Journal of Electrical Engineering, Electronics, Control and Computer Science – JEEECCS, Volume 7, Issue 24, pages 21-30, 2021

A Review of Challenges for Security - Constrained Transmission Expansion Planning

Umair Shahzad
Department of Electrical and Computer Engineering,
University of Nebraska-Lincoln,
Lincoln, NE, USA
umair.shahzad@huskers.unl.edu

***Abstract* –The increasing demand and the corresponding rising penetration of renewable energy generation has brought various challenges for the power system. In this regard, expansion planning of the system is exceedingly significant. Commonly, power system expansion is categorized into generation, transmission, and distribution domains. As the investment involved in transmission expansion planning (TEP) is usually greater than the other two domains, thus, this paper focuses on TEP. The main aim of TEP is to install new devices on a transmission grid to optimize a variable, based on an objective function, while fulfilling some pre-defined technical and economic constraints. The non-linear and non-convex nature of TEP, along with system uncertainties (load, renewable generation, etc.), makes it a stimulating issue. Moreover, the combinatorial explosion of investment replacements, bundled with (*N-1)* security constraints, generally necessitates a huge computational effort to solve it. The security-constrained transmission expansion planning (SCTEP) has various challenges. Thus, the main objective of this research is to review and present some challenges associated with SCTEP problem.**

Keywords- Renewable energy; security; transmission expansion planning; uncertainty; wind

I. INTRODUCTION AND OVERVIEW

A typical electric power system, or an electric grid, consists of three major components: generation, transmission and distribution [1-2], as outlined in Fig. 1. The role of generation is to produce electric power to be able to meet the demand of consumers. The transmission system acts as a bridge to fulfil this significant role.

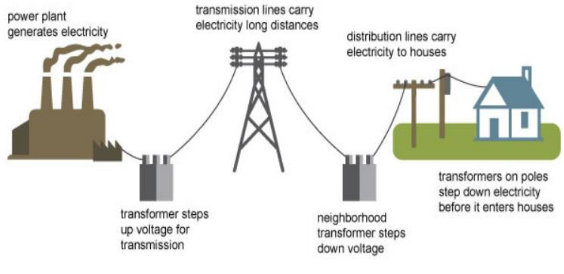

Fig. 1. Components of a typical power system

Transmission system is the crux of a power system. It serves as a bridge between generation and distribution entities. The planning for transmission expansion is a significant problem and must be given due attention. Transmission Expansion Planning (TEP) problem determines the timing, number, and location of transmission lines to be installed to an existing transmission network to proficiently fulfil some objective(s), subject to certain operational constraints. It is one of the most critical decisions in the power system, as it is quite capital intensive and hence, has an enduring effect on the power system operation. With the recent advances in renewable generation, particularly, wind and photovoltaic (PV) generation, this problem has become complicated and must be given consideration [1-3]. TEP has been studied in the academic and research context for years due to its vast significance. Moreover, the uncertainties inherent in the power system and the combinatorial nature of TEP are challenging research issues [4].

Based on the time horizon, TEP problem is generally categorized as static (or single-stage) and dynamic (or multi-stage) planning, as outlined in Fig. 2. In single-stage planning, time horizon is ignored and the optimal plan is evaluated for a single period. On the contrary, in dynamic planning, the years of horizon are distinctly analyzed and new lines for each year are installed individually. Thus, dynamic planning is more complex and time-consuming. The TEP can also be characterized into short-term, mid-term and long-term planning, as shown in Fig. 3. There is no fixed rule for this categorization, but generally, long-term planning has a time-scale of decades (usually 20-30 years); medium-term planning deals with time scales of 10-20 years, and short-term planning deals with issues that must be addressed within 10 years [5-6]. TEP problem can be represented using DC or AC power flow (AC PF) model. DC power flow is a simple linearization of a full AC power flow. DC power flow model only considers real load flows. It neglects voltage support (assumes a flat voltage profile), reactive power control, and transmission losses. Full AC load flow considers both real and reactive power. Though, a full AC PF calculation requires widespread computational effort, particularly, when incorporating *(N-1)* contingency [7-8].

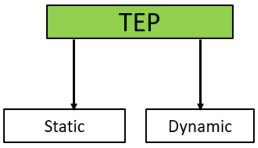

Fig. 2. TEP classification (based on planning horizon)

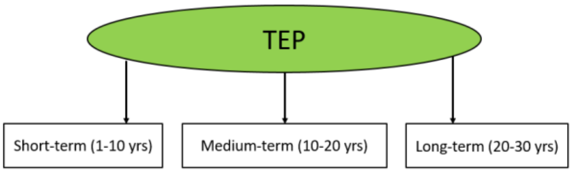

Fig. 3. TEP classification (based on years)

There are two basic solution approaches to solve a TEP problem: classical and non-classical (heuristic/metaheuristic). This is outlined in Fig. 4. The former includes linear programming [9], quadratic programming [10], Mixed Integer Programming (MIP) [11], dynamic programming [4], Benders' decomposition [12], branch-bound method [13], and mixed-integer nonlinear programming (MINLP) [14]. The MIP is the most commonly used methodology in the domain of classical methods, as it can deal appropriately with DC power flow (DC PF) [15-16]. Although, some researches [17-18] use MINLP to accommodate the nonlinearities of an AC PF; however, these methods are used to evaluate an obtained solution, rather than searching the optimal plan. To counter these issues, non-classical methods are suggested. These methods involve meta-heuristic approaches such as Expert system [19], Greedy randomized search [20], Harmony search [21], Tabu search [22], Genetic algorithm [23], Simulated annealing [24], Particle swarm intelligence [25], Ant colony optimization [26], Grey wolf optimization [27] and Differential evolution [28]. A metaheuristic is an advanced heuristic whose goal is to generate a heuristic (partial search algorithm). In this manner, an approximate solution can be determined [29]. Classical approaches determine the optimal solution, which is usually accurate, with a suitable convergence. However, such approaches suffer from two major drawbacks: (1) changing power system equations into optimization programming model is problematic and cumbersome in large scale power systems, and (2) the model should be reorganized to incorporate a new constraint [5].

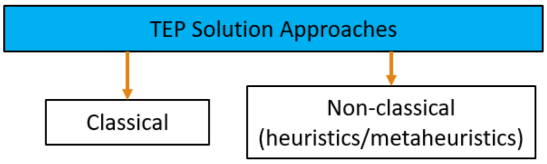

Fig. 4. Common TEP solution approaches

Heuristic methods provide an acceptable substitute to the classical optimization methods. Generally, in such techniques, the computational performance and the convergence are superior when compared with the classical approaches. However, these methods are not robust. This is because the local search approaches frequently stop at local optimum [30]. Metaheuristic methods are very straightforward. These approaches do not require conversion of power system model into an optimization programming set. A typical power system software can easily conduct the power system analysis. However, these methods have three main weaknesses: (1) the optimal solution is approximate, (2) large simulation time, and (3) the solution is trapped in local minima [5].

