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Long term transmission expansion planning to improve power system resilience against cascading outages

Milad Qorbani, Turaj Amraee *

Department of Electrical Engineering, K.N. Toosi University of Technology, Tehran, Iran

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ABSTRACT

A Transmission Expansion Planning (TEP) problem is proposed to find the optimal configuration of the transmission network with considering security and resilience constraints. Due to the importance of blackouts and cascading failure, the proposed Resilient TEP (RTEP) minimizes the effects of cascading outages in term of load curtailment. In order to estimate the size of cascading outages, based on the total lost load, an iterative algorithm is proposed to analyze and simulate the steady state mechanism of cascading outages. A set of initiating events are defined as the triggering points of the cascading failure and the consequent chain of related outages are identified to determine the blackout size. In addition to the resilience constraints, the security constraints based on N-1 security criterion are also considered. Based on the Benders Decomposition (BD) algorithm, a multi-stage solution procedure is developed to handle the investment decisions, security constraints, and resilience requirements efficiently. In order to achieve the optimal resilient TEP configuration, all the master and subproblems are formulated as Mixed Integer Programming optimization models. The proposed RTEP is implemented over the IEEE 24-bus test system.

1. Introduction

Transmission networks are designed for efficient and secure supply of the future load. The Transmission Expansion Planning (TEP) problem is carried out to determine the optimal network plan with minimum investment cost of transmission assets and power generation costs [1-2]. According o N-*k* security criterion, the transmission network should be able to survive the simultaneous forced outages of *k* transmission lines. Due to the budgetary restrictions, practically the N-*k* criterion is limited to the single or credible double contingencies. In [3-4], the impact of security constraints including single contigencies on TEP problem is investigated. The security-oriented transmission plans are vulnerable to high order multiple outages or cascading failures. Upgrading the conventional secure TEP plan to the resilient network plan has been recently addressed to minimize the supply discontinuity under cascading failures [5]. Cascading outages as high-impact and low probability events, are known as major threats to power system stability and security. According to [6], a cascading failure or blackout is defined as "the uncontrolled successive loss of system elements triggered by an incident at any location". A cascading outage is a sequence of interdependent component outages, and therefore their analysis and prediction is very complicated. Dependent outages in a cascading failure occur due to different mechanisms such as thermal overloads, rotor angle instability, and voltage instability [6]. Cascading outages of transmission lines are seen in any large power system blackout [7]. A cascading outage begins with an initial event and progressively propagates across the network. The initiating events are caused by weather storms, earthquakes, hidden failures and operators' errors. The basics of cascading failures are given in [8]. When one or more equipment are out for maintenance purposes, a heavy loading condition may increase the risk of cascading outage. Load interruption, large frequency and voltage deviations, and blackout are the consequences of these cascading outages. A major lesson learned from previous blackouts around the world, is that such cascading outages can be avoided by proper preventive and corrective actions [9-10]. According to [11], while many electrical factors impact the mechanism of cascading outages, the inadequacy of transmission network has been identified as a major root of cascading outage. Therefore, by upgrading transmission network, the consequences of blackouts can be reduced. The blackout mechanism is very complicated and powerful simulation tools are required to estimate the consequences of blackouts. Some package tools have been developed for simulating cascading failures such as PRACTICE [12], TRELSS [13], and OPA [14]. In [15], a Markovian influence graph is proposed to describe the probabilities of

* Corresponding author.
E-mail addresses: amraee@kntu.ac.ir, amraee@eetd.kntu.ac.ir (T. Amraee).

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Nomenclature

Sets and Indices

Λ, i	Set and index of all nodes
Ω_b, b	Set and index of load blocks
Ω_{all}	Set of all transmission lines
Ω_c	Set of all candidate transmission lines
Ω_e	Set of all existing transmission lines
Ω_i	Set of all buses with direct connection to bus i

Parameters

c_{ij}	Annualized Investment cost of transmission line between nodes i and j
π_{ib}	Cost of power generation of generating unit i at load block b ($/MWh)
$\{\bullet\}^{min}$	Minimum of a given variable
$\{\bullet\}^{Max}$	Maximum of a given variable
d_{ib}	Load amount in bus i at load block b
γ_{ij}	Susceptance of transmission line between node i and j
IC	The maximum annualized budget for transmission expansion planning
n_{ij}^{max}	The maximum allowable number of transmission lines in corridor i to j
$\overline{n}_{ij}$	Total number of available or existing lines in corridor i to j
NL_{ij}	The maximum number of total existing and new transmission lines in corridor i to j
Δt_b	Time duration of load block b

Variable

Y	Auxillary variable of the master problem representing total annualized transmission expansion planning cost
$Z1$	Auxillary variable representing the total annualized power generation cost
$Z2$	Auxillary variable representing the total violation in power balance constraint
n_{ij}^{c}	Binary decision variables of transmission expansion (1 if the transmission lines between nodes i and j is constructed, 0 otherwise)
$\widehat{n}_{ij}^{c}$	The fixed value of n_{ij}^{c}
η_{ij}	Duality variable
PG_{ib}	Power generation of unit i at load block b
LS_{ib}	Load Shedding in bus i at load block b
Sg_{ib}	Generation change in bus i at load block b
F_{ijb}	Total power flow across all transmission lines between nodes i to j at load block b
f_{ijb}^{e}	Power flow across existing transmission line between nodes i and j at load block b
f_{ijb}^{c}	Power flow across new transmission line between nodes i and j at load block b
θ_{ib}	Voltage angle of bus i at load block b

