AUT Journal of Electrical Engineering

AUT J. Elec. Eng., 52(1) (2020) 121-130
DOI: 10.22060/eej.2019.16995.5301

A Multi-Year Scenario-Based Transmission Expansion Planning Model Incorporating Available Transfer Capability

Saeed Zolfaghari Moghaddam[1,*], Tohid Akbari[2]

[1] Faculty of Electrical Engineering, Urmia University of Technology, Urmia, Iran.
[2] Department of Electrical Engineering, Pooyesh Institute of Higher Education, Qom, Iran.

ABSTRACT: This paper presents a multi-year scenario-based methodology for transmission expansion planning (TEP) in order to enhance the available transfer capability (ATC). The ATC is an important factor for all players of electricity market who participate in power transaction activities and can support the competition and nondiscriminatory access to transmission lines among all market participants. The transmission expansion planning studies deal with many uncertainties, such as system load uncertainties that are considered in this paper. The Latin hypercube sampling (LHS) method has been applied for generating different scenarios related to the load uncertainty. The objective function in the TEP model is to minimize the sum of investment costs (IC) and the expected operation costs (OC). Both ATC and TEP models are represented based on AC power flow constraints which are more accurate compared with the widely-used DC approach. In this respect, the nonlinear terms in power flow equations are linearized in order to obtain the efficient solutions by existing commercial solvers that can guarantee the achievement to the global optimal solution using branch and bound technique. The proposed model is applied to the IEEE 24-bus Reliability Test System and the results obtained show the efficiency, tractability and applicability of the proposed model.

Review History:

Received: 2019-09-01
Revised: 2019-10-06
Accepted: 2019-10-15
Available Online: 2020-06-01

Keywords:

Available transfer capability
Latin hypercube sampling
Linearization
Scenario generation
Transmission expansion planning

1. INTRODUCTION

Transmission grid as a link between the generation and the demand sector plays a vital role in deregulated power system industries, because it should provide a nondiscriminatory environment for all market participants such that they can freely compete amongst each other. The aim of the TEP is to ensure that there is sufficient transmission capacity to satisfy the growing electricity demand reliably and economically [1]. Indeed, the TEP responds to the problem of where, when and what reinforcement should be added in an established planning horizon meeting techno-economic constraints.

There are two types of TEP, static (single-year) transmission expansion planning (STEP), and dynamic (multi-year) transmission expansion planning (DTEP). In the multi-year nature of the TEP, it is required to consider multi-time periods, determining the possible transmission reinforcements at each time. In the single-year nature, it is identified, for just one stage, where transmission lines should be built. The DTEP problem is much more complex to solve and so, many research studies did not model the time of constructing transmissions lines [2].

Generally, the TEP problem is a mixed-integer, non-convex, large-scale mathematical programing problem. Solution techniques for the TEP problem can be classified into three types: 1) mathematical optimization, 2) heuristic methods and, 3) meta-heuristic methods.

Many research works related to the TEP problem can be found in the literature. Several recent studies of these works have focused on the TEP models considering wind generation. Ref. [3] studies the problem of robust TEP integrating wind power generation. The authors in [3] model the N-k contingency and the load uncertainty. The whole problem is finally formulated as a mixed-integer linear programming (MILP) and is solved by an MILP solver. A TEP model based on stochastic programming is shown in [4], where evolutionary algorithms and Benders decomposition are employed to solve the problem. A two-stage stochastic programming scheme for the TEP problem is presented in [5] in which two dependent random variables, namely, load and wind power are considered. A chance-constrained formulation to cope with the uncertainties of load and wind generation in TEP problem is proposed in [6] in which the authors show that their presented model is more computationally efficient and can effectively handle the corresponding uncertainties. Ref. [7] proposes a stochastic TEP framework to evaluate the effect of wind power penetration and demand response incorporation. It shows that the TEP solutions depend on the variation of wind power characteristics and thus, employing a risk-based approach in the present of wind power is inevitable. A bilevel framework for TEP and reactive power planning considering wind farm integration is proposed in [8]. In the upper level,

*Corresponding author's email: s.zolfaghari@uut.ac.ir

the investment and operation cost is minimized while in the lower level the market clearing process is formulated based on linearized optimal power flow. By using primal-dual formulation the bilevel model is formulated as an MILP. It is proposed a new methodology for TEP based on chronological evaluation that combines Monte Carlo and sensitivity analysis in [9]. A bilevel multi-stage TEP in which the wind investment is modeled, is presented in Ref. [10]. In this paper, the authors formulate the lower level problem as an AC based optimal power flow (OPF) rather than a DC-based OPF. They showed that the latter one results in inaccurate solutions. In Ref. [11] a new scenario generation methodology for the TEP problem to generate efficient load-wind power scenarios is proposed employing a vine-copula based approach. The proposed model is able to capture the inter-spatial dependencies between loads and wind generation. An adaptive robust dynamic TEP and renewable generation planning model is presented by [12] which is formulated as a three-level adaptive robust optimization problem.