TEP is a large-scale, highly constrained, mixed-integer, non-linear, and non-convex optimization problem. In terms of computational complexity theory, it falls under the category of *NP* (nondeterministic polynomial time)-hard optimization problem, i.e., it cannot be solved in polynomial time [31]. This implies that obtaining an optimal solution is very hard, especially for large-scale systems. In addition, the inclusion of *(N-1)* security constraints further exacerbates the complexity and computation time. TEP is a very flexible problem in the sense that it can have different objective functions, subject to different constraints. The objective function is usually the investment cost. The constraints are normally known as mandatory and optional constraints. The mandatory constraints consist of power system operational constraints, such as active and reactive power limits of generators, limits of bus voltage levels, limits of power flows, etc. The optional constraints are environmental impact limits, social welfare, etc. Mandatory constraints must be included in the TEP problem; however, the optional constraints provide more flexibility [5, 32]. It is worth mentioning that not all TEP problems consider the security constraints. Although, the security constraints can be considered in either mandatory or optional constraints, but majority of researchers agree on the former [32]. An avid reader can refer to [33-47] for reviewing the research relevant to security-constrained transmission expansion planning (SCTEP). A generic framework for a typical SCTEP problem is shown in Fig. 5.

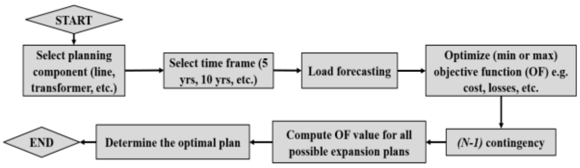

Fig. 5. Generic framework for a typical SCTEP problem

To the best of author's knowledge, there is no existing research work available, specifically, on the challenges associated with SCTEP. Thus, the key motive of this research paper is to review these challenges. The rest of the paper is organized as follows. Section II discusses the challenges associated with SCTEP. Section III concludes the paper with a suggested future research direction.

II. CHALLENGES FOR SECURITY-CONSTRAINED TRANSMISSION EXPANSION PLANNING

This section aims to discuss some of the challenges associated with SCTEP problem. The challenges are pictorially outlined in Fig. 6. The discussion is as follows.

A. Deregulation and Market Considerations

In a regulated (central) electricity market scenario, the SCTEP objective generally is to minimize the investment cost of new transmission lines, subject to operational and financial constraints; but in deregulated electricity markets, the key goal is to supply a competitive environment, which does not differentiate between stakeholders [36]. This deregulation implies that the TEP, which was traditionally centrally performed, is now a decision taken privately by the companies participating in the generation market [48]. This is particularly significant considering that, while building a power plant can take around one to three years for some technologies, transmission projects have a much longer lead-time (normally 20-30 years). The incorporation of market considerations considerably increases the complexity of the SCTEP problem, but this inclusion can provide realistic results. This deregulation also impacts the procedure of coordinated GEP and TEP. As there will be no co-operation between the two individual entities under deregulation, it is difficult to optimize system planning process. Fig. 7 shows a typical deregulation structure for power system markets.

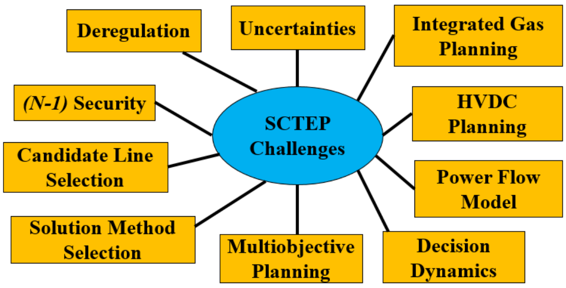

Fig. 6. Major challenges for a SCTEP problem

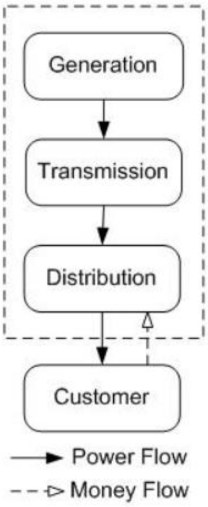

Fig. 7. Typical structure of deregulation of power system markets

B. Uncertainties

Renewable generation (wind and PV) and load introduces the most common uncertainties for SCTEP problem. As wind and PV are intermittent and non-dispatchable sources of energy, there is no way to ascertain when they will be generating power and at what rate. In addition, loads are highly distributed and change on various basis: hourly, daily, weekly, monthly, seasonal, etc. Other uncertainties, which must be incorporated for a realistic SCTEP problem are, supply-side price, availability of power system components, market uncertainties, fuel availability, weather uncertainties, fault type, fault location (in case of stability assessment) etc. The presence of deregulated market further exacerbates this issue, as some specific information regarding transmission expansion, such as generator cost function, are confidential, which cannot be obtained by the planner [5]. The planner only has limited information based on which the decision must be taken. Additional uncertainties are introduced due to bidding behavior of generation companies (GENCOs), market trading rules, and government policies. To make the matters worse, there is a requirement to model correlation between certain input random variables, for instance, correlation among power generations (wind farms, PV, etc.) [49], correlation among system loads [50], and correlation between generation sources and loads [51]. The ignorance of these dependencies can lead to a fallacy in determining the optimal expansion plan. The inclusion of uncertainty and correlation among variables necessitate the use of novel approaches. Although, some approaches exist to quantify uncertainty, such as Monte-Carlo (MC) simulation [52] and point estimate method [53], however, choosing an optimum method amongst them is a significant decision-making challenge. Uncertainties introduced by high impact low probability (HILP) events, such as natural disasters (hurricanes, earth quakes, floods, etc.), extreme weather (ice storms, heat waves, high winds, etc.), cyber-attacks, etc. can prove fatal to the power system and can have an adverse impact on the SCTEP problem. The core challenge in this regard is to model these phenomena and their associated impact accurately enough to be incorporated in a SCTEP problem. Although, this falls under the category of power system resilience, it is significant to propose modeling approaches to incorporate resilience in SCTEP problem. At present, there is very limited literature [54-56] on this area and further research is required in this domain [57-59]. Some common sources of uncertainty in power system are outlined in Fig. 8.

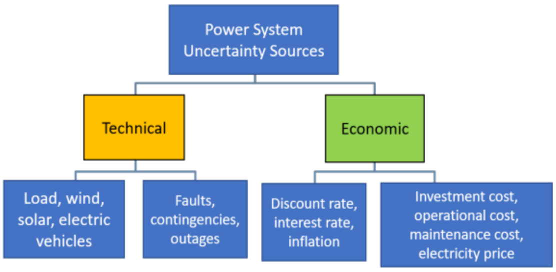

Fig. 8. Common sources of uncertainty in power system

C. Decision Dynamics

As mentioned before, there are two types of TEP (static and dynamic). This is illustrated in Fig. 9. Considerable effort is required to choose which one is the best for a project. There is generally no fixed rule for this, but generally, static planning is preferred for a short-term TEP problem, where the decisions are not required to be revised. For longer-time horizons, dynamic planning is suitable, but its implementation is cumbersome, due to large size of real power systems. Moreover, the number of binary investment variables linearly increase with the number of time stages consider in dynamic planning [60]. Based on [61], the dynamic planning results in a superior and cost-effective planning, but it is complicated, and takes a large amount of time.