line outages and subsequent cascading failures. In conventional secure TEP studies, the possibility of propagation of a singe outage to cause subsequent outages is ignored. However, some low order outages can propagate across the network and may cause a cascading outage with large amount of load shedding and generation outages. Cascading outages are rare events with high impact and by a reasonable additional investment, the transmission configuration can be upgraded to minimize the risk of such cascading outages. The Resilient TEP (RTEP) problem refers to the TEP study in which the vulnerability of transmission network against high-impact low-probability events is considered. In [16-17], the concepts of operational resilience and infrastructure resilience in power system along with resilience metrics are introduced. According to [16-17], a resilient power system is able to survive the extreme events with least possible load interruption and it can be restored to an acceptable performance within acceptable time [18]. In [19], the transmission architecture is optimized to minimize the likelihood of large blackouts. The probability of a large-scale blackout is assessed using Monte Carlo simulation method. The procedure of blackout simulation begins by randomly selecting a line to trip. Then the possibility of next line outage is assessed using steady state power flow model. This cascading process continues until there is no new line outage. In [19], the objective function is defined such that the probability of blackout is minimized while the planning cost remains below the maximum available budget. Blackout size is defined as the total load shed. In [20], a stochastic TEP problem is introduced to consider the risk of blackout. The objective function is defined to minimize the cost of planning and Expected Energy Not Served (EENS). The EENS of each scenario is evaluated using the OPA method proposed previously in [21]. Due to the complexity of the proposed model, in [20], the particle swarm optimization is utilized to solve the probabilistic TEP model. The OPA model is inherently a blackout analysis model that is able to capture the stochastic nature of blackout and the simulation of involved fast and slow dynamics during a cascading failure. An improved OPA model is introduced in [22], where the fast dynamics of the system and the influence of power flow, dispatching, automation, and relay protection are considered. In [23-24], the stochastic "Random Chemistry" (RC)

Table 1
Comparative analysis of previous TEP models.

Ref	Type of TEP model					Main characteristics of TEP model						
	Optimization Model	Solution Method	Power Flow Model	Stochastic/ Deterministic	Multi-Period/ Static	Generation Expansion	Renewable Resources	Volt-Var Modeling	Cogestion Management	Resilience Criteria	Security/ Reliability	Market Issues
[4]	MINLP	E[1]	AC	D[4]	MP[6]	×	×	✓	×	×	✓	×
[5]	MINLP	E	AC	D	MP	×	×	✓	×	×	✓	×
[19]	MINLP	E	DC	S[5]	ST	×	×	×	×	×	✓	×
[20]	MINLP	E	DC	S	ST	×	×	×	×	×	✓	×
[25]	MIP	A[2]	DC	S	ST	×	✓	×	×	✓	✓	×
[26]	MINLP	E	AC	S	ST	×	✓	×	×	✓	✓	×
[28]	MINLP	C[3]	DC	S	ST[7]	✓	×	×	×	✓	✓	×
[29]	MIP	E	DC	S	ST	✓	×	×	×	✓	✓	×
[30]	MINLP	E	DC	S	MP	×	×	×	×	✓	✓	✓
[31]	MINLP	A	DC	S	ST	×	×	×	×	✓	✓	×

1: Evolutionary 2:Analytic 3: Combined (Evolutionary and Analytic) 4: Deterministic 5: Stochastic 6: Multi-Period 7: Static.
✓: Included ×: Not-Included.

algorithm is proposed to identify multiple contingencies that initiate large cascading failures. Due to the complexity of the blackout mechanism, DC load flow is used in [23-24] to estimate the size of blackout. In [23], a data-driven stochastic defender-attacker-defender model is proposed for the transmission planning problem considering wind uncertainty and unknown disruptive natural disaster. In [25], the attackers are extreme weather events while the defenders are the transmission upgrade and generation re-dispatch to minimize the damages. In [25], the mechanism of cascading outages are not considered and the simultaneous multiple contingencies are assumed as the extreme event. In [26], a risk-based TEP model is proposed for optimizing transmission design against extreme weather events with considering uncertainties of wind power, load and component availability. Transmission upgrade and generation re-dispatch are considered in the risk-based TEP model proposed in [26]. In [26], the mechanism of cascading outages are not considered. Due to the complexity of model, a history driven differential evolution (HDDE) algorithm is used to solve the optimization model. In [27], using fragility curves, the weather and time-dependent failure probabilities of system's components are determined. In [28], the transmission and generation expansion planning are optimized to improve the power system resilience against possible earthquakes. The impact of earthquakes on failure of electric components has been addressed in [28]. In [29], a multi-level MIP problem is developed for achieving a resilient TEP against terrorist attacks. The Tabu Search algorithm is used to solve the proposed TEP model. The defense budget and attacker budgets are considered in [29]. In [30], a resilience-based model is presented for multi-period transmission and substation expansion planning problem against extreme weather-related events. The proposed model is applied over the Iranian national grid and the optimization problem is solved using symphony orchestra search algorithm. In [31], a resilient network planning model is proposed by testing the performance of a comprehensive set of system expansion against a set of outages caused by earthquake. For better clarification, the main characteristics of recent TEP models are summarized in Table 1. In order to design a resilient transmission network, the mechanism of the cascading failures should be included in the RTEP model. Also, efficient decomposed formulation is needed to handle the security and resilience constraints in TEP model. The main contributions of this paper are summarized as follows:

1- A RTEP model is proposed to optimize the transmission expansion planning with considering security and resilience criterion, simultaneously. The investment cost of new transmission lines, the generation cost and energy not served are minimized. Generation re-dispatch and load shedding are considered as emergency actions during blackout simulation, while the generation re-dispatch is selected as the first resort.
2- In order to consider the transmission resilience, the size of blackout caused by the cascading line outage is evaluated using a blackout simulation model. The blackout simulation procedure acts based on the DC power flow. The initiating events are defined based on possible contingencies over the connected lines to each bus.
3- In order to achieve the computational tractability of the proposed RTEP model, the Benders Decomposition (BD) algorithm is used to handle the security and resilience constraints. Building new transmission lines is considered as the decision investments. Generation re-dispatch and load shedding are assumed as the control variables in blackout simulation. The proposed BD-based RTEP model is formulated as an MIP optimization algorithm.

The rest of this paper is organized as follows. In Section 2, the proposed RTEP models including the blackout simulation model are introduced. In Section 3, the simulation results of the proposed model over the IEEE 24-Bus system is presented. Finally, the paper is concluded in Section 4.

2. Proposed RTEP model

Security Constrained TEP (SCTEP) refers to the TEP study with conventional N-1 security criterion. RTEP refers to the TEP study in which both security and resilience constraints are included. Since the proposed RTEP formulation contains the SCTEP, the formulations of the RTEP model is presented. In order to achieve the computational tractability, the Benders Decomposition (BD) algorithm is used. Based on the BD, the proposed R-TEP problem is decomposed into a master problem (MP) and some Sub-Problems (SP). In the proposed RTEP model the stability phenomena are not considered.

