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Multi-period generation-transmission expansion planning with an allocation of phase shifter transformers

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Abstract

This study presents a convex formulation for generation-transmission expansion planning in the presence of phase shifter transformers and aims at maximizing social welfare. By changing the voltage angle, the phase shifter transformer can control the transmission power of the line. Therefore, by installing a phase shifter transformer, one can reduce the investment cost of new lines and use the nominal capacity of available transmission lines. Accordingly, the planning of the generation-transmission expansion in this paper is formulated with the assumption that there is a pool electricity market. The problem is formulated in the form of mixed integer programming and the CPLEX solver is used to solve it in the YALMIP Toolbox environment. In the proposed method, the location, capacity and year of installation of generators, transmission lines and new phase shifter transformers will be determined simultaneously. In order to validate the proposed planning, the expansion planning of the IEEE 24-bus system has been simulated in MATLAB software. Simulation results show the efficiency of the proposed method.

Keywords: Generation-transmission expansion planning (GTEP), Phase shifter transformer (PST), Social welfare (SW), Mixed integer programming (MIP)
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1 Introduction

With the increasing demand for electrical energy, it is highly crucial to develop the generation and transmission system in order to meet the load demand. Generation-transmission expansion planning is one of the major challenges of power system designers. Over time, the power system has undergone changes such as consumption growth, interconnection of networks, and the establishment of new power plants and transmission lines. These changes have exposed the system designers with limitations in the power grid operation. In addition to the large number of advantages that connecting power grids have, there are a number of problems. For instance, the passage of power in unwanted paths in the transmission system can lead to increase unauthorized load and consequently lack of optimal utilization of the power system. Therefore, it is vital to find a way to control the power flow of a path. In long lines, the major

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problem is the problem of transient stability limit and unauthorized voltage drop. In other words, to maintain the stability level of the network and stabilize the permitted voltage level, the power flow in the transmission system should be limited. As a result, these problems cause that the loading capacity of the lines decrease dramatically with the increased length of the lines. In the last few decades, the issue of transmission expansion planning (TEP) has been extensively studied, the most important of which have been presented and classified in [23]. Generation-transmission expansion planning (GTEP) is one of the most important parts of planning in the power system and its main role is to determine the optimal configuration of the network based on load demand in the planning horizon. This planning should be such that the installation of new lines and power plants are economical and can also increase the reliability of the network. Network expansion planning first started in 1970 with the aim to minimize the cost of expansion considering constraints of the production of power plants and the capacity of lines using linear programming methods [11]. In [39, 36] network expansion planning is proposed taking into account the centralized structure for the power system, with the goal of reducing investment costs. In these models, the electricity industry is monopolized by an independent system operator (ISO) while the private sector has no share in this industry. By creating a restructuring in the electricity industry, new extension models were introduced for the power system [18, 3]. Therefore, planning of the generation-transmission expansion with the aim of maximizing the social welfare of the entire network is one of the constant challenges of the power system [38, 15] and has an important role in its operation [35]. In the restructured electricity industry, the expansion of generation and transmission is usually planned by a centralized organization (for example, ISO). This is to achieve a robust economic extension plan with high reliability [38]. In other words, transmission systems need to be developed to reduce transmission congestion and provide fair access for all participants in the electricity market [43]. The construction of new transmission lines is difficult because of geographical constraints, high investment costs and the dramatic decline of social welfare [7]. Planning the power system is the knowledge of determining the efficient location, size and time to add new equipment to the power system. In this field, distinct models are proposed for solving the TEP problem [37]. An effective strategy for the planning of transmission expansion was proposed In [34, 29] and it takes into account the uncertainties of load and wind generation. The Bender's decomposition algorithm is used in conjunction with the Monte Carlo simulation (MCS) for probabilistic TEP modeling. In [29] the problem of TEP is solved using an AC-optimal power flow (AC-OPF) which improved the accuracy of the results in comparison with the DC-optimal load flow (DC-OPF). In addition, other uncertainty sources such as uncertainties associated with future load demand, fuel prices, greenhouse gas emissions, and possible disturbances can be considered in the expansion planning models [1]. Improved innovative algorithms have been used to solve the problems associated with the power system planning. In [41, 13] market-based TEP has been solved in the form of a complex mixed integer non-linear programming (MIP) with improved differential evolution algorithm. The main goal is to minimize global production and transmission costs for the participants in the market. In [19, 30] the issue of unit commitment (UC), has been taken into account for a long-term planning. This can consequently help us optimally determine to increase the capacity of units, the prices of the electricity market clearing and the daily scheduling of the power system. Exploratory algorithms, such as the genetic algorithm (GA), have been extensively used to solve the problem of GTEP [4, 40]. The models presented for power system planning in the literature are mainly based on mixed integer linear programming (MILP). Therefore, there is a widespread tendency to solve these problems based on mathematical optimization methods such as linear programming, Benders' decomposition, and two-level optimization [6, 22]. Some issues, such as reliability, security constraints, and uncertainty in the planning of market-based power systems have been extensively documented In [5] while stochastic planning is also one of the most important issues in the power system planning [2, 42]. Some of the studies, such as [31], have considered new factors and utilized a decimal coding genetic algorithm (DCGA) which includes the inflation rate and the effect of load growth on network losses.