Authors of Ref. [13] present a tri-level TEP considering transmission cost allocation (TCA). They verified that a well-designed TCA model can incentivize users to invest in distributed energy resources, which can effectively postpone the investment in transmission sector and thus reduce the total investment costs. A security-constrained TEP based on AC-OPF is proposed in [14] in which the voltage security margin (VSM) is taken into account. A mechanism to select the candidate line for TEP problem is shown in [15] which is a complex task. An MILP model for generation and transmission expansion planning is formulated in [16] where a scenario building procedure for physical deliberate attacks is considered. Authors of this paper show that the proposed approach is able to significantly mitigate the power system vulnerability. A model is presented in [17] that solves the TEP in a stochastic optimization framework. The model uses the Benders' decomposition technique in order to solve the TEP problem. Efficient Bender's cut for TEP is proposed in [18] which are specifically tailored to the binary decision variables of the TEP problem. A two-stage min-max-min model for co-optimizing the TEP and renewable generation capacity expansion under high renewable uncertainty is presented in Ref. [19] in which in order to ensure system security, the compound N-K contingency criteria is employed. An MILP five-level model for TEP problem based on a min-max regret approach is proposed by [20] in which the renewable generation uncertainty is taken into account. Since the two-stage robust optimization is widely used to deal with uncertain demand in TEP problem, Ref. [21] proposes an alternative column-and-constraint generation (C&CG) algorithm in which the max-min problem related to the second stage is solved by means of a block coordinate descent method. The advantage of this method is that it does not rely on the converting of the second-stage problem into a single-level problem. A robust TEP model considering long- and short-term uncertainties is shown in [22] which is solved by primal Benders' decomposition algorithm. A multi-objective bilevel model is presented in [23] in which the objectives are investment cost (IC) and congestion cost (CC).

All the papers surveyed above approach the TEP problem from different perspectives. However, none of them consider the available transfer capability in their formulation, when they decide to expand the transmission network. This issue is particularly much important in the restructured environment, because it can guarantee the nondiscriminatory access of the players to the transmission grid in the electricity market. In other words, it can facilitate the competition between producers and thus, will enhance the system efficiency. Thus, the shortcoming of the existing models is that they ignore the ATC evaluation in their model which as a consequence might jeopardize the competition of the market participants.

In this paper, we propose a novel strategy to expand the transmission network based on the available transfer capability criteria in which both TEP and ATC models are represented using AC power flow equations instead of using the well-known simplified DC method. ATC is used to ensure that electric energy systems can work reliably under all conditions. Also, sufficient ATC is able to support free trading between all market players.

Motivated by the aforementioned points, the contribution of this paper can be listed as follows:

1- To incorporate the ATC as an important criterion in the TEP problem based on AC power flow constraints. In this way, the network is expanded such that the ATC is improved which as a result, lead to a more reliable power systems. Therefore, the market participant can freely compete in order to trade electricity energy.

2- To linearize the ATC formulation around its operating point considering special ordered set of type 2 (SOS2).

We also model the load uncertainty where a normal PDF is assigned to the load at each bus. In order to generate scenarios related to the load uncertainty, LHS is employed that outperform the Monte Carlo simulation (MCS). Additionally, an efficient linearization technique is used in order to ensure that the global optimal solutions can be achieved by existing powerful MILP solvers.

The remainder of this paper is outlined as follows: Section 2 presents the ATC definition and calculation. The TEP problem considering ATC is formulated in section 3. The numerical experiments are presented in section 4, and conclusions are drawn in section 5.

2. AVAILABLE TRANSFER CAPABILITY

In order to enhance the competition between market participants, the Federal Energy Regulatory Commission (FERC) has mandated the open access nondiscriminatory transmission services [24]. In this respect, the ATC criterion plays a vital role in providing a nondiscriminatory environment for all market players. The ATC can considerably affect the energy market equilibrium point and is a suitable factor for planning of a transmission system. As stated by North American Reliability Council (NERC) [25], the ATC is a measure of transfer capability remaining in the physical transmission network for further commercial transactions. Mathematically speaking, the ATC can be written as:

$$\text{ATC} = \text{TTC} - \text{TRM} - \text{CBM} - \text{ETC} \tag{1}$$

where the TTC is the Total Transfer Capability, TRM is the Transmission Reliability Margin (TRM), CBM is the Capacity Benefit Margin and ETC is the Existing Transmission Commitments. More details are given in [25] to determine TRM and CBM. Identifying TRM and CBM is not the focus of this paper and so by ignoring TRM and CBM, the ATC can be simply determined as: ATC=TTC-ETC. Four different methods exist in order to calculate ATC [26] 1) Continuation power flow (CPF) methods; 2) Security-constrained optimal power flow (SCOPF) methods; 3) stochastic programming; and 4) artificial intelligence techniques. In this paper, the same formulation employed in [24] is used to calculate the ATC. In this way, utilizing the AC power flow constraints, the following nonlinear optimization problem should be solved:

$$\max\ OF = \lambda \tag{2}$$

subject to:

$$Pg_i - Pd_i = \sum_j Pl_{ij} \tag{3}$$

$$Qg_i - Qd_i = \sum_j Ql_{ij} \tag{4}$$

$$Pl_{ij} = G_{ij} \times V_i^2 - V_i V_j \left(G_{ij} cos\left(\theta_i - \theta_j\right) + B_{ij} sin\left(\theta_i - \theta_j\right)\right) \tag{5}$$

$$Ql_{ij} = -B_{ij} \times V_i^2 - V_i V_j \left(G_{ij} sin\left(\theta_i - \theta_j\right) - B_{ij} cos\left(\theta_i - \theta_j\right)\right) \tag{6}$$

$$\left(Pl_{ij}\right)^2 + \left(Ql_{ij}\right)^2 \le \left(Sl_{ij}^{max}\right)^2 \tag{7}$$

$$V_i^{min} \le V_i \le V_i^{max} \tag{8}$$

$$Pg_i^{min} \le Pg_i \le Pg_i^{max} \tag{9}$$

$$Qg_i^{min} \le Qg_i \le Qg_i^{max} \tag{10}$$

$$Pg_i = Pg_i^0\left(1 + \lambda \times Kg_i\right) \quad \forall i \in source \tag{11}$$

