743–1755, May 2022, doi: 10.1049/gtd2.12393.

[118] X. Dui, G. Zhu, and L. Yao, "Two-stage optimization of battery energy storage capacity to decrease wind power curtailment in grid-connected wind farms," *IEEE Trans. Power Syst.*, vol. 33, no. 3, pp. 3296–3305, May 2018, doi: 10.1109/TPWRS.2017.2779134.

[119] M. Lu, M. Zhou, and Y. Li, "Dynamic economic dispatch of power systems with optimal transmission switching," in *Proc. IEEE 1st China Int. Youth Conf. Electr. Eng. (CIYCEE)*, Nov. 2020, pp. 1–6, doi: 10.1109/CIYCEE49808.2020.9332555.

[120] A. Papavasiliou, S. S. Oren, and B. Rountree, "Applying high performance computing to transmission-constrained stochastic unit commitment for renewable energy integration," *IEEE Trans. Power Syst.*, vol. 30, no. 3, pp. 1109–1120, May 2015, doi: 10.1109/TPWRS.2014.2341354.

[121] A. Nikoobakht, J. Aghaei, M. Mardaneh, T. Niknam, and V. Vahidinasab, "Moving beyond the optimal transmission switching: Stochastic linearised SCUC for the integration of wind power generation and equipment failures uncertainties," *IET Gener., Transmiss. Distrib.*, vol. 12, no. 15, pp. 3780–3792, Aug. 2018, doi: 10.1049/iet-gtd.2017.0617.

[122] J. Scheel, R. Dib, D. Westermann, and F. Wirtz, "Maximization of the feed-in of renewable energy into high-voltage grids by optimal switching," in *Proc. IEEE Eindhoven PowerTech*, Jun. 2015, pp. 1–5, doi: 10.1109/PTC.2015.7232275.

[123] E. Little, S. Bortolotti, J.-Y. Bourmaud, E. Karangelos, and Y. Perez, "Optimal transmission topology for facilitating the growth of renewable power generation," in *Proc. IEEE Madrid PowerTech*, Jun. 2021, pp. 1–6.

[124] J. C. Villumsen, G. Bronmo, and A. B. Philpott, "Line capacity expansion and transmission switching in power systems with large-scale wind power," *IEEE Trans. Power Syst.*, vol. 28, no. 2, pp. 731–739, May 2013, doi: 10.1109/TPWRS.2012.2224143.

[125] A. Nikoobakht, M. Mardaneh, J. Aghaei, V. Guerrero-Mestre, and J. Contreras, "Flexible power system operation accommodating uncertain wind power generation using transmission topology control: An improved linearised AC SCUC model," *IET Gener., Transmiss. Distrib.*, vol. 11, no. 1, pp. 142–153, Jan. 2017, doi: 10.1049/iet-gtd.2016.0704.

[126] A. V. Ramesh and X. Li, "Reducing congestion-induced renewable curtailment with corrective network reconfiguration in day-ahead scheduling," in *Proc. IEEE Power Energy Soc. Gen. Meeting (PESGM)*, Aug. 2020, pp. 1–5, doi: 10.1109/PESGM41954.2020.9281399.

[127] X. Li and Q. Xia, "Stochastic optimal power flow with network reconfiguration: Congestion management and facilitating grid integration of renewables," in *Proc. IEEE/PES Transmiss. Distrib. Conf. Expo.*, Oct. 2020, pp. 1–5, doi: 10.1109/TD39804.2020.9299954.

[128] E. Nasrolahpour and H. Ghasemi, "A stochastic security constrained unit commitment model for reconfigurable networks with high wind power penetration," *Electric Power Syst. Res.*, vol. 121, pp. 341–350, Apr. 2015, doi: 10.1016/j.epsr.2014.10.014.

[129] Q. An, J. Wang, G. Li, and M. Zhou, "Role of optimal transmission switching in accommodating renewable energy in deep peak regulation-enabled power systems," *Global Energy Interconnection*, vol. 3, no. 6, pp. 577–584, Dec. 2020, doi: 10.1016/j.gloei.2021.01.010.