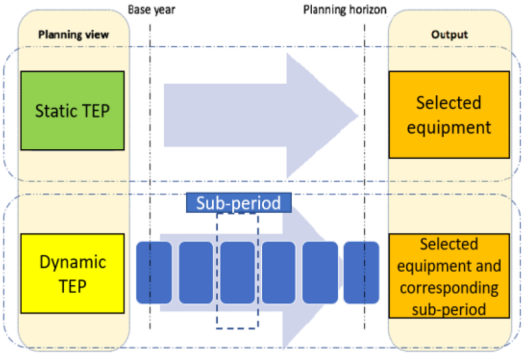

Fig. 9. Different dynamics for SCTEP decision-making

D. *Multiobjective Planning*

Naturally, TEP is a multi-objective problem. These objectives normally include operation cost [62-64], investment cost [19, 65-66], and transmission congestion cost [12]. Other relevant objectives are social acceptance of new corridors, renewable generation integration [67-68], system stability [69-70], system losses [71-72], and carbon emission [73-75]. When the comparative position of the objectives is lucid, it is easy to define weights and thus, using one aggregate objective is the most apt technique. On the other hand, when the tradeoffs are not understandable, and the objectives are conflicting each other (such as minimizing cost and maximizing reliability), multi criteria methods, such as Pareto-optimal methods, weighted sum methods, ε-constraint method, etc. are generally more adequate. These methods have several advantages and disadvantages, for instance; weighted sum methods are comparatively easy to apply, but critical solutions can be overlooked; On the contrary, Pareto-optimal (non-dominated) solutions allow a comprehensive view of the solutions, but their generation can be quite difficult. Fig. 10 shows a graphical version of Pareto-optimal front and dominated solutions for two different objective functions. Similarly, Fig. 11 demonstrates the advantage of ε-constraint method over the weighted sum method for obtaining solutions in non-convex regions. Therefore, a unified criterion to choose a multiobjective optimization method for multiple conflicting objectives, with overlapping interests, is required. Moreover, for multiobjective optimization problems, with more than three objectives, the optimization becomes extremely complicated and the computation complexity increases exponentially. The research on the use of appropriate dimensionality reduction approaches, without compromising the solution accuracy, is a challenging task.

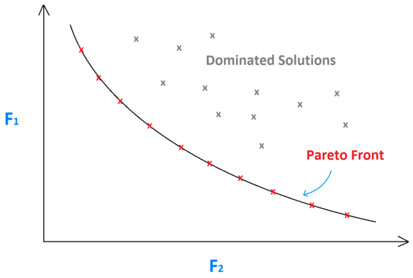

Fig. 10. Pareto-optimal front and dominated solutions

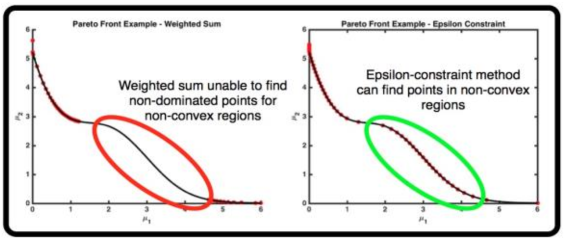

Fig. 11. Superiority of ε -constraint method for non-convex regions.

E. *Power Flow Model*

Generally, two different models are used in SCTEP problem, as outlined in Fig. 12. Majority of SCTEP problems use DC PF [42, 76-82]. The DC model neglects losses, reactive power and voltage limits [83]. It offers a good approximation at a low computational cost on the expense of sacrificing the accuracy. Moreover, ignoring losses for a long-term SCTEP problem can be critical, as it can result in the selection of a suboptimal expansion plan. The AC PF can incorporate voltage limits, reactive power flows, stability, and transmission losses [84-87].

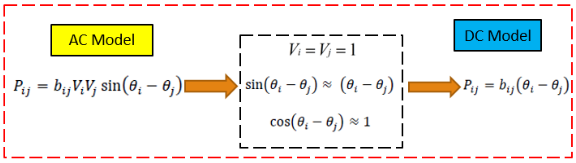

Fig. 12. Two power flow models for SCTEP problem

F. *Integrated Planning with Natural Gas Systems*

In recent times, the interdependency of natural gas system and power system has vastly augmented [88-90]. Conventionally, power systems and natural gas systems are planned separately. As these two energy systems become gradually interconnected [91], it is beneficial to model their joint expansion planning [92]. In majority of relevant researches, the overall system reliability was found to decrease. Moreover, traditionally, contingencies of natural gas system are not considered and are assumed to be 100% reliable. However, natural gas system failure can jeopardize the power system reliability if they are not included in the TEP problem. Combined with *(N-1)* security criterion, this further exacerbates the computational tractability of the TEP problem. Although, in the literature, each of natural gas systems and electric power systems are well-researched individually; however, there are only a limited number of researches on natural gas-electric integrated TEP [93-99]. There is a need to propose a unified approach for incorporating natural gas systems in the SCTEP, including, but not limited to, wells, pipelines, etc. The economic aspects of gas, such as gas price and gas contracts, gas supply constraints, limited transmission capacity of pipeline network, etc. could also impact the natural gas supply adequacy and hence, the TEP. Further research is required in this area. A generic framework for integrated security-constrained power-natural gas planning is shown in Fig. 13.

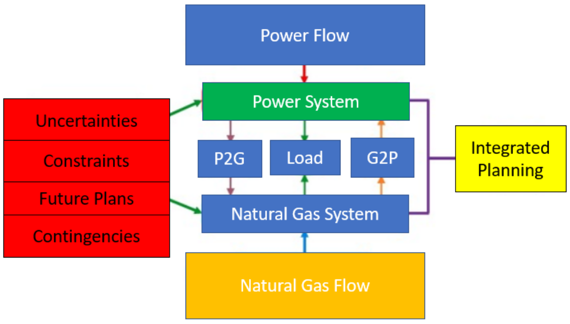

Fig. 13. Generic framework for integrated security-constrained power-natural gas planning

G. HVDC Consideration

Nearly, all research works on SCTEP deal with high voltage AC (HVAC) planning; however, there is a very limited literature [100-101] which does incorporate HVDC into TEP, but without considering security constraints. HVDC system has few advantages [102]: (1) HVDC system can transfer higher amount of power per conductor; (2) the HVDC system can control the power flow. Although, HVDC lines can be more attractive; however, there are certain challenges to its seamless integration into HVAC system-based SCTEP problem [103]: (1) The market for HVDC has been comparatively minor, and there are only a few manufacturers which can provide such systems. (2) The power loss in a HVDC converter station is greater than that in an AC substation. Appropriate techniques need to be developed to conduct a comprehensive benefit-cost analysis for future HVDC-based SCTEP projects. Fig. 14 and Fig. 15 illustrate the layout of a typical HVDC substation and typical components of a HVDC system, respectively.