In [32, 47] the simultaneous expansion of the generation and transmission was carried out taking into account the presence of fixed series compensation (FSCs). In [26, 46] GTEP with three aims with consideration of wind farms in the form of a MILP was carried out. In [10] two planning methods are considered: (1) centralized expansion planning in which investments are fully programmed by a central organization and (2) Decentralized expansion planning in which the extension of generation and transmission capacities is carried out by attracting investors who examine market developments. In [17, 20] a two-level planning model for coordinated planning of wind farm expansion has been proposed simultaneously with the expansion of the transmission network. The wind-heat planning framework is presented In [16] and it examines the optimal plans for the expansion of gas-fired power generating units, taking into account uncertainty in the amount of wind power generation. A flexible method for the expansion of transmission lines is introduced In [44] in which the presence of wind farm is merged with the use of the demand response mechanism. Benders decomposition method is another method of solving the TEP problem in the presence of wind energy, which was investigated In [34, 46]. In [14] a two-step TEP method is used to reduce investment costs and the stopped wind energy (in order to maximize the use of renewable energy). This model takes the normal and N-1 conditions into account. In [31, 45] a non-iterative VAM (NVAM) is presented based on electrical laws, which calculates value of the present and the planned systems by incorporating all system quantities of D/ENS, GNS, WL, CC and RDC together. Due to non-iterative batch approach, it is quite faster compared to the above-mentioned traditional VAMs, i.e., MCMF and LCS. In [8] a MILP is proposed to minimize the cost of installing new transmission lines, reactive power sources, and annual operating costs of the conventional generating units. In [25] This work presents an efficient hybrid algorithm (EHA) that consists of a search space reducer (SSR) and a modified bat-inspired algorithm (MBA) to solve the transmission network expansion planning (TNEP). The contribution of the proposal is to consider, at the same time, the security constraints criterion 'N-1', load scenarios and network losses to give a more comprehensive approach in an efficient manner, which allows applying the EHA to large-scale real system. In [27] the TEP was conducted with the consideration of the uncertainty in generation and demand using robust optimization.

One of the most commonly used FACT devices in the power system is phase shifter transformer (PST). In addition to controlling the transmission power of the line, this equipment can reduce the cost of the transmission expansion. Efficient planning to determine the location, capacity and year for optimal installation of the new equipment in the power system has always been one of the main challenges. In studies in the literature, PST's presence not carried out in the restructured electricity market to aim maximizing social welfare. Furthermore, many of the existing studies on the expansion of transmission lines and generation capacity have employed meta-heuristic algorithms such as PSO, grey wolf algorithm [28, 12] and so on [24]. In [9] presents a 10-year expansion model for Nigerian 330 kV 38-bus transmission network that adequately accommodates probabilistic growing loads using heuristic time-step power flow simulations approach. Past network operation planning was based on assigned and deterministic load projections that created transmission system performance inadequacy and load-shedding conditions under normal demands. These algorithms have a very high potential to formulate engineering issues and can solve complex linear and nonlinear problems; nevertheless, the responses obtained from them may not be the optimal global point. In addition to this drawback, due to the random structure of these algorithms, we encounter different responses each time they run. Also, their run time is very high. Therefore, the use of linear optimization algorithms, which are mathematical methods capable of finding an optimal global point, is very important. Linear programming algorithms can be implemented in software such as GAMS and YALMIP.