$$Pd_i = Pd_i^0\left(1 + \lambda \times Kd_i\right) \quad \forall i \in sink \tag{12}$$

$$Qd_i = Qd_i^0\left(1 + \lambda \times Kd_i\right) \quad \forall i \in sink \tag{13}$$

where Pg_i^0 , Qg_i^0 and Pd_i^0 are the active and reactive power generation and the demand in base case. Kg_i and Kd_i are constant parameters used to determine the change rate in generation and demand, respectively. Objective function is defined by Eq. (2). Decision variable λ is an auxiliary variable used to calculate the ATC. Indeed, it shows that how much the amount of active and reactive power demand at different buses of power system can be increased -as defined by equations (12) and (13)- without violating the system constraints. Note that the power factor is assumed to be constant. It is clear that power generation should be increased as well to satisfy the demand which has been denoted by Eq. (11). Eqs. (3) and (4) are active and reactive power balance. Eq. (5) and (6) are active and reactive power flow through line *ij*. Apparent power flow through line is restricted by Eq. (7). Voltage magnitude and active and reactive power generation is limited by Eqs. (8) to (10).

After identifying the scalar variable λ, the TTC is obtained from the following equation:

$$TTC = \sum_{i \in sink} Pd_i\left(\lambda_{max}\right) - \sum_{i \in sink} Pd_i^0 \tag{14}$$

In [27], an iterative distributed algorithm for real-time ATC assessment is proposed and then the proposed nonlinear optimization power flow is solved by an augmented Lagrangian method. A non-deterministic model for the ATC assessment is developed in [28] in which the effect of existing and future wind power generation is investigated. They showed that the wind generation uncertainties can be effectively handled by their proposed method. In order to consider the wind uncertainty impact on economic dispatch (ED) and ATC evaluation, a bilevel model is proposed in [29] in which the upper level shows the ATC calculation and the lower level is the ED problem. Authors in Ref. [30] create a multi-area representation of power system based on ATCs between each pair of buses.

3. MULTI-YEAR STOCHASTIC FORMULATION OF TEP

This section is divided into three subsections. Subsection 3.1 demonstrates the scenario generation technique. Subsection 3.2 formulates the TEP problem and finally subsection 3.2 discusses how the ATC-related coefficients in the TEP problem can be identified.

3.1. Scenario generation

Stochastic programming is a mathematical programming that includes some uncertain parameters with known probability distribution function (PDF) based on which the expected objective function is optimized. To solve the stochastic programming problems, it is needed to generate scenarios based on the assumed PDF. In this paper, the load uncertainty is considered in which the normal PDF are assumed for the future loads.

In order to generate the corresponding scenarios, it is needed to employ sampling techniques. Sampling is a key process required in Monte Carlo (MC) analysis. The most widely used sampling technique is Monte Carlo Sampling (MCS). However, the MCS technique, does not guarantee that sample numbers will cover the whole sample range [31]. Latin Hypercube Sampling (LHS) is another efficient sampling technique that produces random sample elements from the marginal cumulative distribution function (CDF). Compared with MCS, LHS is able to generate a more precise result with a much smaller sample size [32]. Ref. [33] details the procedure to implement LHS.

3.2. AC-TEP problem formulation

In this section, the TEP problem based on the AC power flow equations is formulated. It is assumed that the ISO (Independent System Operator) is responsible for transmission network planning. The objective function consists of the investment cost (*IC*) plus the operation cost (*OC*) that includes the total generation cost which is defined by Eq. (15) [14].

$$\text{Min}\ \ OF = \sum_{t=1}^{nt} \frac{1}{(1+r)^{t-1}} \left(\underbrace{\sum_{ij} \psi_{ijt} u_{ijt} IC_{ij}}_{\text{Investment Cost(IC)}} + \sigma \sum_{s=1}^{ns} \pi_s \underbrace{\sum_{i=1}^{nb} Cg_i Pg_{its}}_{\text{Operation Cost(OC)}} \right) \tag{15}$$

subject to:

$$Pg_{its} - Pd_{its} = \sum_j Pl_{ijts} \tag{16}$$

$$Qg_{its} - Qd_{its} = \sum_j Ql_{ijts} \tag{17}$$

$$Pl_{ijts} = u_{ijt} \left(V_{its}^2 G_{ij} - V_{its} V_{jts} \times \left(G_{ij} \cos\left(\theta_{its} - \theta_{jts}\right) + B_{ij} \sin\left(\theta_{its} - \theta_{jts}\right) \right) \right) \tag{18}$$

$$Ql_{ijts} = u_{ijt} \left(-V_{its}^2 B_{ij} - V_{its} V_{jts} \times \left(G_{ij} \sin\left(\theta_{its} - \theta_{jts}\right) - B_{ij} \cos\left(\theta_{its} - \theta_{jts}\right) \right) \right) \tag{19}$$

$$Pg_i^{min} \le Pg_{its} \le Pg_i^{max} \tag{20}$$

$$Qg_i^{min} \le Qg_{its} \le Qg_i^{max} \tag{21}$$

$$\left(Pl_{ijts} \right)^2 + \left(Ql_{ijts} \right)^2 \le u_{ijt} \left(Sl_{ij}^{\max} \right)^2 \tag{22}$$

$$V_i^{min} \le V_i \le V_i^{max} \tag{23}$$

Eqs. (16) and (17) indicate active and reactive power balance at each bus, respectively. Eqs. (18) and (19) represent active and reactive power flow, respectively. Eqs. (20) and (21) show the power generation limits of generators. Limits on transmission flow are shown by (22). Voltage magnitude is restricted by (23).