[130] Y. Liu, T. Wang, and X. Gu, "Robust optimal transmission switching for wind farm-integrated power systems from a perspective of steady-state security region," *IET Renew. Power Gener.*, vol. 16, no. 5, pp. 945–955, Apr. 2022, doi: 10.1049/rpg2.12404.

[131] J. Jiang, X. Han, J. Wang, X. Zhu, D. Sun, and Y. Ma, "Optimal power flow with transmission switching for power system with wind/photovoltaic generation," in *Proc. Chin. Autom. Congr. (CAC)*, Oct. 2017, pp. 5802–5806, doi: 10.1109/CAC.2017.8243820.

[132] S. M. Mohseni-Bonab, I. Kamwa, A. Rabiee, and C. Y. Chung, "Stochastic optimal transmission switching: A novel approach to enhance power grid security margins through vulnerability mitigation under renewables uncertainties," *Appl. Energy*, vol. 305, Jan. 2022, Art. no. 117851, doi: 10.1016/j.apenergy.2021.117851.

[133] F. Qiu and J. Wang, "Chance-constrained transmission switching with guaranteed wind power utilization," *IEEE Trans. Power Syst.*, vol. 30, no. 3, pp. 1270–1278, May 2015, doi: 10.1109/TPWRS.2014.2346987.

[134] M. Khanabadi, Y. Fu, and L. Gong, "A fully parallel stochastic multiarea power system operation considering large-scale wind power integration," *IEEE Trans. Sustain. Energy*, vol. 9, no. 1, pp. 138–147, Jan. 2018, doi: 10.1109/TSTE.2017.2719659.

[135] E. Little, S. Bortolotti, J.-Y. Bourmaud, E. Karangelos, and Y. Perez, "Optimal transmission topology for facilitating the growth of renewable power generation," in *Proc. IEEE Madrid PowerTech*, Jun. 2021, pp. 2–7, doi: 10.1109/PowerTech46648.2021.9495032.

[136] S. Dehghan and N. Amjady, "Robust transmission and energy storage expansion planning in wind farm-integrated power systems considering transmission switching," *IEEE Trans. Sustain. Energy*, vol. 7, no. 2, pp. 765–774, Apr. 2016, doi: 10.1109/TSTE.2015.2497336.

[137] T. Lan and G. M. Huang, "Transmission line switching in power system planning with large scale renewable energy," in *Proc. 1st Workshop Smart Grid Renew. Energy (SGRE)*, Mar. 2015, pp. 1–6, doi: 10.1109/SGRE.2015.7208740.

[138] Y. Zhang, M. Bansal, and A. R. Escobedo, "Risk-neutral and risk-averse transmission switching for load shed recovery with uncertain renewable generation and demand," *IET Gener., Transmiss. Distrib.*, vol. 14, no. 21, pp. 4936–4945, Nov. 2020, doi: 10.1049/iet-gtd.2020.0964.

[139] A. K. Kamga, S. Voller, and J. F. Verstege, "Congestion management in transmission systems with large scale integration of wind energy," in *Proc. CIGRE/IEEE PES Joint Symp. Integr. Wide-Scale Renew. Resour. Power Del. Syst.*, 2009, pp. 1–11.

[140] P. V. Gomes and J. T. Saraiva, "State-of-the-art of transmission expansion planning: A survey from restructuring to renewable and distributed electricity markets," *Int. J. Electr. Power Energy Syst.*, vol. 111, pp. 411–424, Oct. 2019, doi: 10.1016/j.ijepes.2019.04.035.

[141] R. Hemmati, R.-A. Hooshmand, and A. Khodabakhshian, "State-of-the-art of transmission expansion planning: Comprehensive review," *Renew. Sustain. Energy Rev.*, vol. 23, pp. 312–319, Jul. 2013, doi: 10.1016/j.rser.2013.03.015.

[142] S. Mousavian, J. Valenzuela, and J. Wang, "A two-phase investment model for optimal allocation of phasor measurement units considering transmission switching," *Electric Power Syst. Res.*, vol. 119, pp. 492–498, Feb. 2015, doi: 10.1016/j.epsr.2014.10.025.