This article investigates GTEP in the presence of PST from the perspective of ISO. It aims at increasing the social welfare of the market and reducing the cost of investment. Also, constraints such as load flow, the transmission capacity of new and old lines, the electricity market mechanism and other technical aspects are considered when formulating it. The problem is formulated in the form of MIP and CPLEX solver is used to solve it in the YALMIP Toolbox environment. CPLEX uses mathematical methods to solve this MIP problem and is able to find an optimal solution. Therefore, since the formulation presented in this article is convex, the obtained plan will be global.

Structure of the article is as follows: 2^{th} chapter presents the generation-transmission expansion model. The network modeling and mathematical analysis of optimization problem is described in 3^{th} chapter. $4^{th}, 5^{th}$ chapters are simulation results and conclusion, respectively.

2 Generation-transmission expansion model

2.1 Market model

In this paper, the proposed model for the electricity market is a highly competitive model in which generation companies (GENCOs) and load serving entities (LSEs) offer their sales and purchases on a pool market. It is assumed that market power is not feasible in this system, and GENCOs and LSEs offer their proposed prices in accordance with the actual costs and their actual needs. ISO coordinates the transmission system expansion and generation units in accordance with the sale and purchase offers made by the participants in the market [7]. The main purpose of GENCOs and LSEs is to maximize their profits, while the main objective of ISO is to maximize social welfare [21]. In fact, the expansion of the transmission network can affect the benefit rate of the market participants. In this paper, it is also assumed that GTEP is done by ISO with the goal of maximizing social welfare. Therefore, the purpose of the proposed model in this research is to determine an expansion of generation and transmission simultaneously in the presence of PST in order to respond to the growth of load in the planning horizon.

2.2 Load modeling

As Figure 1 shows, the annual load curve is illustrated by separate blocks. Each scenario represents a load level. For example, if the first scenario indicates a load level of N1%, it means that in the first scenario, the network load level is equal to N1% of the nominal load that the network nominal load grows each year.

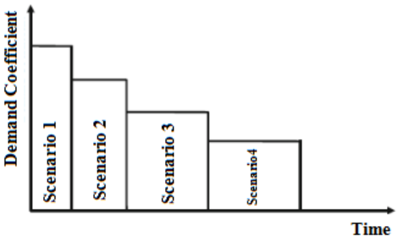

Figure 1: Annual load curve

In this modeling approach, several load levels based on the load data during a year are considered and the network total load within one year is divided into several categories. Then, the probability of occurrence of each level is calculated and this probability appears in the objective function as the weighting coefficient of that scenario.

3 Network modeling and mathematical analsis of optimization problem

In this section, we present the generation-transmission expansion planning in the presence of PST in a pool electricity market and in the framework of a MIP problem. The purpose of planning is to determine the optimal location and time for the installation of new equipment, such as power plant, line or PST. In Eq. (1), the objective function is expressed as a minimization problem.

$$\begin{aligned}\min -\Bigg\{&\sum_{t\in T}\left(\sum_{i\in\gamma_c} w_i\left(\sum_{n\in\gamma_D}\sum_{m\in\gamma_n}\frac{\mu_{D_{nm}}^{t_i}p_{D_{nm}}^{t_i}}{(1+I)^{t-t_0}}-\sum_{h\in\gamma_G}\sum_{j\in\gamma_h}\frac{\mu_{G_{hj}}^{t_i}p_{G_{hj}}^{t_i}}{(1+I)^{t-t_0}}\right)\right)\\&-\alpha\left(\sum_{r\in\gamma_k}\left(\sum_{t=t_0+1}^{T}\left(\frac{C_r(n_r^t-n_r^{t-1})}{(1+I)^{t-t_0}}\right)+C_r n_r^{t_0}\right)+\sum_{h\in\gamma_G}\left(c_h(y_h^{t_0})+\sum_{t=t_0+1}^{T}\frac{C_h(y_h^t-y_h^{t-1})}{(1+I)^{t-t_0}}\right)\right.\\&\left.+\sum_{p\in\gamma_P}\left(c_p(x_p^{t_0})+\sum_{t=t_0+1}^{T}\frac{C_p(x_p^t-x_p^{t-1})}{(1+I)^{t-t_0}}\right)\right)\Bigg\}\end{aligned}\tag{1}$$