3.3. Linearization of the AC-TEP problem

The AC-TEP model presented in subsection 3.2 is nonlinear. An efficient linearization technique based on the model presented in [34] is employed here. For the sake of simplicity, we drop the index of scenarios *s* and time *t*.

Assume $m_{ij} = \cos\delta_{ij}$ and $n_{ij} = \sin\delta_{ij}$. Using the Taylor series expansion with respect to the variables $(V_i, V_j, m_{ij}, n_{ij})$ around point $(V_i, V_j, \delta_{ij}) = (1,1,0)$, Eq. (18) can be written as (24):

$$Pl_{ij} = u_{ij} \left(G_{ij} \left(2V_i - 1 \right) - G_{ij} \left(V_i + V_j + m_{ij} - 2 \right) - B_{ij} \left(n_{ij} \right) \right) \tag{24}$$

Using big-M technique, Eq. (24) is recast as below which is linear with respect to V_i, V_j, m_{ij}, n_{ij}:

$$P_{ij} - \left(g_{ij} \left(2V_i - 1 \right) - g_{ij} \left(V_i + V_j + m_{ij} - 2 \right) - b_{ij} \left(n_{ij} \right) \right) \le M_1 \left(1 - z_{ij} \right) \tag{25}$$

$$P_{ij} - \left(g_{ij} \left(2V_i - 1 \right) - g_{ij} \left(V_i + V_j + m_{ij} - 2 \right) - b_{ij} \left(n_{ij} \right) \right) \ge -M_1 \left(1 - z_{ij} \right) \tag{26}$$

In a similar way, Eq. (19) can be linearized. Variables of $m_{ij} = cos\delta_{ij}$ and $n_{ij} = sin\delta_{ij}$ can be approximated by PWL approximation using SOS2 [34]:

$$\delta_{ij} = \sum_k \lambda_{ijk} \delta_{ijk}^{val} \tag{27}$$

$$m_{ij} = \sum_k \lambda_{ijk} cos\delta_{ijk}^{val} \tag{28}$$

$$n_{ij} = \sum_k \lambda_{ijk} sin\delta_{ijk}^{val} \tag{29}$$

$$\sum_k \lambda_{ijk} = 1 \tag{30}$$

$$\lambda_{ijk}\ is\ SOS2 \tag{31}$$

For more details about the concept and implementation of SOS2 readers are referred to [34]. In the above-mentioned equations, δ_{ijk}^{val} are the set of break-points. Eq. (22) shows a circle which can be effectively approximated by an *n*-sided regular polygon. Therefore, nonlinear Eq. (22) is replaced with the following linear equations [35]:

$$-z_{ij} \times M_2 \le P_{ij} \le z_{ij} \times M_2 \tag{32}$$

$$-z_{ij} \times M_3 \le Q_{ij} \le z_{ij} \times M_3 \tag{33}$$

$$\left(sin\left(2\pi l / 64\right) - sin\left(2\pi \left(l-1\right) / 64\right) \right) P_{ij} - \left(cos\left(2\pi l / 64\right) - cos\left(2\pi \left(l-1\right) / 64\right) \right) Q_{ij} - S_{ij}^{max} \times \sin\left(2\pi / 64\right) \le 0 \tag{34}$$

It should be highlighted here that the ATC formulation can be linearized in the same way. Therefore, it is possible to use mixed-integer linear (MIL) solvers to efficiently solve both problem.