In certain classes of optimization problems such as Mixed Integer Linear Programming (MIP) Problems, simultaneous considering of all decision variables and constraints is not practical. Benders decomposition (BD) algorithm partitions the entire MIP problem into multiple small optimization problems including master problem and sub-problems. In our problem, the proposed R-TEP problem is decomposed into a master problem (MP) and some Sub-Problems (SP). The MP contains the transmission investment decisions (i.e. adding new transmission lines) with technical and economic constraints of transmission planning. It is noted that benders cuts refer to the constraints generated based on the necessity conditions for feasibility of SP2 or the optimality conditions of SP1. The MP contains the transmission investment decisions (i.e. adding new transmission lines) with technical and economic constraints of transmission planning. The formulation of the MP is given by (1)–(7).

$$\mathrm{Min}\{Y\} \tag{1}$$

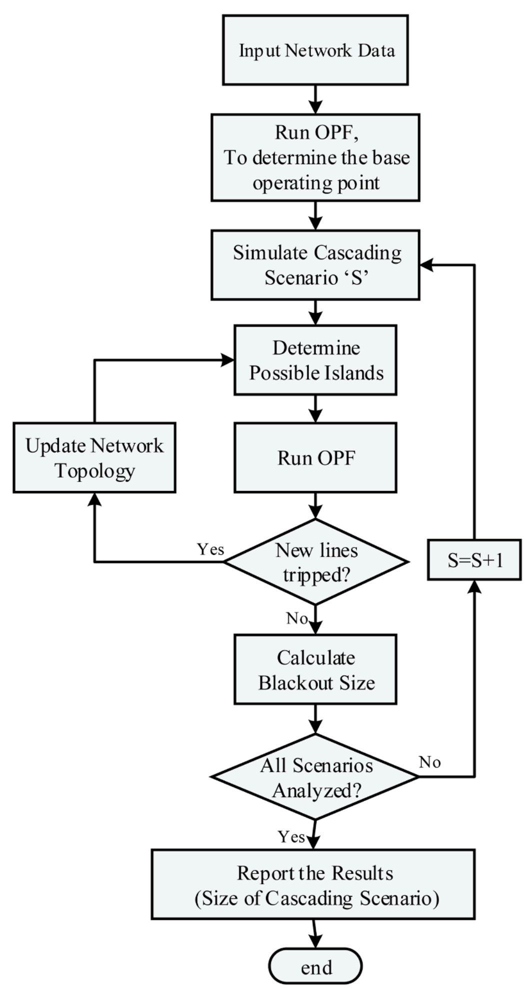


Fig. 1. The overal procedure of cascading failure analysis.

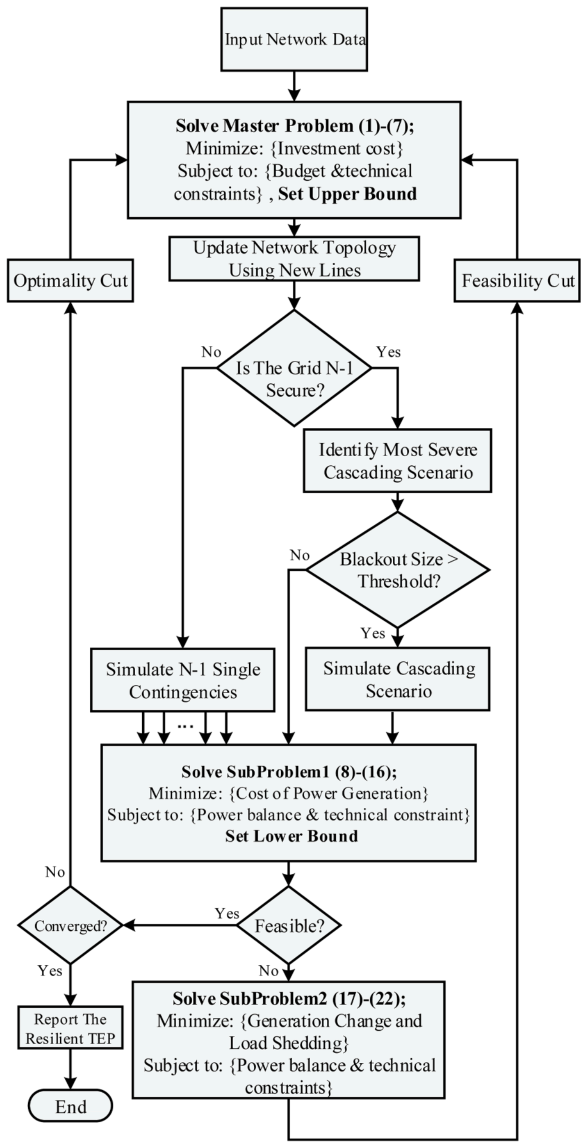


Fig. 2. The detailed structure of the proposed RTEP using BD algorithm.

$$Y \geq \sum_{(i,j)\epsilon\Omega_c} \sum_{c=1}^{n_{ij}^{max}} c_{ij}.n_{ij}^c \tag{2}$$

$$Z2 + \sum_{(i,j)\epsilon\Omega_c} \sum_{c=1}^{n_{ij}^{max}} \eta_{ij} \cdot \left(n_{ij}^c - \widehat{n}_{ij}^c \right) \leq 0; \ \forall \ (i,j)\epsilon\Omega_c \tag{3}$$

$$Y \geq \sum_{(i,j)\epsilon\Omega_c} \sum_{c=1}^{n_{ij}^{max}} c_{ij}.n_{ij}^c + Z1 + \sum_{(i,j)\epsilon\Omega_c} \sum_{c=1}^{n_{ij}^{max}} \eta_{ij} \cdot \left(n_{ij}^c - \widehat{n}_{ij}^c \right) \tag{4}$$

$$\sum_{(i,j)\epsilon\Omega_c} \sum_{c=1}^{n_{ij}^{max}} c_{ij}.n_{ij}^c \leq IC \tag{5}$$

$$n_{ij} \leq NL_{ij} - \overline{n}_{ij}; \ \forall \ (i,j)\epsilon\Omega_c \tag{6}$$

$$n_{ij} = \sum_{c=1}^{n_{ij}^{max}} n_{ij}^c; \ \forall \ (i,j)\epsilon\Omega_c \tag{7}$$