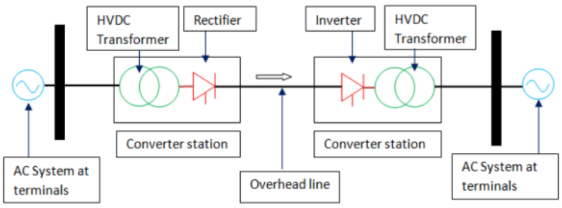

Fig. 14. Layout of a typical HVDC substation

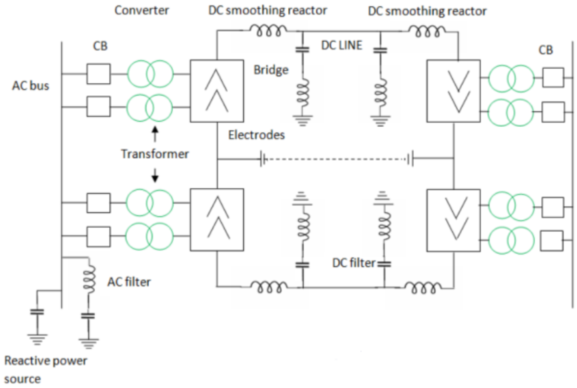

Fig. 15. Typical components of a HVDC system

H. Choosing a Solution Method

In the past few years, power transportation models were used for TEP. These models disregard the power flow constraints and thus, deliver an approximate solution which may not be optimal [104]. Most of the research on SCTEP problems uses DC flow models and hence, apply MILP for optimization. Research that uses AC based models applies MINLP. Obviously, the former is faster, but gives an approximate solution at the expense of accuracy. The latter is computationally intensive with no guarantee of a global solution. Some researches propose heuristic methods to counter this dilemma, but still they give an approximate solution. Moreover, heuristic approaches pose the risk of falling into a local minimum rather than a global minimum. A method which can give fast results, with a reasonable accuracy, is the need of the hour [30].

I. Selection of Candidate Lines

Generally, solving a SCTEP problem involves selecting the transmission lines, from a set of candidate lines, to build to satisfy given constraints, while optimizing an objective function. Majority of existing research assumes that candidate lines are manually selected or/and are based on planner’s engineering judgement and previous experience [1, 37-38, 46, 105]. Other research works [42, 60, 106-108] select all existing transmission corridors as location of candidate lines, while a few of them choose them just randomly [109-111]. This approach may be suitable for a small system, but for a large system, this results in huge computation burden (for n candidate lines, the expansion plans are 2^n-1). There is very limited literature on selection of candidate lines for a SCTEP problem, for instance, [112] uses line congestion to select candidate lines, but it uses approximate (DC) model and ignores the uncertainties introduced by wind generation. However, the current context of the power system requires approaches that should not depend on the planner’s expertise to suggest the investment alternatives. Even small inaccuracies, because of limited planners’ experience/judgement, can cause huge losses for the system. This may result in implementation of a suboptimal expansion plan. Therefore, an appropriate methodology must be devised to select the candidate lines.

J. Incorporating (N-1) Security Criterion

Employing *(N-1)* security criterion for all contingencies may be suitable for a small power system but for a large system, this entails a huge computation burden. Combined with the AC PF optimization, the SCTEP problem becomes too complex and time-consuming. Almost, all research works [38, 106, 113-116] incorporate this security criterion deterministically by considering either every possible *(N-1)* contingency, or pre-selecting them before the analysis. Moreover, to counter the computation burden issue, majority of these works use the DC PF based optimization. Obviously, this is at the expense of a much better accurate solution. Therefore, some procedure must be devised to consider the *(N-1)* security criterion probabilistically and to reduce the computation burden without sacrificing the accuracy.

To conclude the discussion, it can be inferred that there are various challenges which need to be addressed for TEP, with security constraints. With the rising importance of renewable energy resources, the demand to transform the existing power system to a smart grid, the increasing high-risk events (cyber attacks, natural disasters, severe weather, etc.) and probabilistic risk assessment approaches in power system [117-124], it is very important to come up with efficient solutions and plans to counter these challenges.

This study reviewed some major challenges which are encountered in the process of SCTEP. This can be an excellent starting point for researchers in the field of power system planning. Moreover, the present study can be useful for suggesting novel solutions to the challenges presented.

III. CONCLUSION AND FUTURE WORK

Efficient TEP, considering the security constraints, is very imperative for proper operation of power system. Without this, the system will collapse and would not perform as desired. There are many hurdles in the way of successful implementation of SCTEP. This paper reviewed some major challenges associated with SCTEP. These challenges include deregulation, uncertainties, decision dynamics, multiobjective planning, power flow model, integrated planning with natural gas systems, considering HVDC, choosing a solution method, selecting candidate lines, and incorporating *(N-1)* security criterion. It is important to research and devise plausible solutions to these challenges. It is believed that this review would provide a good starting point for any research in the domain of power system planning and would certainly be helpful for further research on the significant area of power system planning under security constraints.

REFERENCES

[1] S. Lumbreras and A. Ramos, “The new challenges to transmission expansion planning. Survey of recent practice and literature review”, *Electric Power Systems Research*, vol. 134, pp. 19-29, May 2016.

[2] J. Kaltenbach, J. Peschon and E. H. Gehrig, "A mathematical optimization technique for the expansion of electric power transmission systems," in *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-89, no. 1, pp. 113-119, Jan. 1970.

[3] T. Chaniotis, “Security of supply, sustainability, competitiveness. A European approach”, ENTSO-E, 2012.

[4] Y. P. Dusonchet and A. El-Abiad, "Transmission planning using discrete dynamic optimizing," in *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-92, no. 4, pp. 1358-1371, July 1973.

[5] R. Hemmati et al., “State-of-the-art of transmission expansion planning: Comprehensive review”, *Renewable and Sustainable Energy Reviews*, vol. 23, pp. 312-319, July 2013.

[6] W. Li, Probabilistic Transmission System Planning, Feb. 2011, Wiley.

[7] D. V. Hertem et al., "Usefulness of DC power flow for active power flow analysis with flow controlling devices," *The 8th IEE International Conference on AC and DC Power Transmission*, London, UK, 2006, pp. 58-62.

[8] N. S. Verma and V. Mukherjee, "Transmission expansion planning: A review," *2016 International Conference on Energy Efficient Technologies for Sustainability (ICEETS)*, Nagercoil, 2016, pp. 350-355.

[9] R. Villasana, L. L. Garver and S. J. Salon, "Transmission Network Planning Using Linear Programming," in *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-104, no. 2, pp. 349-356, Feb. 1985.

[10] Z.M. Al-Hamouz, A.S. Al-Faraj, “Transmission-expansion planning based on a non-linear programming algorithm”, *Applied Energy*, 76, pp. 169-177, 2003.