Based on the following constraints:

$$x_p^t-x_p^{t-1}\geq 0\qquad\{\forall t\in T,\forall p\in\gamma_P\}\tag{2}$$

$$y_h^t-y_h^{t-1}\geq 0\qquad\{\forall t\in T,\forall h\in\gamma_G\}\tag{3}$$

$$n_r^t-n_r^{t-1}\geq 0\qquad\{\forall t\in T,\forall r\in\gamma_k\}\tag{4}$$

$$\sum_{(pq)\in\gamma_{pq,t}}f_{pq}^{ti}-\sum_{(pq)\in\gamma_{qp,t}}f_{pq}^{ti}+\sum_{h=p}p_{Gh}^{ti}-\sum_{n=p}p_{Dn}^{ti}=0\qquad\{\forall t\in T,\forall i\in\gamma_c\}\tag{5}$$

$$f_{pq}^{ti}=\frac{\theta_p^{ti}-\theta_q^{ti}+\theta_{PST,pq}^{ti}}{X_{pq}}-f_{pq}^{\max}\leq f_{pq}^{ti}\leq f_{pq}^{\max}-x_p^t\times\theta_{PST}^{\max}\leq\theta_{PST,pq}^{ti}\leq x_p^t\times f_{PST}^{\max}-\theta_{pq}^{\max}\leq\theta_{pq}^{ti}\leq\theta_{pq}^{\max}\tag{9}$$

where, t is the index of year, n is index of load, h is index of the generator, r is the index of candidate line for construction, p is index of PST and i is index of load scenario.

The variables used in formulate the problem are defined in the following:

$p_{D_{nm}}^{ti}$ is The power consumed by the m block of the n-th load in the i-th scenario and t-th year, $p_{G_{hj}}^{ti}$ is the power generated by the j-th block in the h-th generator in the i-th scenario and t-th year, $f_{pq,r,new}^{ti}$ is the active power passing through the r-th new line in path p to q (from bus p to bus q) in the i-th scenario and t-th year, f_{pq}^{ti} is the active power passing from the available line in path p to q in the i-th scenario and t-th year, θ_p^{ti} is the angle of p-th bus in the i-th scenario and t-th year, $P_{D_n}^{ti}$ is the power consumed by n-th load in the i-th scenario and the t-th year, $P_{G_h}^{ti}$ is the power generated by the h-th generator in the i-th scenario and t-th year.

The parameters (constant values) used in formulate the problem include the following:

w_i is weighting index of i-th Scenario, $\mu^{ti}_{D_{nm}}$ is the proposal to buy m-th block of n-th load in the i-th scenario and t-th year, $\mu^{ti}_{G_{hj}}$ is proposal to sell the j-th block of the h-th generator in the i-th scenario and t-th year, C_p is the cost of construction p candidate PST, C_r is the cost of construction r candidate line, C_h is transitional vector of investment costs of new generating units, α is operating and design costs adjustment coefficient, x_{pq} is transmission line reactance in path $p-q$, n^0_{pq} is the transmission line in the initial topology (line in the path $p-q$), M is a positive constant value that is large enough, $f^{\max}_{pq}$ is maximum transmission power in one of the lines of path $q-p$, $P^{\max}_{G_{hj}}$ is the size of j-th block of the h-th generator, $P^{\max}_{G_h}$ is the maximum generation of the h-th generator, I is the fall rate and t_0 is the base year.

The sets used in formulate the problem are as follows:

γ_c is set of all scenarios, γ_N is set of all buses, γ_k is set of all candidate lines for installation in the planning horizon, γ_P is set of all candidate PSTs for installation in the planning horizon, γ_h is set of all blocks of the h-th generator unit, γ_G is the set of candidate generator units, γ_n is the set of all n-th load blocks, γ_D is the set of all loads, T is the set of all years of the planning horizon.