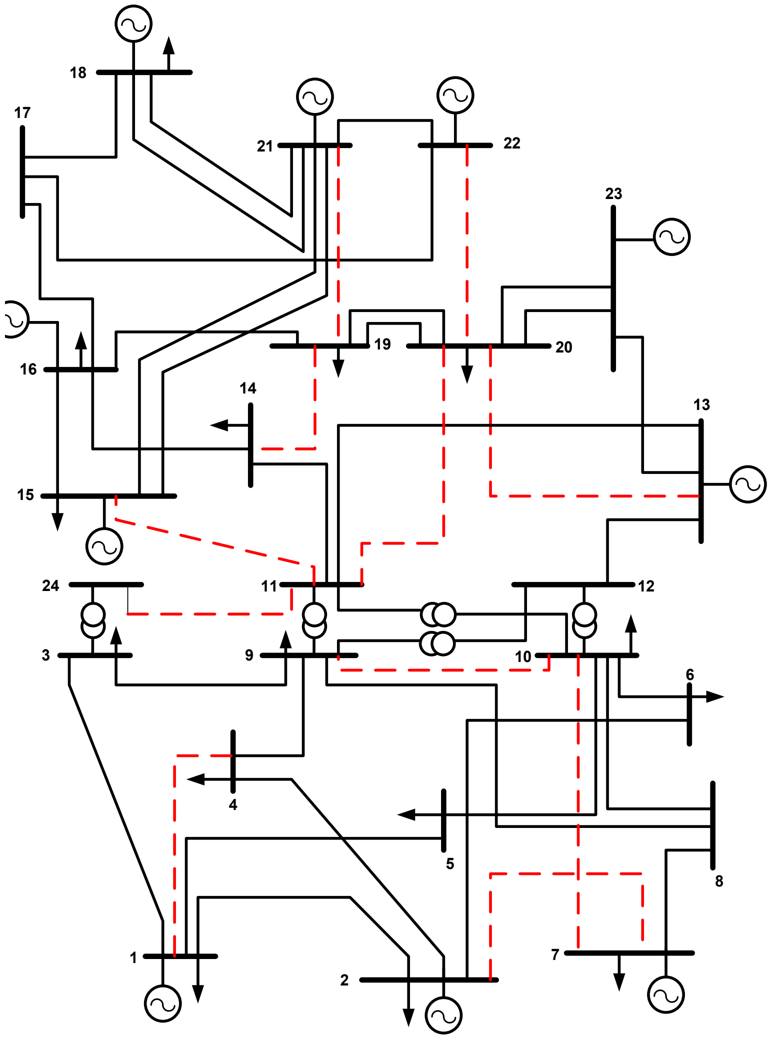


Fig. 1. IEEE 24-bus RTS

3.4. Calculation of the ATC coefficients in the TEP problem

In this part, we discuss a method through which the ATC coefficients can be calculated. Having *ns* scenarios generated by LHS, ATC is calculated for each scenario. After ATC calculation, the buses and lines in which the voltage magnitude or thermal limits is violated, are determined. It is required to specify the effect of candidate line closure on the voltage magnitude and power flow of overloaded lines. This can be carried out either by power flow analysis or by sensitivity analysis. It is obvious that the latter is faster but less accurate, if compared with the exact power flow analysis. Afterwards, the expected change (in percent) in voltage magnitude or power flow due to closing the candidate line can be determined as follows:

$$\overline{\Delta X}_{ij} = \sum_{s=1}^{ns} \pi_s \Delta X_{ijs} \tag{35}$$

where X refers to voltage magnitude or power flow through a line and ΔX_s denotes the effect of candidate line closure on value of X in scenario s. After identifying these expected values, we define a function as follows:

$$\psi_{ij} = \begin{cases} \psi_{ij} \geq 1 & if \quad -1 \leq \overline{\Delta X}_{ij} \leq 0 \\ \psi_{ij} = 1 & if \quad \overline{\Delta X}_{ij} = 0 \\ \psi_{ij} \leq 1 & if \quad 0 \leq \overline{\Delta X}_{ij} \leq 1 \end{cases} \tag{36}$$

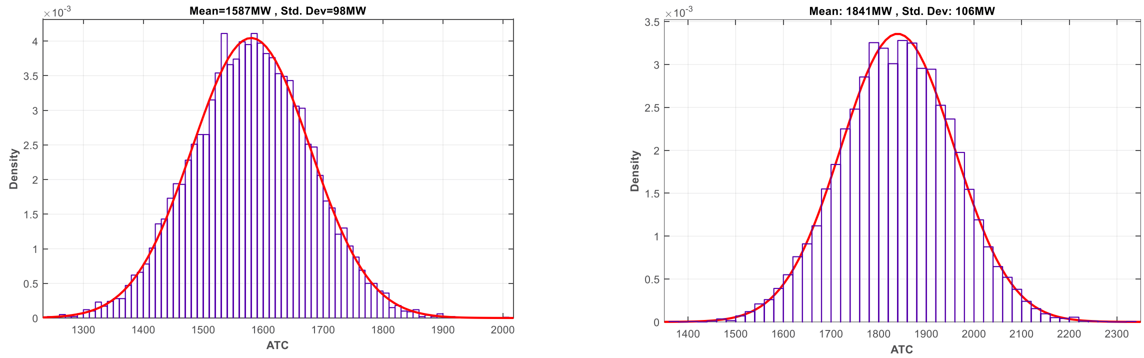
ψ_{ij} can be considered as $\psi_{ij} = a^{-b\blacklozenge\overline{X_{ij}}}$ $a \geq 1$.

4. NUMERICAL RESULTS:

The presented scheme demonstrated in previous section, is applied here to the modified IEEE 24-bus reliability test system (RTS) as shown in Fig. 2 [36] where the red dashed lines shows the candidate lines. The IEEE 24-bus RTS consists of 32 units, 17 demands, 38 lines and two areas in which area 1 is the 138-kV network and area 2 is the 230-kV network connecting with 5 tie-lines. The presented model was coded in GAMS using CPLEX. The GAMS code is run on a computer with Intel Core™ i7 processor clocking at 2.5GHz and with installed memory of 8.00GB. Power flow studies are carried out by Matpower 6.0 [37]. In all numerical experiments,

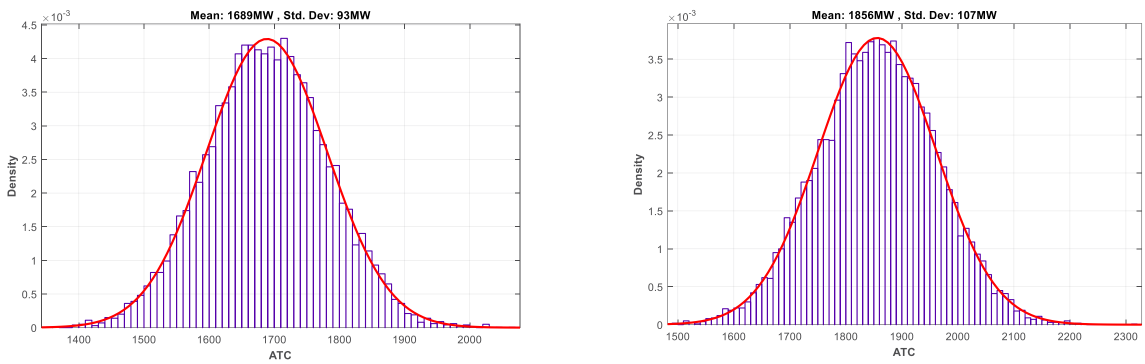
Table 1. Optimal results with and without considering ATC