[143] H. Zhang, H. Cheng, L. Liu, S. Zhang, Q. Zhou, and L. Jiang, "Coordination of generation, transmission and reactive power sources expansion planning with high penetration of wind power," *Int. J. Electr. Power Energy Syst.*, vol. 108, pp. 191–203, Jun. 2019, doi: 10.1016/j.ijepes.2019.01.006.

[144] Y. Yuan, H. Cheng, H. Zhang, Z. Wang, and W. Zhou, "Transmission expansion planning with optimal transmission switching considering uncertain N-K contingency and renewables," *Energy Rep.*, vol. 8, pp. 573–583, Aug. 2022, doi: 10.1016/j.egyr.2022.02.241.

[145] Y. Hu, M. Wang, X. Lian, S. Liu, and Q. Zhang, "A reduced disjunctive model for transmission expansion planning considering unit commitment and optimal transmission switching," in *Proc. IEEE Int. Conf. Electr. Eng. Mechatronics Technol. (ICEEMT)*, Jul. 2021, pp. 623–627, doi: 10.1109/ICEEMT52412.2021.9601896.

[146] S. Zhao and C. Singh, "Studying the reliability implications of line switching operations," *IEEE Trans. Power Syst.*, vol. 32, no. 6, pp. 4614–4625, Nov. 2017.

[147] A. Khodaei and M. Shahidehpour, "Transmission switching in security-constrained unit commitment," *IEEE Trans. Power Syst.*, vol. 25, no. 4, pp. 1937–1945, Nov. 2010, doi: 10.1109/TPWRS.2010.2046344.

[148] L. Peng, B. Hu, K. Xie, H.-M. Tai, and K. Ashenayi, "Analytical model for fast reliability evaluation of composite generation and transmission system based on sequential Monte Carlo simulation," *Int. J. Electr. Power Energy Syst.*, vol. 109, pp. 548–557, Jul. 2019, doi: 10.1016/j.ijepes.2019.02.039.

[149] P. Henneaux and D. S. Kirschen, "Probabilistic security analysis of optimal transmission switching," *IEEE Trans. Power Syst.*, vol. 31, no. 1, pp. 508–517, Jan. 2016, doi: 10.1109/TPWRS.2015.2409152.

[150] P. Dehghanian and M. Kezunovic, "Probabilistic decision making for the bulk power system optimal topology control," *IEEE Trans. Smart Grid*, vol. 7, no. 4, pp. 2071–2081, Jul. 2016, doi: 10.1109/TSG.2016.2544794.

[151] M. T. Hagh, M. Z. Gargari, and M. J. V. Pakdel, "Sequential analysis of optimal transmission switching with contingency assessment," *IET Gener., Transmiss. Distrib.*, vol. 12, no. 6, pp. 1390–1396, Mar. 2018, doi: 10.1049/iet-gtd.2017.0435.

[152] W. E. Brown and E. Moreno-Centeno, "Transmission-line switching for load shed prevention via an accelerated linear programming approximation of AC power flows," *IEEE Trans. Power Syst.*, vol. 35, no. 4, pp. 2575–2585, Jul. 2020, doi: 10.1109/TPWRS.2020.2969625.

[153] T. Han, Y. Song, and D. J. Hill, "Ensuring network connectedness in optimal transmission switching problems," *IEEE Trans. Circuits Syst. II, Exp. Briefs*, vol. 68, no. 7, pp. 2603–2607, Jul. 2021, doi: 10.1109/TCSII.2021.3059070.