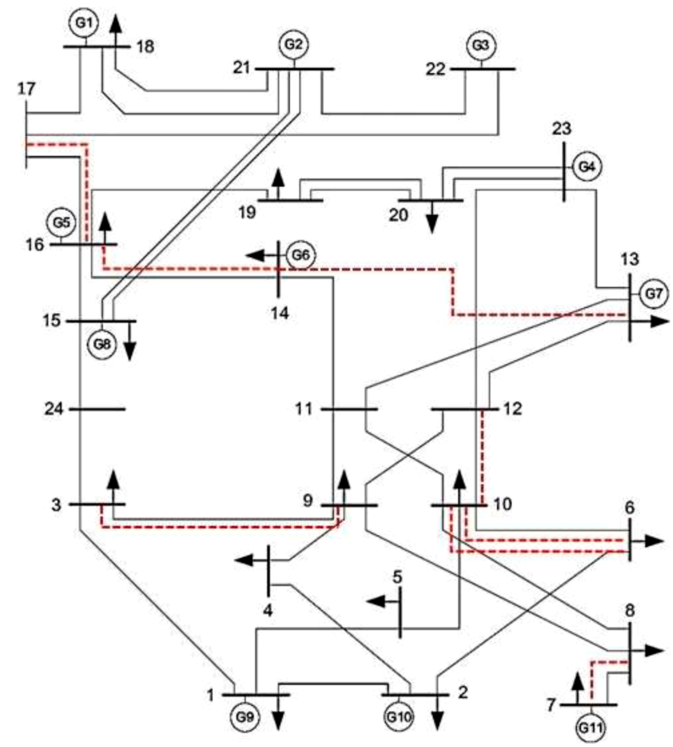


Fig. 3. The transmission expansion plan using the secure TEP model.

According to (1)-(2), the capital cost of new transmission lines is minimized. The feasibility and optimality cuts are formulated using (3) and (4), respectively. The maximum available budget for transmission expansion planning is considered using (5). The maximum number of transmission lines that can be constructed in each corridor is limited according to (6). The total number of new transmission lines in each corridor is enumerated using (7). In addition to the cost of new transmission lines, the cost of power generation should be minimized.

Variable Z1 is an auxiliary continuous variable representing the total power generation cost in the first sub-problem (SP1). The objective function of the SP1 is defined to minimize the total power generation cost (i.e. minimization of Z1). Variable Z2 is an auxiliary continuous variable representing the violation of power balance constraint in the second sub-problem (SP2). The objective function of the SP2 is defined to minimize the total power balance violation (i.e. minimization of Z2). To this end, the first sub-problem, SP1, is defined as given by (8)–(16). In SP_1, based on (8), the cost of power generation is minimized. The power balance is satisfied using (9)–(10). The power flows across existing and new transmission lines are calculated using (11)–(12). Also, the limits of power flows across existing and new transmission lines are enforced based on (13) and (14). The maximum limit of power generation is considered using (15). The constraint given by (16) is defined to fix the status of c^{th} new transmission lines in corridor ij (i.e. n_{ij}^c) at its related value (i.e. $\widehat{n}_{ij}^c$) obtained from MP. The lagrange multiplier of (16) will be used to generate the optimality cut. The optimality cut is passed to the MP.

$$Z1 = \sum_{b\epsilon\Omega_b} \Delta t_b \left(\sum_{i\epsilon\Lambda} \pi_{ib}.PG_{ib} \right) \tag{8}$$

$$PG_{ib} - d_{ib} = \sum_{j\epsilon\Omega_i} F_{ijb}; \ \forall \ i\epsilon\Lambda, \ b\epsilon\Omega_b \tag{9}$$

$$F_{ijb} = f_{ijb}^e + \sum_{c=1}^{n_{ij}^{max}} f_{ijb}^c; \ \forall \ (i,j)\epsilon\Omega_{all}, \ b\epsilon\Omega_b \tag{10}$$

$$f^e_{ijb} = \gamma_{ij}.(\theta_{ib} - \theta_{jb});\ \forall\ (i,j)\epsilon\Omega_e,\ b\epsilon\Omega_b \tag{11}$$

$$-M.\left(1-n^c_{ij}\right)\langle f^c_{ijb} - \gamma_{ij}.(\theta_{ib}-\theta_{jb})\langle M.\left(1-n^c_{ij}\right);\ \forall\ (i,j)\epsilon\Omega_c,\ b\epsilon\Omega_b \tag{12}$$

$$-\bar{f}_{ijb} < f^e_{ijb} < \bar{f}_{ijb};\ \forall\ (i,j)\epsilon\Omega_e,\ b\epsilon\Omega_b \tag{13}$$

$$-\bar{f}_{ijb}.n^c_{ij} < f^c_{ijb} < \bar{f}_{ijb}.n^c_{ij};\ \forall\ (i,j)\epsilon\Omega_c,\ b\epsilon\Omega_b \tag{14}$$

$$PG^{min}_i \le PG_{ib} \le PG^{max}_i;\ \forall\ i\epsilon\Lambda,\ b\epsilon\Omega_b \tag{15}$$

$$n^c_{ij} = \widehat{n}^c_{ij};\ \forall\ (i,j)\epsilon\Omega_{all},\ c = 1,\dots,NL \tag{16}$$

If there is no solution for SP1, then the second sub-problem, SP2, is defined to determine the amount of violations in constraints. The formulation of SP2 is given in (17)-(22). According to (17), the objective function of SP2 is defined to minimize the violation in power balance of all buses. Indeed, this SP2 tries to restore power balance using generation increasing or load shedding, while the load shedding is the last resort. The violation is removed by load shedding or generation change. The amount of load shedding (i.e. $\sum_{b\epsilon\Omega_b}\left(\sum_{i\epsilon\Lambda} LS_{ib}\right)$ in all buses represents the Energy Not Supplied in this study. Indeed, the variables of LS_{ib} and Sg_{ib} remove the violations in power balance constraint. The power balance is represented by (18)–(19). It is noted that the constraint given in (19) refers to the set of constraints given by (10)–(15). According to (20)–(21), the amount of load shedding and generation redispatch is not allowed to exceed a predetermined value. The constraint given by (22) enforces the status of c^{th} new transmission lines in corridor ij (i.e. n^c_{ij}) at its related value (i.e. $\widehat{n}^c_{ij}$) obtained from MP. The lagrange multiplier of (22) is used to construct the optimality cut. The optimality cut is then added to the MP.