Candidate line (From-To)	Without ATC			With ATC		
	Year 1	Year 2	Year 3	Year 1	Year 2	Year 3
1 (1-4)	1	0	0	1	1	0
2 (2-7)	0	1	0	1	1	0
3 (7-10)	0	1	0	0	1	0
4 (9-10)	0	0	1	0	1	1
5 (11-15)	0	0	1	0	0	1
6 (11-20)	0	1	0	1	1	0
7 (11-24)	1	1	1	1	1	1
8 (13-20)	1	1	0	1	1	0
9 (14-19)	1	1	0	0	1	1
10 (19-21)	1	1	0	1	1	0
11 (20-22)	0	0	1	0	1	1
Total investment cost ($\$10^6$US)	128			167.11		
Total production cost ($\$10^6$US)	2834.17			2816.93		



(a) (b)

Fig. 2. PDF of ATC employing the AC power flow: (a) without considering ATC in the TEP (b) with considering ATC in the TEP



(a) (b)

Fig. 3. PDF of ATC employing the DC power flow (a) without considering ATC in the TEP (b) with considering ATC in the TEP

minimum and maximum of the voltage magnitude of buses is supposed to be 0.95 pu and 1.05 pu, respectively. A 5% annual interest rate is assumed. Bus 23 is considered to be the slack bus. The expected load at each bus is considered to be increased at the rate of 5%. Candidate line data along with uncertain load data are provided in [38]. Resistance of candidate lines is one fifth of their corresponding reactance. In order to put the transmission system under more pressure, the demand and generators capacity in the base year is increased by 50% at each bus. Future horizon of 3 years has been considered in

Table 2. $\overline{\Delta X}_{ij}$ coefficients of candidate lines

Candidate Line	$\overline{\Delta X}_{ij}$	$\psi_{ij} = 2^{-\overline{\Delta X}_{ij}}$
1 (1-4)	0.09	0.9395
2 (2-7)	0.10	0.9330
3 (7-10)	-0.29	1.2226
4 (9-10)	0.08	0.9461
5 (11-15)	0.21	0.8645
6 (11-20)	0.82	0.5664
7 (11-24)	-0.43	1.3472
8 (13-20)	0.02	0.9862
9 (14-19)	0.36	0.7792
10 (19-21)	0.79	0.5783
11 (20-22)	-0.46	1.3755

Table 3. Number of variables and equations in the linearized TEP model

Blocks of equations	25
Blocks of variables.	12
Single equations	950125
Single variables	27174

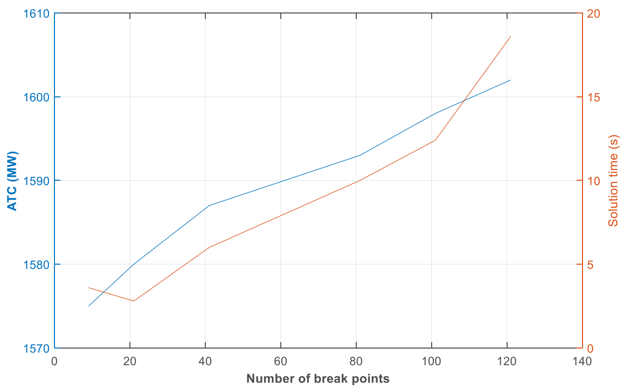


Fig. 4. ATC versus different number of breakpoints

this paper. It is assumed that up to three lines can be added to each right of way. Number of breakpoints is considered to be 21 in SOS2 method. In addition, a 128-sided regular polygon is used to approximate the circle of Eq. (22).

Table 1 shows the results with and without considering ATC. Fig. 1. denotes the histogram of the ATC in both cases. Also, a normal PDF has been fitted to these. As it can be observed, the mean of ATC is increased from 1587MW to 1841MW. Thus, it clearly shows that the proposed method is able to expand the transmission network securely while enhancing the ATC. The ATC improvement is due to building the more transmission lines and therefore the more investment cost. Another observation is that the mean of ATC is less than that provided in [38]. This is due to employing the AC power flow constraints rather than the DC power flow constraints as used in [38]. Since in the DC approach, the voltage magnitude is ignored, therefore the voltage magnitude limitation is no longer a constraint when calculating the ATC which consequently lead to more ATC. Furthermore, due to the reactive power flow, a portion of the line capacity is filled by the reactive power.

We have also calculated the PDF of ATC in the case in which linear DC power flow is used. The results are depicted in Fig. 3. As previously stated, the mean values are less that in the AC power flow. Also, these values are slightly less than that provided in [38]. This is due to the utilization of phase shifter in [38] which is effectively able to change the power flow pattern and thereby reducing the congestion in the power system. As a result, ATC is increased by appropriate setting of phase shifters.

In Table 2, we have presented the $\overline{\Delta X}_{ij}$ for all candidate lines.

Table 3 shows the number of variables and equations reported by GAMS. It takes about 16 s to solve the problem.

Although the preciseness of the linearization methodology in the TEP problem has been shown in Ref. [34], the preciseness of this technique in the ATC calculation is not provided. Fig. 4 depicts the approximated ATC in the base case, i.e., the case in which random variables are replaced by their mean values. The exact ATC is 1602 MW. As it can be seen, as the number of breakpoints is increased, the more precise results are obtained but at the price of more solution time. The solution time is also provided in Fig. 3.