Finally, the binary variables that control the location and year of installation of the new equipment include:

$n^t_{pq,r}$ is a binary variable that controls the installation of the r-th transmission line in the path $p-q$ in t-th year (1 means that it's installed and 0 mean that the line is not installed), y^t_{hj} is a binary variable that installs the h-th generator in the j-th bus in the t-th year (1 means that the generator is installed and 0 mean that it is not installed), x^t_p is a binary variable that controls installation of the p-th candidate PST in the t-th year (1 means that the PST is installed and 0 mean that it is not installed) and $\theta^{t,i}_{PST,pq}$ is a continuous variable that controls the phase shift rate of the PST of the pq candidate in the i-th scenario and the t-th year.

The objective function Eq. (1) represents the symmetry of total social welfare. Because if social welfare is to be maximized, then its symmetry should be minimized. The total social welfare consists of two basic terms: a) the social welfare of the market (the total purchase of demand bid minus the total sale of generators offer) and b) the investment costs of new lines, generators and new PSTs.

In this section, each load scenario (scenario i) with weight coefficient w_i, which indicates the importance of this scenario, has appeared in the context of social welfare. The coefficient of each scenario is proportional to the total number of hours during the year when the network load in them is the same and equal to the load of that scenario. Taking into account different scenarios for modeling the load of network covers the uncertainty of load and the corresponding changes throughout the year.

Since the first part of the function is the social welfare of the market and the second part is the cost of investment, the investment cost in the second part of the objective function is multiplied by the coefficient α. The coefficient α is the ratio between investment cost and the weighted scenario-driven social welfare. In fact, α is a positive value which controls the importance of investment cost in terms of social welfare. The larger the α coefficient, the higher the cost of investment and the fewer the number of new equipment to be installed. As α decreases, the effect of the investment cost on the objective function is reduced; consequently, more new equipment will be installed to increase social welfare. Therefore, the coefficient α represents the ratio between social welfare and line investment cost, PST and new power plants. The α coefficient is determined by ISO. If the tendency of ISO is to increase social welfare, it must reduce the α coefficient. However, with the decrease of coefficient α, the number of new equipment increases, and too much reduction in the α will lead to very high investment costs. Ultimately, this is the ISO that selects the degree of α according to the total social welfare and the cost of installing new equipment.

4 Simulation results(IEEE 24-BUS)

To evaluate the function of the proposed expansion model, the GTEP of IEEE 24-bus system will be simulated in the presence of PST in a MATLAB software environment. The results will be presented in this section. Simulation is done in two different scenarios:

- **First Scenario:** GTEP without the presence of PST
- **Second Scenario:** GTEP in the presence of PST

In this paper, the IEEE 24-Bus system is considered as a case study. The information on the transmission lines in the network along with their transformers is presented in Table 1 as the available branches in the IEEE 24-Bus network. Furthermore, the information related to the total consumed and generated power for each bus in the IEEE 24-bus network is presented in Table 2. In this paper, the cost of constructing new lines is 500 ($/MW-mile) and the falling rate (I) is assumed to be 0.1. Also, the cost of constructing PST is 100 ($/KVA).

Table 1: The information of avilable branches in the IEEE 24-bus network

From	To	Capacity (MW)	Circuit Length (Mile)	Reactance (pu)
1	2	175	3	0.0139
1	3	175	55	0.2112
1	5	175	22	0.0845
2	4	175	33	0.1267
2	6	175	50	0.192
3	9	175	31	0.119
3	24	400	50	0.0839
4	9	175	27	0.1037
5	10	175	23	0.0883
6	10	175	16	0.0605
7	8	175	16	0.0614
8	9	175	43	0.1651
8	10	175	43	0.1651
9	11	400	50	0.0839
9	12	400	50	0.0839
10	11	400	50	0.0839
10	12	400	50	0.0839
11	13	500	33	0.0476
11	14	500	29	0.0418
12	13	500	33	0.0476
12	23	500	67	0.0966
13	23	500	60	0.0865
14	16	500	27	0.0389
15	16	500	12	0.0173
15	21	500	34	0.049
15	21	500	34	0.049
15	24	500	36	0.0519
16	17	500	18	0.0259
16	19	500	16	0.0231
17	18	500	10	0.0144
17	22	500	73	0.1053
18	21	500	18	0.0259
18	21	500	18	0.0259
19	20	500	27.5	0.0396
19	20	500	27.5	0.0396
20	23	500	15	0.0216
20	23	500	15	0.0216
21	22	500	47	0.0678

In this paper the planning horizon is assumed 10 years. Each of the new equipment, the transmission line, the generator, and the PST, can be installed from the first to the 10th year. They can remain in the network after installation. Whatever installation time is delayed, the costs are reduced because of taking the falling rate. This is because the cost that is supposed to be paid at one time in the first year will be postponed to the next years, which is more economical. It should be mentioned that installing new equipment may significantly improve social welfare in that year and the subsequent years. In this paper, in all scenarios, the coefficient α is considered to be 0.0005.