$$Z2 = \sum_{b\epsilon\Omega_b}\left(\sum_{i\epsilon\Lambda} LS_{ib} + \sum_{i\epsilon\Lambda} Sg_{ib}\right) \tag{17}$$

$$PG_{ib} - d_{ib} + LS_{ib} - Sg_{ib} = \sum_{j\epsilon\Omega_i} F_{ijb};\ \forall\ i\epsilon\Lambda,\ b\epsilon\Omega_b \tag{18}$$

$$(10) - (15) \tag{19}$$

$$PG^{min}_i \le Sg_{ib} \le PG^{max}_i;\ \forall\ i\epsilon\Lambda,\ b\epsilon\Omega_b \tag{20}$$

$$0 \le LS_{ib} \le d_{ib};\ k\epsilon\Lambda,\ b\epsilon\Omega_b \tag{21}$$

$$n^c_{ij} = \widehat{n}^c_{ij};\ \forall\ (i,j)\epsilon\Omega_{all},\ c = 1,\dots,NL \tag{22}$$

The aim of RTEP is to minimize the impact of cascading failures. Here, the amount of load shedding in each cascading scenario is used as the size of that cascading outage. A suitable procedure is required to define the cascading mechanism with considering possible interdependent outages. In this paper, the cascading outage is simulated using the procedure shown in Fig. 1. The cascading failures are very complicated with various mechanism such as thermal overloads, stability phenomenon, and protection schemes. Since the TEP study is inherently a complicated optimization problem, it is not possible to consider all cascading mechanisms. Therefore, in the proposed RTEP model, the transmission overloads are considered. Also, the generation change and load shedding are taken into account to remove the possible violations. According to Fig. 1, the mechanism of the cascading outage is described as follows. An initial Optimal Power Flow (OPF) is carried out to match the load and generation. Based on the operating point obtained by OPF, a set of input scenarios are defined. Each scenario contains an initiating or triggering events for the cascading outage. In this paper, the initiating events are assumed to be the double line outage in each substation. In other words, all double line outages in each bus are considered as the triggering event. It is noted that all single outages are considered via the N-1 security constraints. No single outage results in cascading failure. The initiating events are then assumed as the input of the cascading analysis procedure. Under each scenario (i.e. each triggering event) the possible islands are identified. These islands may directly result from the input initiating event. Afterward, each possible island is handled separately. At the next step, an OPF is carried out and the overloaded transmission lines are identified. In case of overload, the related transmission line is tripped and the network topology is updated and will be analyzed again. This process continues until there is no new line trip. Then, the size of cascading blackout is determined. The size of blackout is defined as the total load shed caused by the cascading failure. This procedure is repeated for all scenarios. The procedure given in Fig. 1, is used as a part of the proposed RTEP.

The detailed structure of the proposed RTEP using BD is illustrated in Fig. 2. The MP and both SPs are illustrated in Fig. 2. The MP is devoted to the transmission investment, while the costs of generation and load shedding are minimized in SP1. Both the security criterion (i.e. N-1 criterion) and the cascading failure simulation procedure (i.e. resilience

Table 2
The set of new transmission lines obtained by secure and resilient TEP models.

TEP Model	Total Cost(M$)	Expansion Plan(Lines: from-to)
N-1 Secure (SCTEP)	281	(10–12) (7–8) (6–10)*2 (3–9) (16–17) (14–16) (13–14)
Plan1 (RTEP)	294	(7–8) (6–10) (10–11) (3–24) (16–17) (15–24) (14–16)
Plan2 (RTEP)	330	(7–8) (6–10) (10–11) (3–24) (16–17) (15–24) (15–21)*2 (14–16)
Plan3 (RTEP)	517	(10–11) (7–8) (6–10)*2 (3–9) (14–16)*2 (13–14) (11–14) (16–17)*2 (15–21)
Plan4 (RTEP)	537	(10–11) (7–8) (6–10)*2 (3–9) (16–17)*3 (14–16)*2 (11–14)*2 (18–21) (17–18)
Plan5 (RTEP)	555	(6–10)*2 (3–24) (3–9) (14–16)*2 (11–14) (10–11)*2 (17–18) (16–17)*2 (15–21)
Plan7 (RTEP)	595	(10–11)*2 (7–8) (6–10)*2 (3–9) (15–21) (14–16)*2 (11–14)*2 (17–18) (16–19) (16–17)*2

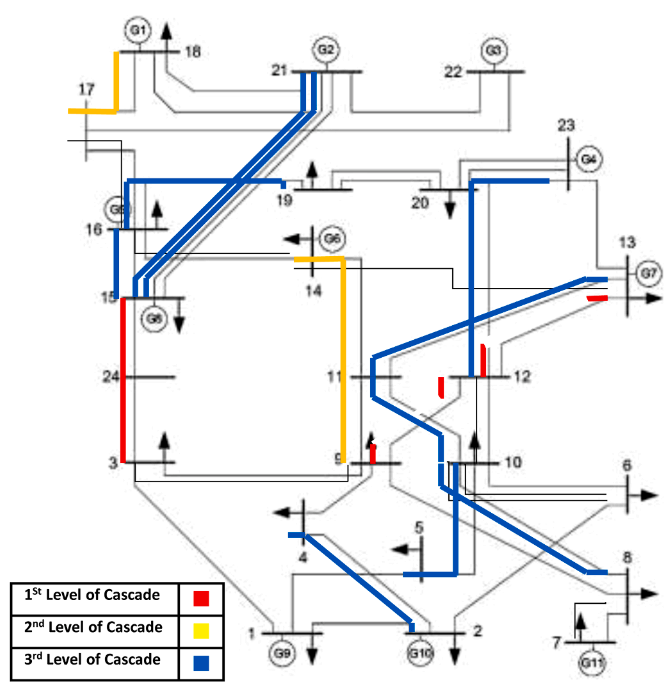


Fig. 4. The worst cascading outage in the N-1 secure TEP plan.