[11] L. Bahiense et al., “A mixed integer disjunctive model for transmission network expansion”, *IEEE Transactions on Power Systems*, vol. 16, pp. 560-565, Aug. 2001.

[12] O. B. Tor, A. N. Guven and M. Shahidehpour, "Congestion-Driven Transmission Planning Considering the Impact of Generator Expansion," in *IEEE Transactions on Power Systems*, vol. 23, no. 2, pp. 781-789, May 2008.

[13] J. Choi, T. D. Mount and R. J. Thomas, "Transmission Expansion Planning Using Contingency Criteria," in *IEEE Transactions on Power Systems*, vol. 22, no. 4, pp. 2249-2261, Nov. 2007.

[14] J. Mareček, M. Mevissen and J. C. Villumsen, "MINLP in transmission expansion planning," *2016 Power Systems Computation Conference (PSCC)*, Genoa, 2016, pp. 1-8.

[15] S. T. Y. Lee, K. L. Hicks and E. Hnyilicza, "Transmission Expansion by Branch-and-Bound Integer Programming with Optimal Cost - Capacity Curves," in *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-93, no. 5, pp. 1390-1400, Sept. 1974.

[16] S. Lumbreras and A. Ramos, "Transmission expansion planning using an efficient version of Benders' decomposition. A case study," *2013 IEEE Grenoble Conference*, Grenoble, 2013, pp. 1-7.

[17] J. Alseddiqui and R. J. Thomas, "Transmission expansion planning using multi-objective optimization," *2006 IEEE Power Engineering Society General Meeting*, Montreal, Que., 2006, pp.1-8.

[18] M. Rahmani, M. Rashidinejad, E.M. Carreno, R. Romero, “Efficient method for AC transmission network expansion planning”, *Electr. Power Syst. Res*. 80, pp. 1056–1064, 2010.

[19] N. F. Silva et al., “Development of an expert system for long-term planning of power transmission networks, *Proceedings of the 2nd Symposium Experts Syst Applicat Power Syst*, pp. 237–42, 1989.

[20] S. Binato, G. C. de Oliveira and J. L. de Araujo, "A greedy randomized adaptive search procedure for transmission expansion planning," in *IEEE Transactions on Power Systems*, vol. 16, pp. 247-253, May 2001.

[21] A. Verma, B. K. Panigrahi and P. R. Bijwe, "Harmony search algorithm for transmission network expansion planning," in *IET Generation, Transmission & Distribution*, vol. 4, no. 6, pp. 663-673, June 2010.

[22] F. Wen, C.S. Chang, “Transmission network optimal planning using the Tabu search method”, *Electr. Power Syst. Res.*, vol. 42, pp. 153–163, 1997.

[23] H.A. Gil, E.L. da Silva, “A reliable approach for solving the transmission network expansion planning problem using genetic algorithms”, *Electric Power Systems Research., vol.* 58, pp. 45–51, 2001.

[24] R. Romero, R.A. Gallego, A. Monticelli, “Transmission system expansion planning by simulated annealing”, *Power Industry Computer Application Conference,* 1995. Conference Proceedings, pp. 278–283.

[25] Y. Jin, H. Cheng, J. Yan, L. Zhang, “New discrete method for particle swarm optimization and its application in transmission network expansion planning”, *Electr. Power Syst. Res.*, vol. 77, pp. 227–233, 2007.

[26] I. Fuchs, T. Gjengedal, “Ant colony optimization and analysis of time step resolution in transmission expansion computations for wind power integration”, *Intelligent System Application to Power Systems (ISAP), 2011 16th International Conference on*, 2011, pp. 1–6.

[27] A. Khandelwal et al., “Security constrained transmission network expansion planning using grey wolf optimization algorithm”, *Journal of Statistics and Management Systems*, pp. 1239-1249, Nov. 2019.

[28] G.A. Orfanos, P.S. Georgilakis, G.N. Korres, N.D. Hatziargyriou, “Transmission expansion planning by

enhanced differential evolution", *Intelligent System Application to Power Systems (ISAP), 2011 16th International Conference on, 2011*, pp. 1–6.

[29] R. Balamurugan, A.M. Natarajan, K. Premalatha, "Stellar-Mass Black Hole Optimization for Biclustering Microarray Gene Expression Data", *Applied Artificial Intelligence an International Journal*, vol. 29, pp. 353–381, 2015.

[30] I. Alhamrouni et al., "Review on Transmission Expansion Planning Models", *Applied Mechanics and Materials*, vol. 818, pp. 129-133, 2016.

[31] J. Vaes, Optimal Transmission Expansion Planning, M.Sc. Dissertation, Aug. 2017 [Online], Available: http://uclengiechair.be/wp-content/uploads/2017/08/TFE-JVaes.pdf

[32] R. Hemmati, R. Hooshmand and A. Khodabakhshian, "Comprehensive review of generation and transmission expansion planning," in *IET Generation, Transmission & Distribution*, vol. 7, no. 9, pp. 955-964, Sept. 2013.

[33] NERC System Performance Under Normal Conditions [Online]. Available: http://www.nerc.com/files/tpl-001-0.pdf

[34] T. Akbari et al., "Security-constrained transmission expansion planning: a multi-objective approach", *IEEE 19th Iranian Conference on Electrical Engineering (ICEE); 2011*, pp. 1–6.

[35] T. Akbari, A. Rahimi-Kian, M. Tavakoli Bina, "Security-constrained transmission expansion planning: a stochastic multi-objective approach", *International Journal of Electrical Power and Energy Systems*, vol. 43, pp. 444-453, 2012.

[36] I. de J Silva et al., "Transmission network expansion planning with security constraints", *IET Generation, Transmission, and Distribution*, vol. 152, pp. 828-836, 2005.

[37] M. S. Sepasian, H. Seifi, A. Akbari Foroud and A. R. Hatami, "A Multiyear Security Constrained Hybrid Generation-Transmission Expansion Planning Algorithm Including Fuel Supply Costs," in *IEEE Transactions on Power Systems*, vol. 24, no. 3, pp. 1609-1618, Aug. 2009.

[38] V. H. Hinojosa et al., "A simulated rebounding algorithm applied to the multi-stage security-constrained transmission expansion planning in power systems", *International Journal of Electrical Power and Energy Systems*, vol. 47, pp. 168-180, May 2013.

[39] A. Seifu, S. Salon and G. List, "Optimization of transmission line planning including security constraints," in *IEEE Transactions on Power Systems*, vol. 4, no. 4, pp. 1507-1513, Nov. 1989.

[40] A. Verma, P. R. Bijwe and B. K. Panigrahi, "Heuristic method for transmission network expansion planning with security constraints and uncertainty in load specifications," *2009 Transmission & Distribution Conference & Exposition: Asia and Pacific*, Seoul, 2009, pp. 1-4.

[41] S. Kamalinia et al., "Security-constrained expansion planning of fast-response units for wind integration", *Electric Power Systems Research*, vol. 81, pp. 107-116, Jan 2011.