[154] R. Saavedra, A. Street, and J. M. Arroyo, "Day-ahead contingency-constrained unit commitment with co-optimized post-contingency transmission switching," *IEEE Trans. Power Syst.*, vol. 35, no. 6, pp. 4408–4420, Nov. 2020, doi: 10.1109/TPWRS.2020.2996499.
[155] S. Pinzon, D. Carrion, and E. Inga, "Optimal transmission switching considering N-1 contingencies on power transmission lines," *IEEE Latin Amer. Trans.*, vol. 19, no. 4, pp. 534–541, Apr. 2021.
[156] T. Han, D. J. Hill, and Y. Song, "Formulating connectedness in security-constrained optimal transmission switching problems," *IEEE Trans. Power Syst.*, vol. 37, no. 5, pp. 4137–4140, Sep. 2022, doi: 10.1109/TPWRS.2022.3184122.
[157] T. Hussain, S. Suryanarayanan, T. M. Hansen, and S. M. S. Alam, "A fast and scalable transmission switching algorithm for boosting resilience of electric grids impacted by extreme weather events," *IEEE Access*, vol. 10, pp. 57893–57901, 2022, doi: 10.1109/ACCESS.2022.3179470.
[158] A. Delgadillo, J. M. Arroyo, N. Alguacil, J. M. Arroyo, and N. Alguacil, "Analysis of electric grid interdictionwith line switching," *IEEE Trans. Power Syst.*, vol. 25, no. 2, pp. 633–641, May 2010.
[159] T. Amraee and H. Saberi, "Controlled islanding using transmission switching and load shedding for enhancing power grid resilience," *Int. J. Electr. Power Energy Syst.*, vol. 91, pp. 135–143, Oct. 2017, doi: 10.1016/j.ijepes.2017.01.029.
[160] Z.-A. Sergio, P. B. Tatiana, B. D. Stalin, L. G. Edwin, and F. J. Fredy, "Optimal subtransmission switching using a reliability simulation-based multi-objective optimization model," *Electric Power Syst. Res.*, vol. 210, Sep. 2022, Art. no. 108068, doi: 10.1016/j.epsr.2022.108068.
[161] Y. Ding, C. Singh, L. Goel, J. Østergaard, and W. Wang, "Short-term and medium-term reliability evaluation for power systems with high penetration of wind power," *IEEE Trans. Sustain. Energy*, vol. 5, pp. 896–906, 2014, doi: 10.1109/TSTE.2014.2313017.
[162] M. Khaji and M. R. Aghamohammadi, "Emergency transmission line switching to suppress power system inter-area oscillation," *Int. J. Electr. Power Energy Syst.*, vol. 87, pp. 52–64, May 2017, doi: 10.1016/j.ijepes.2016.10.011.
[163] A. Khodaei and M. Shahidehpour, "Security-constrained transmission switching with voltage constraints," *Int. J. Electr. Power Energy Syst.*, vol. 35, no. 1, pp. 74–82, Feb. 2012, doi: 10.1016/j.ijepes.2011.09.014.
[164] M. Heidarifar, P. Andrianesis, P. Ruiz, M. C. Caramanis, and I. C. Paschalidis, "An optimal transmission line switching and bus splitting heuristic incorporating AC and N-1 contingency constraints?" *Int. J. Electr. Power Energy Syst.*, vol. 133, pp. 1–10, Jan. 2021, doi: 10.1016/j.ijepes.2021.107278.
[165] P. Balasubramanian, M. Abdi-Khorsad, S. Korad, and K. W. Hedman, "Effect of topology control on system reliability: TVA test case," in *Proc. CIGRE US Nat. Committee Grid Future Symp.*, 2014, pp. 1–8.
[166] F. Pourahmadi, M. Jooshaki, and S. H. Hosseini, "A dynamic programming-based heuristic approach for optimal transmission switching problem with N-1 reliability criterion," in *Proc. Int. Conf. Probabilistic Methods Appl. Power Syst. (PMAPS)*, Oct. 2016, pp. 1–5, doi: 10.1109/PMAPS.2016.7764208.
[167] P. Masache, D. Carrion, and J. Cardenas, "Optimal transmission line switching to improve the reliability of the power system considering AC power flows," *Energies*, vol. 14, pp. 1–17, Jun. 2021.