criterion) are considered in SP1. If SP1 is feasible, then the convergence criterion is checked. If the convergence criterion is satisfied then the optimal transmission plan is obtained, otherwise, the optimality cut is constructed and added to the MP. If SP1 is infeasible, then the SP2 is solved and the resulted feasibility cut is added to the MP. This iterative process continues until the optimal plan is obtained. The convergence criterion is defined as given by (23), where the UB and LB are calculated using (24) and (25), respectively.

$$\varepsilon = \frac{(UB - LB)}{UB} \tag{23}$$

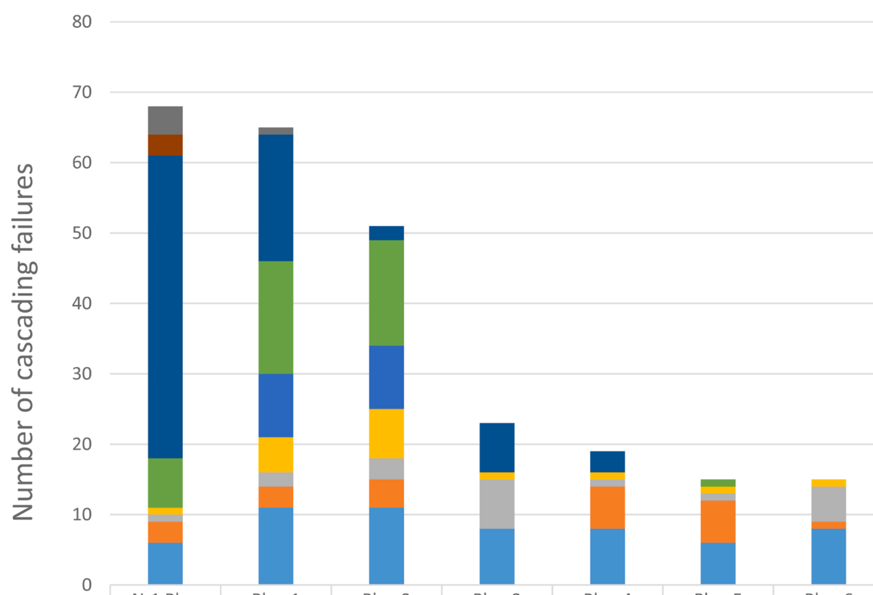
$$UB = \sum_{(i,j)\epsilon\Omega_c} \sum_{c=1}^{n_{ij}^{max}} c_{ij}.n_{ij}^{c} + Z1 \tag{24}$$

$$LB = Y \tag{25}$$

Initially, it is assumed that $= -\infty$, and $\boldsymbol{UB} = +\infty$. The MP is solved to determine the new transmission lines. These new transmission lines are assumed as the input of SP1 and SP2. According to Fig. 2, the feasibility cut is constructed using SP2 based on the Lagrange multiplier of the constraint given by (22). The feasibility cut is then added to the MP. This constraint is named the feasibility cut because it enforce the necessary conditions for feasibility of the SP2. Indeed, each benders cut is actually a constraint which is constructed based on the feasibility or optimality conditions. When the SP1 is feasible and the convergence criterion is passed, the iterative solution is ended and the optimal solution, which is secure and resilient, is determined. If the SP1 is feasible but the convergence criterion is not satisfied, the optimality cut is then constructed based on the Lagrange multiplier of the constraint given by (16) and is then added to the MP. The optimality cut is generated based on the optimality conditions of SP1. The input and output of each part of the proposed RTEP are shown in Fig. 2.

3. Simulation results

The proposed RTEP model is applied over the IEEE 24-Bus test system. The base case data of this test system can be found in [32]. The utilized test system has 41 corridors (i.e. the path of transmission lines between two different nodes) and 14 generating units. The proposed method is simulated for a given target year. All the N-1 outages are considered as the security requirement. A total number of 97 double line outages are considered as the initiating events that may cause subsequent outages or even a major cascading failure. The results are presented in two parts including the secure and resilient TEP plans. The secure TEP plan considers only the N-1 security constraints, while the resilient TEP plan considers both N-1 single outages and cascading failure scenarios. In TEP studies, due to reducing computational complexity, conventionally the DC power flow model is used. The AC power flow model is accurate, however, the AC-based TEP models are Mixed Integer Non-Linear Programming (MINLP) models. Obtaining the optimal global solution in MINLP problems is very challenging and in some cases impossible. Using the DC power flow model, the resulted TEP model is an MIP optimization model and the global optimal solution can be achieved using the commercial solvers such as CPLEX. All the



	N-1 Plan	Plan 1	Plan 2	Plan 3	Plan 4	Plan 5	Plan 6
1800MW-2000MW	4	1	0	0	0	0	0
1600MW-1800MW	3	0	0	0	0	0	0
1400MW-1600MW	43	18	2	7	3	0	0
1200MW-1400MW	7	16	15	0	0	1	0
1000MW-1200MW	0	9	9	0	0	0	0
800MW-1000MW	1	5	7	1	1	1	1
600MW-800MW	1	2	3	7	1	1	5
400MW-600MW	3	3	4	0	6	6	1
200MW-400MW	6	11	11	8	8	6	8

200MW-400MW 400MW-600MW 600MW-800MW 800MW-1000MW 1000MW-1200MW 1200MW-1400MW 1400MW-1600MW 1600MW-1800MW 1800MW-2000MW

Fig. 5. The size and number of cascading failure scenarios using secure and resilient TEP plans.

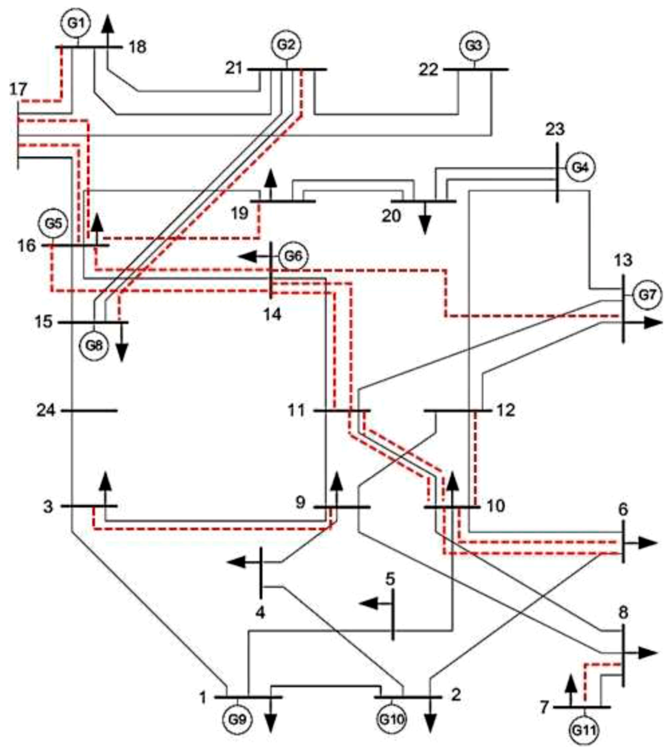


Fig. 6. The resilient transmission expansion plan using the proposed RTEP mode (Plan-6).

optimization master and sub-problems are solved using CPLEX in GAMS [33].