5. CONCLUSION

This paper presents a multi-year TEP model under uncertainty to enhance ATC. In this way, a novel TEP methodology is proposed in which the investment cost of candidate transmission lines is modified according to their effect on the ATC enhancement. Both TEP and ATC problems are formulated based on AC power flow constraints. Owing to the nonlinearity of the formulated problems, a linearized model with sufficient accuracy is employed which can ensure the planner that global optimal solution is obtained. The corresponding scenarios related to the load uncertainty were generated using Latin Hypercube Sampling (LHS) technique. The presented method was applied to the IEEE 24-bus RTS. From the obtained results, one can conclude that the proposed approach is an effective tool in order to enhance the ATC in power system which as a result increase the competition and security of the system.

Future works of this research are to take reactive power planning and FACTS devices into account. Reactive power sources can affect the voltage magnitude of buses and thus can have significant effect on ATC evaluation. Additionally, reactive power sources as well as FACTS devices have less investment cost, if compared with building new transmission lines.

NOMENCLATURE:

Indices

i, j	Index of buses.
s	Index of scenarios.
t	Index of years.

Constants

r	Annual interest rate.
IC_{ij}	Investment cost of candidate line *ij* [$].
nb	Number of buses.
nc	Number of candidate lines.
ns	Number of scenarios.
Cg_i	Operation cost of generator *i* [$/MWh].
Pd_{its}, Qd_{its}	Active and reactive power demand at bus *i* for scenario *s,* in year *t* [MW] and [MVar].
Pg_i^{min} , Pg_i^{max}	Minimum and maximum active power of generator at bus *i* [MW].
Qg_i^{min} , Qg_i^{max}	Minimum and maximum reactive power of generator at bus *i* [MVar].
Sl_{ij}^{max}	Maximum apparent power flow of line *ij* [MVA].
ψ_{ijt}	Weighting factor for including ATC in the TEP problem.
G_{ij} , B_{ij}	Conductance and susceptance of line *ij* [pu].
M_1, M_2, M_3	Disjunctive (Big-M) parameters.
V_i^{min} , V_i^{max}	Minimum and maximum voltage magnitude at bus *i* [pu].
π_s	Probability of scenario *s*.
σ	Weighting factor.

Variables

Pg_{its} , Qg_{its}	Active and reactive power of generator at bus *i* in year *t* for scenario *s* [MW] and [MVar].
Pl_{ijts} , Ql_{ijts}	Active and reactive power flow of line *ij* in year *t* for scenario *s* [MW] and [MVar].
u_{ijt}	Binary variable: 1 if line *ij* is constructed in year *t*, 0 otherwise. For all existing lines $u_{ijt}=1$.
V_i	Voltage magnitude at bus *i* [pu].
λ_{ijk}	SOS2 variable.
δ_{ijts}	Voltage phase angle at bus *i* for scenario *s,* in year *t* [Rad].

REFERENCES

[1] J. Choi, T.D. Mount, R.J. Thomas, Transmission expansion planning using contingency criteria, IEEE Transactions on Power Systems, 22(4) (2007) 2249-2261.

[2] C. Lee, S.K. Ng, J. Zhong, F.F. Wu, Transmission expansion planning from past to future, in: 2006 IEEE PES power systems conference and exposition, IEEE, 2006, pp. 257-265.

[3] Z. Wu, Y. Liu, W. Gu, Y. Wang, C. Chen, Contingency-constrained robust transmission expansion planning under uncertainty, International Journal of Electrical Power & Energy Systems, 101 (2018) 331-338.

[4] G. Chen, Z. Dong, D.J. Hill, Transmission network expansion planning with wind energy integration: A stochastic programming model, in: 2012 IEEE Power and Energy Society General Meeting, IEEE, 2012, pp. 1-10.

[5] H. Park, R. Baldick, D.P. Morton, A stochastic transmission planning model with dependent load and wind forecasts, IEEE Transactions on Power Systems, 30(6) (2015) 3003-3011.

[6] H. Yu, C. Chung, K. Wong, J. Zhang, A chance constrained transmission network expansion planning method with consideration of load and wind farm uncertainties, IEEE Transactions on Power Systems, 24(3) (2009) 1568-1576.

[7] J. Qiu, J. Zhao, Z.Y. Dong, Probabilistic transmission expansion planning for increasing wind power penetration, IET Renewable Power Generation, 11(6) (2017) 837-845.