[168] X. Li, "Real-time contingency analysis with corrective transmission switching," *IEEE Trans. Power Syst.*, vol. 32, no. 4, pp. 2604–2617, Jul. 2017.
[169] M. Sahraei-Ardakani, X. Li, P. Balasubramanian, K. W. Hedman, and M. Abdi-Khorsand, "Real-time contingency analysis with transmission switching on real power system data," *IEEE Trans. Power Syst.*, vol. 31, no. 3, pp. 2501–2502, May 2016, doi: 10.1109/TPWRS.2015.2465140.
[170] M. Lu, H. Nagarajan, E. Yamangil, R. Bent, S. Backhaus, and A. Barnes, "Optimal transmission line switching under geomagnetic disturbances," *IEEE Trans. Power Syst.*, vol. 33, no. 3, pp. 2539–2550, May 2018, doi: 10.1109/TPWRS.2017.2761178.
[171] M. Li, P. B. Luh, L. D. Michel, Q. Zhao, and X. Luo, "Corrective line switching with security constraints for the base and contingency cases," *IEEE Trans. Power Syst.*, vol. 27, no. 1, pp. 125–133, Feb. 2012, doi: 10.1109/TPWRS.2011.2164098.
[172] S. Yang, W. Chen, X. Zhang, and Y. Jiang, "Blocking cascading failures with optimal corrective transmission switching considering available correction time," *Int. J. Electr. Power Energy Syst.*, vol. 141, no. Nov. 2021, pp. 1–12, 2022, doi: 10.1016/j.ijepes.2022.108248.
[173] X. Li and K. W. Hedman, "Enhanced energy management system with corrective transmission switching strategy—Part I: Methodology," *IEEE Trans. Power Syst.*, vol. 34, no. 6, pp. 4490–4502, Nov. 2019.
[174] X. Li and K. W. Hedman, "Enhanced energy management system with corrective transmission switching strategy—Part II: Results and discussion," *IEEE Trans. Power Syst.*, vol. 34, no. 6, pp. 4503–4513, Nov. 2019.
[175] A. S. Korad and K. W. Hedman, "Robust corrective topology control for system reliability," *IEEE Trans. Power Syst.*, vol. 28, no. 4, pp. 4042–4051, Nov. 2013, doi: 10.1109/TPWRS.2013.2267751.
[176] T. Ding and C. Zhao, "Robust optimal transmission switching with the consideration of corrective actions for N-K contingencies," *IET Gener., Transmiss. Distrib.*, vol. 10, no. 13, pp. 3288–3295, Oct. 2016, doi: 10.1049/iet-gtd.2016.0126.
[177] G. Ayala and A. Street, "Energy and reserve scheduling with post-contingency transmission switching," *Electr. Power Syst. Res.*, vol. 111, pp. 133–140, Jun. 2014, doi: 10.1016/j.epsr.2014.02.014.
[178] S. Abbas, T. Khorram, and M. Fotuhi-firuzabad, "Optimal transmission switching as a remedial action to enhance power system reliability," in *Proc. Smart Grids Conf.*, 2016, pp. 1–6, doi: 10.1109/SGC.2016.7882944.
[179] A. R. Bhowmik, A. K. Chakraborty, and S. Mukherjee, "Impact of sensitivity index based transmission network topology control on contingency constraints," in *Proc. 20th Int. Conf. Intell. Syst. Appl. to Power Syst. (ISAP)*, Dec. 2019, pp. 1–7, doi: 10.1109/ISAP48318.2019.9065962.
[180] M. Khanabadi, H. Ghasemi, and M. Doostizadeh, "Optimal transmission switching considering voltage security and N-1 contingency analysis," *IEEE Trans. Power Syst.*, vol. 28, no. 1, pp. 542–550, Feb. 2013, doi: 10.1109/TPWRS.2012.2207464.
[181] R. Xiao, Y. Xiang, L. Wang, and K. Xie, "Power system reliability evaluation incorporating dynamic thermal rating and network topology optimization," *IEEE Trans. Power Syst.*, vol. 33, no. 6, pp. 6000–6012, Nov. 2018, doi: 10.1109/TPWRS.2018.2829079.
[182] H. Zhang, H. Cheng, J. Zhang, J. Lu, and C. Li, "Stochastic optimal transmission switching considering N-1 security constraints," in *Proc. IEEE Power Energy Soc. Gen. Meeting (PESGM)*, Aug. 2018, pp. 1–5, doi: 10.1109/PESGM.2018.8586358.