[42] H. Zhang, V. Vittal, G. T. Heydt and J. Quintero, "A Mixed-Integer Linear Programming Approach for Multi-Stage Security-Constrained Transmission Expansion Planning," in *IEEE Transactions on Power Systems*, vol. 27, no. 2, pp. 1125-1133, May 2012.

[43] G. A. Orfanos, P. S. Georgilakis and N. D. Hatziargyriou, "A recursive harmony search algorithm for security constrained transmission expansion planning," *2013 IEEE Grenoble Conference*, Grenoble, 2013, pp. 1-6.

[44] F. Ugranli and E. Karatepe, "Transmission expansion planning for wind turbine integrated power systems considering contingencies," *2014 IEEE International Symposium on Innovations in Intelligent Systems and Applications (INISTA) Proceedings*, Alberobello, 2014, pp. 350-355.

[45] M. Mehrtash, A. Mohammadi, M. Barati and A. Kargarian, "Security-Constrained Transmission Expansion Planning with Risk Index of N-1 Security Obtained from PMU Data," *2018 IEEE Power & Energy Society General Meeting (PESGM)*, Portland, OR, 2018, pp. 1-5.

[46] S. Das et al., "Security constrained AC transmission network expansion planning", *Electric Power Systems Research*, vol. 172, pp. 277-289, July 2019.

[47] P. V. Gomes and J. T. Saraiva, "A two-stage strategy for security-constrained AC dynamic transmission expansion planning", *Electric Power Systems Research*, vol. 180, March 2020.

[48] European Parliament, Directive 2009/72/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal market in electricity and repealing Directive 2003/54/EC. L 211/55. Off J Eur Un (L 211/55), European Parliament and of the Council Policy, 2009.

[49] K. N. Hasan and R. Preece, "Impact of stochastic dependence within load and non-synchronous generation on frequency stability", *Bulk power systems dynamics and control symposium* – IREP, Espinho, Portugal; 2017.

[50] M. T. Bina and D. Ahmadi, "Stochastic Modeling for the Next Day Domestic Demand Response Applications," *in IEEE Transactions on Power Systems*, vol. 30, no. 6, pp. 2880-2893, Nov. 2015.

[51] X. Li, X. Zhang, L. Wu, P. Lu, and S. Zhang, "Transmission Line Overload Risk Assessment for Power Systems with Wind and Load-Power Generation Correlation," in *IEEE Transactions on Smart Grid*, vol. 6, no. 3, pp. 1233-1242, May 2015.

[52] J. H. Roh, M. Shahidehpour and L. Wu, "Market-Based Generation and Transmission Planning with Uncertainties," in *IEEE Transactions on Power Systems*, vol. 24, no. 3, pp. 1587-1598, Aug. 2009.

[53] M. Moeini-Aghtaie, A. Abbaspour and M. Fotuhi-Firuzabad, "Incorporating Large-Scale Distant Wind Farms in Probabilistic Transmission Expansion Planning—Part II: Case Studies," in *IEEE Transactions on Power Systems*, vol. 27, no. 3, pp. 1594-1601, Aug. 2012.

[54] C. Shao, M. Shahidehpour, X. Wang, X. Wang and B. Wang, "Integrated Planning of Electricity and Natural Gas Transportation Systems for Enhancing the Power Grid Resilience," in *IEEE Transactions on Power Systems*, vol. 32, no. 6, pp. 4418-4429, Nov. 2017.

[55] C. J. Newlun, A. L. Figueroa-Acevedo, J. D. McCalley, A. Kimber and E. O'Neill - Carrillo, "Co-Optimized Expansion Planning to Enhance Electrical System Resilience in Puerto Rico," *2019 North American Power Symposium* (NAPS), Wichita, KS, USA, 2019, pp. 1-6.

[56] N. R. Romero, L. K. Nozick, I. D. Dobson, N. Xu, and D. A. Jones, "Transmission and Generation Expansion to Mitigate Seismic Risk," in *IEEE Transactions on Power Systems*, vol. 28, no. 4, pp. 3692-3701, Nov. 2013.

[57] Preparing for high-impact, low-probability events, Chatham House report, Jan. 2012 [Online] Available: https://www.chathamhouse.org/sites/default/files/public/Research/Energy,%20Environment%20and%20Development/r0112_highimpact.pdf

[58] Preparing for high consequence, low probability events: heat, water & energy in the Southwest, Report to the U.S. Bureau of Reclamation from the project Enhancing Water Supply Reliability (University of Arizona), Jan. 2016 [Online] Available: https://environment.arizona.edu/sites/default/files/High-Low_Report_FINAL.pdf

[59] High-impact, low-probability events, and the framework for reliability in the national electricity market, Technical report for Australian Energy Market Commission, Feb. 2019 [Online] Available: https://www.aemc.gov.au/sites/default/files/2019-02/Brattle%20report.pdf

[60] G. C. Oliveira et al., "Security-constrained transmission planning: A mixed-integer disjunctive approach", [Online] Available: http://www.optimization-online.org/DB_FILE/2004/08/919.pdf

[61] G. Latorre, R. D. Cruz, J. M. Areiza and A. Villegas, "Classification of publications and models on transmission expansion planning," in *IEEE Transactions on Power Systems*, vol. 18, no. 2, pp. 938-946, May 2003.

[62] C. F. Heuberger et al., "Power capacity expansion planning considering endogenous technology cost learning", *Applied Energy*, vol. 204, pp. 831-845, Oct. 2017.

[63] J. Choi, J. Cha, J. Watada, T. D. Mount and R. Thomas, "Transmission System Expansion Planning Considering Outage Cost," *Second International Conference on Innovative Computing, Information, and Control* (ICICIC 2007), Kumamoto, 2007, pp. 381-381.

[64] A. K. Kazerooni and J. Mutale, "Transmission Network Planning Under Security and Environmental Constraints," in *IEEE Transactions on Power Systems*, vol. 25, pp. 1169-1178, May 2010.

[65] H. Zhao, Z.Y. Dong, P. Lindsay, K.P. Wong, "Flexible transmission expansion planning with uncertainties in an electricity market", *IEEE Transactions on Power Systems,* 24 (2009), pp. 479-488.

[66] M. Eghbal, T. K. Saha and K. N. Hasan, "Transmission expansion planning by meta-heuristic techniques: A comparison of Shuffled Frog Leaping Algorithm, PSO and GA," *2011 IEEE Power and Energy Society General Meeting*, Detroit, MI, USA, 2011, pp. 1-8.

[67] A. Obushevs and I. Oleinikova, "Transmission expansion planning considering wholesale electricity market and integration of renewable generation," *11th International Conference on the European Energy Market (EEM14),* Krakow, 2014, pp. 1-6.

[68] C. A. Sima, G. C. Lazaroiu and V. Dumbrava, "Transmission expansion planning optimization for improving RES integration on electricity market," *2017 10th International Symposium on Advanced Topics in Electrical Engineering (ATEE)*, Bucharest, 2017, pp. 855-859.