In order to expand the transmission, each existing branches can be selected as an installation candidate in the planning horizon. In this paper, the rate of load growth and generation, during each year, are 3.1%. Also, the rate

Table 2: The generation and consumption rates of each bus in the IEEE 24-bus network

Bus no.	Total consumption(pu)	Total generation (pu)
1	0	4.95
2	0.97	1.44
3	1.8	0
4	0.74	0
5	0.71	0
6	1.36	0.5
7	1.25	2.25
8	1.71	0.5
9	1.75	0
10	1.95	0
11	0	0
12	0	0
13	2.65	4.4325
14	1.94	0.4
15	3.17	1.6125
16	1	1.1625
17	0	0
18	0	3
19	1.81	0
20	1.28	0
21	0	3
22	0	2.25
23	1.08	1.44
24	0	0

of the purchase of demand bid and sale of generators offer will increase by 5% annually. The simulation scenarios in which loads are at different levels are given in Table 3.

Table 3: Weight and demand coefficient associated with each scenario

Scenario	Weight	Demand coefficient
1	0.412	0.47
2	0.3597	0.85
3	0.1172	1.2
4	0.1111	1.7

Simulations were conducted in MATLAB software environment. To solve the planning problem, the YALMIP Toolbox has been used [33].

4.1 First scenario

In this scenario, expansion planning only involves finding transmission lines and new generators and PST cannot be used to expand the system. In other words, in this scenario, only the transmission line and the new generator are proposed. Optimal transmission lines and generators for installation in the first scenario are shown in Tables 4 and 5, respectively.

Table 4: Optimal lines for installation in the first scenario

From	To	Cost ($)	Installation year
1	2	262500	1
1	5	1925000	1
7	8	1400000	7

In the first scenario, the market social welfare is 0.97336 M$. The total investment cost in this scenario is 6.0875 M$, 3.5875 M$ of which is the cost of building new transmission lines, and 2.5 M$ of which is the cost of building new generators.

Table 5: Optimal generators for installation in the first scenario

Bus	Cost ($)	Installation year
8	2500000	1

4.2 Second scenario

In the second scenario, GTEP is done with PST consideration. In other words, in this scenario, in addition to the construction of a transmission line and a new power plant, a new PST can be used to expand the system. The results of the new PSTs and new transmission lines are presented in the Tables 6 and 7, respectively.

Table 6: Optimal PSTs for installation in the second scenario

From	To	Number of PSTs	Cost ($)	Installation year
1	2	1	175000	1
1	3	1	175000	1
2	4	1	175000	1
2	6	1	175000	1
3	9	1	175000	1
3	24	1	400000	1
5	10	1	175000	1
8	9	1	175000	1
8	10	1	175000	1
9	11	1	400000	1
9	12	1	400000	1
15	21	2	500000	1

Table 7: Optimal transmission lines for installation in the second scenario

From	To	Cost ($)	Installation year
1	2	262500	1
1	5	1925000	3

In the second scenario, the market social welfare is 1.0158 M$. The total investment cost in this scenario is 5.7875 M$, 2.1875 M$ of which is the cost of building new transmission lines, and 3.6 M$ of which is the cost of PSTs installation. The cost of building new power plants in this scenario is zero. This means that using the PSTs can be used from the actual capacity of existing plants and do not need to build new power plants. Comparison of different scenarios for IEEE 24-bus network is presented in Table 8.