MUHAMMAD NUMAN received the B.Eng. degree in electrical engineering from the National University of Sciences and Technology (NUST), Islamabad, Pakistan, in 2013, the M.Sc. degree in electric power systems from North China Electric Power University (NCEPU), Beijing, China, in 2016, and the Ph.D. degree in electrical engineering from Shanghai Jiao Tong University (SJTU), Shanghai, China, in 2021. He is currently an Assistant Professor with the U.S.-Pakistan Center for Advanced Studies in Energy, NUST. His current research interests include power system operation, optimization, network expansion planning, transmission network topologies, and optimal integration of renewable energy sources.

MUHAMMAD FARASAT ABBAS was born in Multan, Pakistan, in February 1992. He received the M.S. and Ph.D. degrees in electrical engineering from Xián Jiaotong University (XJTU), China, in July 2015 and July 2021, respectively. He is currently an Assistant Professor with the Electrical Power Engineering Department, U.S.-Pakistan Center for Advanced Studies in Energy (USPCAS-E), National University of Sciences and Technology (NUST), Pakistan. He is also associated with the High Voltage Laboratory, NUST. His research interests include high-voltage insulation, low-temperature discharge plasma, and power system protection.

MUHAMMAD YOUSIF received the bachelor's degree in electrical engineering from the National University of Sciences and Technology (NUST), Islamabad, Pakistan, in 2012, the master's degree from Xi'an Jiaotong University (XJTU), Xi'an, China, in 2014, and the Ph.D. degree from Shanghai Jiao Tong University (SJTU), Shanghai, China, in 2019. He is currently an Assistant Professor with the U.S.-Pakistan Center for Advanced Studies in Energy, NUST. His research interests include power systems optimization, microgrid, distributed generation, and dispatch algorithms.

SHERIF S. M. GHONEIM (Senior Member, IEEE) received the B.Sc. and M.Sc. degrees from the Faculty of Engineering at Shoubra, Zagazig University, Egypt, in 1994 and 2000, respectively, and the Ph.D. degree in electrical power and machines from the Faculty of Engineering, Cairo University, in 2008. Since 1996, he has been teaching with the Faculty of Industrial Education, Suez Canal University, Egypt. From 2005 to 2007, he was a Guest Researcher with the Institute of Energy Transport and Storage (ETS), University of Duisburg–Essen, Germany. He joined the Electrical Engineering Department, Faculty of Engineering, Taif University, as an Associate Professor. His research interests include grounding systems, dissolved gas analysis, breakdown in SF6 gas, and AI technique applications.

ALSHAREF MOHAMMAD (Member, IEEE) was born in Taif, Saudi Arabia, in 1985. He received the bachelor's degree (Hons.) in electrical engineering science from the King Fahd University of Petroleum and Minerals (KFUPM), in 2007, and the M.Sc. degree in electrical and computer engineering and the Ph.D. degree in electrical and computer engineering from the University of Western Ontario (UWO), London, Canada, in 2011 and 2016, respectively. In 2014, he joined the Department of Electrical Engineering, Taif University, as a Lecturer. In 2016, he has been promoted as an Assistant Professor with Taif University, where he taught several courses in the area of electrical engineering. In 2018, he has been assigned as the Head of the Electrical Engineering Department, Taif University. His research interests include wireless communications, digital communications, spread spectrum techniques, and continuous phase modulation techniques.

ABDULFATTAH NOORWALI received the Ph.D. degree in electrical and computer engineering from the University of Western Ontario, London, ON, Canada, in 2017. He is currently the Chairperson of the Electrical and Computer Engineering Department, Faculty of Engineering and Islamic Architecture, Umm AlQura University, where he is also an Assistance Professor. He is also a Senior Consultant with the Umm Al-Qura Consultancy Oasis, Institute of Consulting Research and Studies (ICRS), Umm Al-Qura University, where he is also the Chairperson of the Vision Office of Consultancy. His research interests include smart grid communications, cooperative communications, wireless networks, the Internet of Things, crowd management applications, and smart city solutions.