[69] T. Ngo, M. Lwin and S. Santoso, "Power transmission expansion planning based on voltage stability indexes," *2017 IEEE Power & Energy Society General Meeting*, Chicago, IL, 2017, pp. 1-4.

[70] K. Yimchuen and K. Udomwongseree, "Transmission Expansion Planning with consideration of voltage stability using Genetic Algorithm," *The 8th Electrical Engineering/ Electronics, Computer, Telecommunications and Information Technology (ECTI) Association of Thailand - Conference 2011*, Khon Kaen, 2011, pp. 909-912.

[71] J. T. Jiménez, J. L. Guardado, N. G. Cabrera, J. R. Rodriguez and F. Figueroa, "Transmission expansion planning systems using algorithm genetic with multi-objective criterion," in *IEEE Latin America Transactions*, vol. 15, no. 3, pp. 563-568, March 2017.

[72] M. A. A. Arifidin, S. P. Hadi, L. M. Putranto and M. Yasirroni, "Optimization of Transmission Expansion Planning Considering the System Losses: A Case Study of the Garver's 6-Bus System," *2019 4th International Conference on Information Technology, Information Systems and Electrical Engineering (ICITISEE*), Yogyakarta, Indonesia, 2019, pp. 501-506.

[73] J. Qiu et al., "A low-carbon oriented probabilistic approach for transmission expansion planning," in *Journal of Modern Power Systems and Clean Energy*, vol. 3, no. 1, pp. 14-23, March 2015.

[74] Y. Hu et al., "Integrated generation and transmission expansion planning with carbon capture operating constraints," *2016 IEEE Power and Energy Society General Meeting (PESGM),* Boston, MA, 2016, pp. 1-5.

[75] C. Rathore, S. Sundeep, M. Mishra and R. Roy, "Transmission expansion planning considering environmental issue," *Proceedings of the 2014 International Conference on Control, Instrumentation, Energy and Communication (CIEC),* Calcutta, 2014, pp. 451-456.

[76] A. Motamedi, H. Zareipour, M. O. Buygi and W. D. Rosehart, "A Transmission Planning Framework Considering Future Generation Expansions in Electricity Markets," in *IEEE Transactions on Power Systems,* vol. 25, no. 4, pp. 1987-1995, Nov. 2010.

[77] M. Cortes-Carmona, R. Palma-Behnke and O. Moya, "Transmission Network Expansion Planning by a Hybrid Simulated Annealing Algorithm," *2009 15th International Conference on Intelligent System Applications to Power Systems*, Curitiba, 2009, pp. 1-7.

[78] A. Sadegheih and P. R. Drake, "System network planning expansion using mathematical programming, genetic algorithms and tabu search", *Energy Conversion and Management*, vol. 49, pp. 1557-1566. June 2008.

[79] N. Dong, "Properly Pareto Optimality Based Multiobjective Evolutionary Algorithm for Constrained Optimization," *2016 12th International Conference on Computational Intelligence* and Security (CIS), Wuxi, 2016, pp. 39-43.

[80] T. Akbari et al., "Towards integrated planning: Simultaneous transmission and substation expansion planning", *Electric Power Systems Research*, vol. 86, pp. 131-139, May 2012.

[81] M. Rahmani et al., "Efficient method for AC transmission network expansion planning", *Electric Power Systems Research*, vol. 80, September 2010, pp. 1056-1064.

[82] K. R. Padiyar and R. S. Shanbhag, "Comparison of methods for transmission system expansion using network flow and DC load flow models", *International Journal of Electrical Power & Energy Systems,* vol. 10, January 1988, pp. 17-24.

[83] M.V.F. Pereira, L.M.V.G. Pinto, S.H.F. Cunha, G.C. Oliveira, "A decomposition approach to automated generation/transmission expansion planning", *IEEE Trans. Power Apparatus Syst. PAS-104 (1985) 3074–3083 (11/01).*

[84] Y. Jin et al., "New discrete method for particle swarm optimization and its application in transmission network expansion planning", *Electric Power Systems Research*, vol. 77, March 2007, pp. 227-233.

[85] R. Leou, "A multi-year transmission planning under a deregulated market", *International Journal of Electrical Power & Energy Systems*, vol. 33, March 2011, pp. 708-714.

[86] N. Alguacil, A. L. Motto and A. J. Conejo, "Transmission expansion planning: a mixed-integer LP approach," in *IEEE Transactions on Power Systems*, vol. 18, pp. 1070-1077, Aug. 2003.

[87] A. P. Meliopoulos, R. P. Webb, R. J. Bennon and J. A. Juves, "Optimal Long-Range Transmission Planning with AC Load Flow," in *IEEE Transactions on Power Apparatus and Systems,* vol. PAS-101, pp. 4156-4163, Oct. 1982.

[88] M. Shahidehpour, Y. Fu, and T. Wiedman, "Impact of natural gas infrastructure on electric power systems," *Proc. IEEE,* vol. 93, pp. 1042– 1056, May 2005.

[89] C. Liu, M. Shahidehpour, Y. Fu, and Z. Li, "Security-constrained unit commitment with natural gas transmission constraints*," IEEE Trans. Power Syst*., vol. 24, pp. 1523–1536, Aug. 2009.

[90] A. Martinez-Mares and C. R. Fuerte-Esquivel, "A unified gas and power flow analysis in natural gas and electricity coupled networks," *IEEE Trans. Power Syst*., vol. 27, pp. 2156–2166, Nov. 2012.

[91] Y. Wen, X. Qu, W. Li, X. Liu, and X. Ye, "Synergistic operation of electricity and natural gas networks via ADMM," *IEEE Trans. Smart Grid*, vol. 9, pp. 4555–4565, Sep. 2018.

[92] C. Vila et al., "A Model to Long-Term, Multiarea, Multistage, and Integrated Expansion Planning of Electricity and Natural Gas Systems," in *IEEE Transactions on Power Systems*, vol. 25, pp. 1154-1168, May 2010.

[93] C. Unsihuay, J. W. M. Lima and A. C. Z. de Souza, "Modeling the Integrated Natural Gas and Electricity Optimal Power Flow," *2007 IEEE Power Engineering Society General Meeting*, Tampa, FL, 2007, pp. 1-7.

[94] Y. Zhang, Y. Hu, J. Ma and Z. Bie, "A Mixed-Integer Linear Programming Approach to Security-Constrained Co-Optimization Expansion Planning of Natural Gas and Electricity Transmission Systems," in *IEEE Transactions on Power Systems,* vol. 33, pp. 6368-6378, Nov. 2018.

[95] J. Qiu et al., "A linear programming approach to expansion co-planning in gas and electricity markets," *IEEE Trans. Power Syst.,* vol. 31, pp. 3594–3606, Sep. 2016.

[96] L. A. Barroso et al., "Integrated gas-electricity adequacy planning in Brazil: technical and economical aspects," *IEEE Power Engineering Society General Meeting, 2005*, San Francisco, CA, 2005, pp. 1977-1982 Vol. 2.