3.1. Case 1. The SCTEP model

In this part, the security constrained TEP model is simulated over the test case. The resilience constraints including cascading failures are not taken into account. The obtained results including the new transmission lines and the related costs are reported in Fig. 3 to Fig. 5 and Table 2. The total cost of secure TEP is 281 M$. According to the obtained results, in order to have a secure transmission network, eight new transmission lines including the transmission lines (10–12), (7–8), (6–10)*2, (3–9), (16–17), (14–16), and (13–14) should be added to the existing network. It is noted that the expression of (6–10)*2 refers to two transmission lines from Bus-6 to Bus-10. Since in SCTEP (i.e. N-1 secure plan), the resilience constraints are not considered, under cascading outages triggered by an initiating event (i.e. initiating events include 97 double line outages over the connected lines to each bus), the amount of load shedding is significantly high as shown in Fig. 5. According to Fig. 5, the most sever load curtailments occur under N-1 secure TEP plan. For example, according to Fig. 5, it can be seen that the obtained N-1 secure TEP plan results in 4 cascading failures with a load curtailment of 1800MW-2000MW. Also, 3, 43, and 7 cascading scenarios are expected with a load curtailment of 1600MW-1800MW, 1400MW-1600MW, and 1200MW-1400MW, respectively. Therefore, the N-1 secure TEP is not able to minimize the consequences of cascading failure. Indeed, the initiating events can be any fault including very rare events such as the simultaneous outages of two elements far from each other. However, in this paper, we have focused on credible imitating events.

For example, the worst-case cascading scenario begins with the simultaneous outages of transmission lines (9–12) and (12–13) which finally result in a load curtailment of 1981.6 MW. As shown in Fig. 4, this cascade causes line outages in three steps. In the first step, which is shown by red lines in Fig. 4, two transmission lines including (9–12) and (12–13) are outaged. This initiating event results in the overload of transmission line (3–24) and (15–24). By tripping transmission lines (3–24) and (15–24), in the second step (which is shown by yellow lines in Fig. 4), the transmission lines including (9–11), (11–14), and (17–18) are overloaded and tripped. Finally, the cascading outage ended by tripping transmission lines including (15–16), (15–21), (16–19), (11–13), (11–10), (8–10), (5–10), and (2–4). The amount of load shedding in the first step of cascade is 21MW. The load curtailment is increased to 309.4 MW, and 1981.6 MW in the second and third steps of the cascading outage.

3.2. Case 2. The resilient TEP model

In this part, the proposed RTEP model is applied to the test system. Both the security and resilience constraints are considered. The obtained results including the new transmission lines, size of cascading failures, and the related costs are reported in Fig. 5 and Table 2. Six different

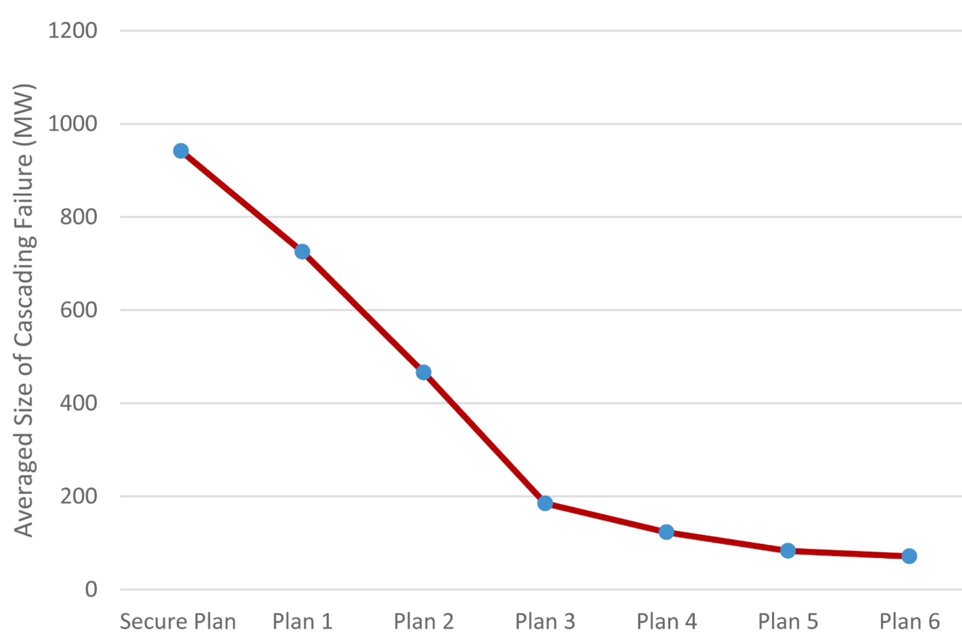


Fig. 7. The averaged size of cascading failures in secure and resilient TEP plans.