Table 8: Comparison of different scenarios for IEEE 24-bus network

	first scenario	second scenario
Market social welfare (M$)	0.97336	1.01581
The cost of building new line (M$)	3.5875	2.1875
The cost of building PST (M$)	0	3.6
The cost of building new power plant (M$)	2.5	0
Total investment cost (M$)	6.0875	5.7875

According to Table 8, in the first scenario, the total investment cost required to expand IEEE 24-bus system in 10-year horizon is 6.0875 M$. 2.5 M$ of this cost is used for the construction of a new power plants and 3.5875 M$ is employed for the construction of new transmission lines. In the first scenario, it is assumed that only the new lines and power plants can be installed and PSTs cannot be used. Consequently, the investment cost required to expand the system is more in this scenario in comparison with the second scenario. However, spending more investment cost in this scenario has not resulted in an increase in social welfare in comparison with the other scenario, and the market social welfare in the first scenario is lower than the second scenario. In the second scenario using PSTs, better results are achieved. In second scenario, not only the total investment cost is less, but also more social welfare is obtained. In second scenario, since the optimal PSTs are used, power flow in the transmission system is optimally managed. So that there is no need to invest in the construction of new power plants. In this scenario, 3.6 M$ are spent on installing new PSTs in the system and 2.1875 M$ are spent on installing new transmission lines.

Examining the results shows PST excellence in improving system expansion planning. When PSTs are installed, not only does the cost of installing new power plants reduce to zero, but the social welfare of the market also reaches its maximum. Therefore, GTEP in the presence of PSTs (scenario 2) can result in the best social welfare and the lowest investment cost compared to scenario 1.

5 Conclusion

GTEP in power systems has both technical and economic effects on the performance of the power system. Since the expansion of power system is costly and requires large investments, it is important to determine the optimal time, location and capacity of the new equipment to be installed in the system. Therefore, expansion planning should be such that with the least possible investment cost, the most favorable effects are achieved. In this paper, GTEP was carried out from the perspective of ISO with the aim of maximizing the social welfare. The total social welfare, in this paper, is considered to be equal to the total social welfare of the market minus the weighted cost of investment in new equipment (line, generator, and new PSTs). In this paper, since PST can control the transmission power of the line, it has been used to reduce the cost of investment. Therefore, by installing PST, one can reduce the investment cost required to install new lines. The formulation presented in this paper is a MIP model with convex structure. Therefore, the resulting answer is global. To solve the proposed MIP problem, the YALMIP toolbox has been used in the MATLAB environment. Furthermore, CPLEX has been used as a solver. The results of this study show that the social welfare level in the second scenario (with PST) reaches its highest level, while it needed the lowest investment cost. In other words, by installing PST in the second scenario, the highest social welfare can be achieved with minimal investment. It also increases the flexibility of the network in response to part of the demand growth without new transmission lines.

6 Nomenclature

Variables	
$p^{ti}_{D_{nm}}$	the power consumed by the m block of the n-th load in the i-th scenario and t-th year
$p^{ti}_{G_{hi}}$	the power generated by the j-th block in the h-th generator in the i-th scenario and t-th year
$f^{ti}_{pq,r,new}$	the active power passing through the r-th new line in path p to q (from bus p to bus q) in the i-th scenario and t-th year
f^{ti}_{pq}	the active power passing from the available line in path p to q in the i-th scenario and t-th year
$P^{ti}_{D_n}$	the power consumed by n-th load in the i-th scenario and the t-th year
$P^{ti}_{G_h}$	the power generated by the h-th generator in the i-th scenario and t-the year
parameters	
w_i	weighting index of i-th Scenario
$\mu^{ti}_{D_{nm}}$	the proposal to buy m-th block of n-th load in the i-th scenario and t-th year
$\mu^{ti}_{G_{hj}}$	proposal to sell the j-th block of the h-th generator in the i-th scenario and t-th
C_r	the cost to construction the r candidate line
α	operating and design costs adjustment coefficient
x_{pq}	transmission line reactance in path $p-q$
n^0_{pq}	the transmission line in the initial topology (line in the path $p-q$)
f^{max}_{pq}	maximum transmission power in one of the lines of path $p-q$
t_0	the base year
Sets	
γ_c	set of all scenarios
γ_N	set of all buses
γ_k	set of all candidate lines
γ_p	set of all candidate PSTs
γ_h	set of all blocks of the h-th generator unit
γ_G	set of candidate generator units
γ_n	set of all n-th load blocks

Indices	
GTEP	generation-transmission expansion planning
PST	phase shifter transformer
SW	social welfare
MIP	mixed integer programming
ISO	independent system operator
LSEs	load serving entities
GENCOs	generation companies

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