[97] J. Qiu, Z. Y. Dong, J. H. Zhao, K. Meng, Y. Zheng and D. J. Hill, "Low Carbon Oriented Expansion Planning of Integrated Gas and Power Systems," in *IEEE Transactions on Power Systems,* vol. 30, pp. 1035-1046, March 2015.

[98] B. Zhao, A. J. Conejo and R. Sioshansi, "Coordinated Expansion Planning of Natural Gas and Electric Power Systems," in *IEEE Transactions on Power Systems*, vol. 33, pp. 3064-3075, May 2018.

[99] F. Yang, X. Yuan, H. Bai, S. Yin and H. Liu, "Collaborative Planning of Integrated Natural Gas and Power Supply System Considering P2G Technique," *2018 China International Conference on Electricity Distribution (CICED)*, Tianjin, 2018, pp. 2216-2220.

[100] Z. Zhang et al., "Transmission network including VSC-HVDC expansion planning based on genetic algorithm with shift operation," *2016 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*, Xi'an, 2016, pp. 722-726.

[101] A. H. Dominguez, A. H. Escobar Zuluaga, L. H. Macedo and R. Romero, "Transmission network expansion planning considering HVAC/HVDC lines and technical losses," *2016 IEEE PES Transmission & Distribution Conference and Exposition-Latin America* (PES T&D-LA), Morelia, 2016, pp. 1-6.

[102] A. H. Dominguez, L. H. Macedo, A. H. Escobar and R. Romero, "Multistage Security-Constrained HVAC/HVDC Transmission Expansion Planning With a Reduced Search Space," in *IEEE Transactions on Power Systems*, vol. 32, pp. 4805-4817, Nov. 2017.

[103] B. R. Andersen, "HVDC transmission-opportunities and challenges," *The 8th IEE International Conference on AC and DC Power Transmission*, London, UK, 2006, pp. 24-29.

[104] M. Mehrtash, A. Kargarian and M. Rahmani, "Security-constrained transmission expansion planning using linear sensitivity factors," in *IET Generation, Transmission & Distribution*, vol. 14, pp. 200-210, 2020.

[105] I. de J Silva, M. J. Rider, R. Romero, A. V. Garcia and C. A. Murari, "Transmission network expansion planning with security constraints," in *IEE Proceedings - Generation, Transmission and Distribution*, vol. 152, pp. 828-836, Nov. 2005.

[106] X. Zhang, K. Tomsovic and A. Dimitrovski, "Security Constrained Multi-Stage Transmission Expansion Planning Considering a Continuously Variable Series Reactor," in *IEEE Transactions on Power Systems*, vol. 32, pp. 4442-4450, Nov. 2017.

[107] H. Zhang, V. Vittal, G. T. Heydt and J. Quintero, "A Mixed-Integer Linear Programming Approach for Multi-Stage Security-Constrained Transmission Expansion Planning," in *IEEE Transactions on Power Systems*, vol. 27, pp. 1125-1133, May 2012.

[108] D. Liu, L. Liu and H. Cheng, "A contingency-aware method for N-2 security-constrained transmission expansion planning," in *Journal of Modern Power Systems and Clean Energy*, vol. 7, pp. 1008-1019, September 2019.

[109] S. Zuluaga et al., "Transmission network expansion planning considering weighted transmission loading relief nodal indexes", [Online] Available: https://revistas.itm.edu.co/index.php/tecnologicas/article/view/777/732

[110] R. Moreno et al., "Planning low-carbon electricity systems under uncertainty considering operational flexibility and smart grid technologies", *Philosophical Transactions* [Online], Available: https://royalsocietypublishing.org/doi/pdf/10.1098/rsta.2016.0305

[111] M. Sun et al., "An objective-based scenario selection method for transmission network expansion planning with multivariate stochasticity in load and renewable energy sources", *Energy*, vol. 145, 15 February 2018, pp. 871-885.

[112] Z. Wu, X. Du, W. Gu, X. Zhang and J. Li, "Automatic Selection Method for Candidate Lines in Transmission Expansion Planning," in *IEEE Access*, vol. 6, pp. 11605-11613, 2018.

[113] C. A. Correa, R. Bolanos, A. Sanchez, A. Garces, and A. Molina, "Multiobjective transmission planning with security constraints," *Eurocon*, 2013, pp. 1215–1221.

[114] E. B. Obio and J. Mutale, "A comparative analysis of energy storage and N-1 network security in transmission expansion planning," in *2015 50th International Universities Power Engineering Conference (UPEC)*, 2015, pp. 1–6.

[115] M. Majidi-Qadikolai and R. Baldick, "Integration of Contingency Analysis with Systematic Transmission Capacity Expansion Planning: ERCOT Case Study," *IEEE Trans. Power Syst*., vol. 31, pp. 2234–2245, May 2016.

[116] A. Sharifnia and H. Z. Aashtiani, "Transmission network planning: A method for synthesis of minimum-cost secure networks," *IEEE Trans. Power App. Syst*., vol. PAS-104, pp. 2026–2034, Aug. 1985.

[117] U. Shahzad, "The Need for Renewable Energy Sources", *Information Technology and Electrical Engineering Journal*, vol. 4, pp. 16-18, Aug. 2015.

[118] U. Shahzad, "Significance of Smart Grids in Electric Power Systems: A Brief Overview", *Journal of Electrical Engineering, Electronics, Control and Computer Science*, vol. 6, no. 19, pp. 7-12, 2020.

[119] U. Shahzad and S. Asgarpoor, "Probabilistic Risk Assessment of an Active Distribution Network Using Monte Carlo Simulation Approach," *2019 North American Power Symposium*, pp. 1-6.

[120] U. Shahzad and S. Asgarpoor, "Probabilistic Evaluation of Line Loading and Line Active Power in an Active Distribution Network using Numerical and Analytical Approaches", *2018 North American Power Symposium*, pp. 1-6.

[121] A. Cataliotti, V. Cosentino, D. Di Cara, P. Russotto, E. Telaretti and G. Tinè, "An Innovative Measurement Approach for Load Flow Analysis in MV Smart Grids," in *IEEE Transactions on Smart Grid*, vol. 7, pp. 889-896, Mar. 2016.

[122] S. Yunting, H. Hailei, Z. Dongxia and G. Jianbo, "Probabilistic Security Evaluation of Bulk Power System Considering Cascading Outages," *2006 International Conference on Power System Technology*, Chongqing, 2006, pp. 1-6.

[123] T. Zhao, D. Lu, D. Wang, Y. Zeng and Y. Liu, "A risk assessment approach for power system based on a comprehensive fault probabilistic model," *2015 5th International Conference on Electric Utility Deregulation and Restructuring and Power Technologies (DRPT)*, Changsha, 2015, pp. 574-577.

[124] U. Shahzad, "Resilience in Electric Power Systems", *Journal of Electrical Engineering, Electronics, Control and Computer Science*, vol. 7, no. 2, pp. 1-6, 2021.