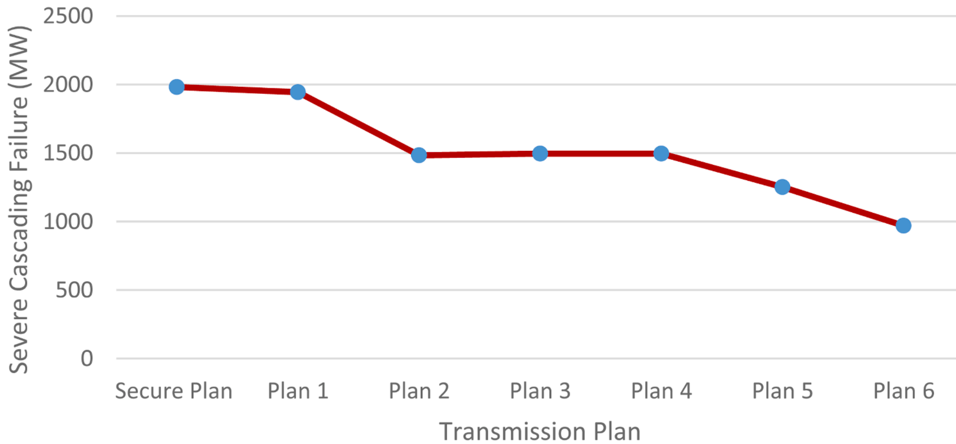


Fig. 8. The most severe cascading failures in secure and resilient TEP plans.

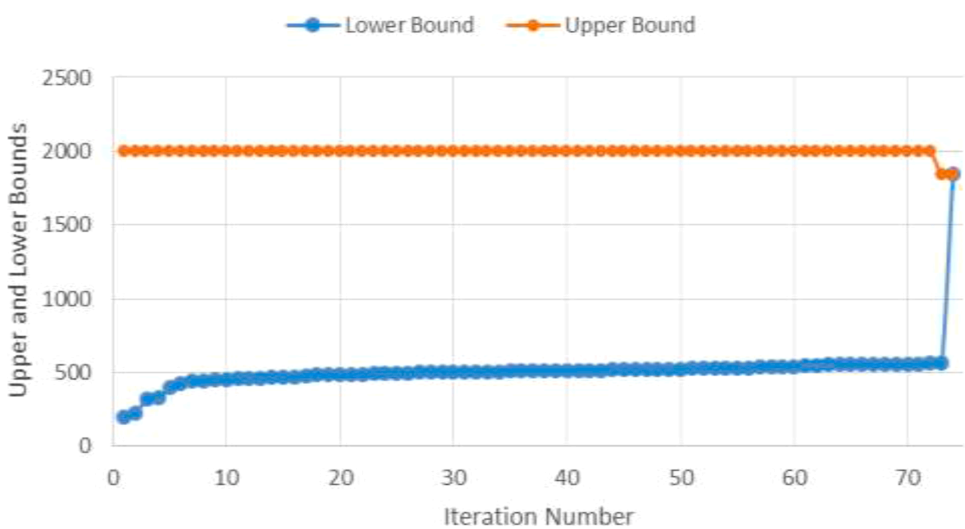


Fig. 9. The convergnece of upper and lower bounds during optimization of Plan-6.

resilient transmission plans are obtained using RTEP model based on the allowable amount of load curtailment. According to Table 2, by assigning more budgets, the obtained resilient transmission plans result in lower load curtailment. Based on Table 2, the total planning cost is increased from 294 M$ in Plan-1 to 595 M$ in Plan-6. The performances of secure TEP plan (i.e. N-1 secure) and resilient TEP plans (i.e. Plan-1 to Plan-6) under all input cascading scenarios are illustrated in Fig. 5 based on the related load curtailment. In N-1 secure plan, only the security constraints are considered and no cascading scenario is included. In resilient plans all the contingencies including single contingencies and cascading scenarios are included. Based on Fig. 5, in Plan-1, there are 44 cascading scenarios that result in load curtailment of at least 1000 MW. However, in Plan-6, no cascading scenario results in load curtailment more than 1000 MW. Other transmission plans can be compared with each other in a similar way. For better clarification, the scenarios with load curtailment lower than 200 MW are not reported. The transmission configuration in Plan-6 is illustrated in Fig. 6.

In Fig. 7, the averaged size of blackouts is illustrated for both secure and resilient transmission plans. It can be seen that the averaged sizes of all cascading failures reduce from 941.2 MW in N-1 secure plan to 70.9 MW in resilient Plan-6. Therefore, the transmission planner can select the optimal RTEP plan based on the available budget. Also, according to Fig. 8, the size of (i.e. the load curtailment of) the most sever cascading failure is reduced from 1981.6 MW in Secure N-1 TEP plan to 970 MW in resilient TEP configuration obtained by Plan-6. According to Fig. 6, beyond the resilient Plan-3, no significant reduction is achieved in averaged load curtailment. To this end, the resilient TEP Plan-3 may be a proper choice for transmission planner. In fact, the allowable amount of load shedding is the driven factor in selecting the proper transmission expansion plan. In other words, by increasing the total planning cost, the amount of load shedding is reduced. However, beyond Plan-3, by increasing the planning cost, the amount of load shedding will not reduce significantly. Therefore, Plan-3 may be a suitable choice. All in all, the planner can select the proper RTEP plan based on the available budget for additional transmission investment.

The overall iterative process between the MP and SPs is ended when the convergence criteria is reached. The convergence criteria is our Key Performance Indicator (KPI) and we have used the relative duality gap as the KPI. The convergence rate of UB and LB is illustrated in Fig. 9.

4. Conclusion

A resilient transmission expansion planning model was proposed to consider both the security and resilience constraints. The major findings of this research work are summarized as follows. 1) The conventional TEP plans are not able to minimize the consequences of cascading failures or blackouts. 2) In order to capture the mechanism of cascading failures or blackouts, a simulation procedure based on the steady state performance of transmission network is required to estimate the blackout size. The transmission overloads are the main phenomenon to estimate the chain of cascading failure. 3) The Resilient TEP plans increase the total cost of expansion planning. The major benefit of RTEP model is the reduction of number and size of severe cascading failures in term of load curtailment. The planner can select the optimal resilient TEP plan based on the available budget. 4) The input scenarios for simulating cascading failures is an essential task in blackout simulation. In this paper, the credible double line outages over the connected lines to each bus or substation were assumed as the triggering event. The averaged or expected load curtailment under all possible cascading failures and the number of severe cascading failure scenarios can be selected as performance measure in evaluating the resilience of the RTEP model. 5) The blackout simulation adds more computational burden to the TEP model. It was shown that the Benders Decomposition technique is a valuable procedure to handle the security and resilience constraints, efficiently. In this paper, the effects of the protective relays in simulating the chain of cascading outages were ignored and this issue can be investigated in future works in more details.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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