[8] F. Ugranli, E. Karatepe, A.H. Nielsen, MILP approach for bilevel transmission and reactive power planning considering wind curtailment, IEEE Transactions on Power Systems, 32(1) (2016) 652-661.
[9] W. Wu, Z. Hu, Y. Song, G. Sansavini, H. Chen, X. Chen, Transmission network expansion planning based on chronological evaluation considering wind power uncertainties, IEEE Transactions on Power Systems, 33(5) (2018) 4787-4796.
[10] S. Zolfaghari, T. Akbari, Bilevel transmission expansion planning using second-order cone programming considering wind investment, Energy, 154 (2018) 455-465.
[11] M. Sun, J. Cremer, G. Strbac, A novel data-driven scenario generation framework for transmission expansion planning with high renewable energy penetration, Applied energy, 228 (2018) 546-555.
[12] C. Roldán, A.S. de la Nieta, R. García-Bertrand, R. Mínguez, Robust dynamic transmission and renewable generation expansion planning: walking towards sustainable systems, International Journal of Electrical Power & Energy Systems, 96 (2018) 52-63.
[13] J. Wang, H. Zhong, W. Tang, R. Rajagopal, Q. Xia, C. Kang, Tri-level expansion planning for transmission networks and distributed energy resources considering transmission cost allocation, IEEE Transactions on Sustainable Energy, 9(4) (2018) 1844-1856.
[14] T. Akbari, A. Rahimi-Kian, M.T. Bina, Security-constrained transmission expansion planning: A stochastic multi-objective approach, International Journal of Electrical Power & Energy Systems, 43(1) (2012) 444-453.
[15] S. Lumbreras, A. Ramos, P. Sánchez, Automatic selection of candidate investments for Transmission Expansion Planning, International Journal of Electrical Power & Energy Systems, 59 (2014) 130-140.
[16] H. Nemati, M.A. Latify, G.R. Yousefi, Coordinated generation and transmission expansion planning for a power system under physical deliberate attacks, International Journal of Electrical Power & Energy Systems, 96 (2018) 208-221.
[17] S. Lumbreras, A. Ramos, F. Banez-Chicharro, Optimal transmission network expansion planning in real-sized power systems with high renewable penetration, Electric Power Systems Research, 149 (2017) 76-88.
[18] O. Alizadeh-Mousavi, M. Zima-Bočkarjova, Efficient Benders cuts for transmission expansion planning, Electric Power Systems Research, 131 (2016) 275-284.
[19] A. Moreira, D. Pozo, A. Street, E. Sauma, Reliable renewable generation and transmission expansion planning: co-optimizing system's resources for meeting renewable targets, IEEE transactions on power systems, 32(4) (2016) 3246-3257.
[20] A. Moreira, G. Strbac, R. Moreno, A. Street, I. Konstantelos, A five-level milp model for flexible transmission network planning under uncertainty: A min–max regret approach, IEEE Transactions on Power Systems, 33(1) (2017) 486-501.
[21] R. Minguez, R. García-Bertrand, J.M. Arroyo, N. Alguacil, On the solution of large-scale robust transmission network expansion planning under uncertain demand and generation capacity, IEEE Transactions on Power Systems, 33(2) (2017) 1242-1251.
[22] X. Zhang, A.J. Conejo, Robust transmission expansion planning representing long-and short-term uncertainty, IEEE Transactions on Power Systems, 33(2) (2017) 1329-1338.
[23] S. Zolfaghari-Moghaddam, T. Akbari, A Multi-objective Transmission Expansion Planning Strategy: A Bilevel Programming Method, AUT Journal of Electrical Engineering, 50(2) (2018) 163-168.
[24] Y. Ou, C. Singh, Assessment of available transfer capability and margins, IEEE Transactions on Power Systems, 17(2) (2002) 463-468.
[25] N. Rep, Available transfer capability Definitions and determinations, North American Electric Reliability Council (NERC), (1996).
[26] N.F. Avila, C.-C. Chu, Distributed probabilistic ATC assessment by optimality conditions decomposition and LHS considering intermittent wind power generation, IEEE Transactions on Sustainable Energy, 10(1) (2018) 375-385.
[27] J.-H. Liu, C.-C. Chu, Iterative distributed algorithms for real-time available transfer capability assessment of multiarea power systems, IEEE Transactions on Smart Grid, 6(5) (2015) 2569-2578.
[28] P. Du, W. Li, X. Ke, N. Lu, O.A. Ciniglio, M. Colburn, P.M. Anderson, Probabilistic-based available transfer capability assessment considering existing and future wind generation resources, IEEE Transactions on sustainable Energy, 6(4) (2015) 1263-1271.
[29] H. Chen, X. Fang, R. Zhang, T. Jiang, G. Li, F. Li, Available transfer capability evaluation in a deregulated electricity market considering correlated wind power, IET Generation, Transmission & Distribution, 12(1) (2017) 53-61.
[30] E. Shayesteh, B.F. Hobbs, L. Söder, M. Amelin, ATC-based system reduction for planning power systems with correlated wind and loads, IEEE Transactions on Power Systems, 30(1) (2014) 429-438.
[31] J.C. Helton, F.J. Davis, Latin hypercube sampling and the propagation of uncertainty in analyses of complex systems, Reliability Engineering & System Safety, 81(1) (2003) 23-69.
[32] D. Cai, D. Shi, J. Chen, Probabilistic load flow computation using Copula and Latin hypercube sampling, IET Generation, Transmission & Distribution, 8(9) (2014) 1539-1549.
[33] Z. Shu, P. Jirutitijaroen, Latin hypercube sampling techniques for power systems reliability analysis with renewable energy sources, IEEE Transactions on Power Systems, 26(4) (2011) 2066-2073.
[34] A. Arabpour, M.R. Besmi, P. Maghouli, Transmission expansion planning with linearized AC load flow by special ordered set method, Journal of Energy Engineering, 144(2) (2018) 04018008.
[35] T. Akbari, M.T. Bina, A linearized formulation of AC multi-year transmission expansion planning: A mixed-integer linear programming approach, Electric Power Systems Research, 114 (2014) 93-100.
[36] R.N. Allan, R. Billinton, N. Abdel-Gawad, The IEEE reliability test system-extensions to and evaluation of the generating system, IEEE Transactions on Power Systems, 1(4) (1986) 1-7.
[37] R.D. Zimmerman, C.E. Murillo-Sánchez, R.J. Thomas, MATPOWER: Steady-state operations, planning, and analysis tools for power systems research and education, IEEE Transactions on power systems, 26(1) (2010) 12-19.
[38] T. Akbari, A. Rahimikian, A. Kazemi, A multi-stage stochastic transmission expansion planning method, Energy conversion and Management, 52(8-9) (2011) 2844-2853.

HOW TO CITE THIS ARTICLE

S. Zolfaghari Moghaddam, T. Akbari, A Multi-Year Scenario-Based Transmission Expansion Planning Model Incorporating Available Transfer Capability, AUT J. Elec. Eng., 52(1) (2020) 121-130.

DOI: 10.22060/eej.2019.16995.5301

This page intentionally left blank