Iran J Sci Technol Trans Electr Eng (2017) 41:305–317
https://doi.org/10.1007/s40998-017-0034-4

RESEARCH PAPER

Dynamic Market-Based Generation-Transmission Expansion Planning Considering Fixed Series Compensation Allocation

M. Zeinaddini-Meymand[1] · M. Pourakbari-Kasmaei[2] · M. Rahmani[3] · A. Abdollahi[1] · M. Rashidinejad[1]

Received: 10 August 2016 / Accepted: 21 July 2017 / Published online: 19 September 2017

Abstract This paper presents a market-based multi-period generation-transmission expansion planning (GTEP) along with fixed series compensation (FSC) allocation. FSCs can dispatch power more efficiently over the transmission network as well as trading opportunities for market participants and thus improve market surplus and reduce the total transmission investment. The proposed planning may accordingly enhance network efficiency and improve social welfare for all participants. The proposed model is structured as a mixed integer linear programming (MILP) problem. The CPLEX solver, as a commercial solver, is used to solve this MILP problem. Moreover, to find a reliable and viable optimal topology, $N-1$ security criterion is employed through the proposed model. This criterion is used to take into account any unanticipated operating condition due to unexpected transmission line failures. The proposed model is applied to the Garver and IEEE 24-bus systems as well-known systems to show the effectiveness of FSC in dynamic GTEP.

Keywords Dynamic generation-transmission expansion planning · Fixed series compensation · Social welfare · Mixed integer linear programming

✉ M. Zeinaddini-Meymand
m.meymand@eng.uk.ac.ir

1 Department of Electrical Engineering, Shahid Bahonar University of Kerman, Kerman, Iran

2 Department of Electrical Engineering, Sao Paulo State University, São Paulo, SP, Brazil

3 Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA, USA

List of symbols

Variables

$p_{D_{nm}}^{tie}$ Power consumed by mth block of nth consumer in scenario i, condition e, and year t

$p_{G_{hj}}^{tie}$ Power generated by jth block of hth generator in scenario i, condition e, and year t

$f_{pq,r}^{tie}$ Power flowed in rth line of corridor $p-q$ in scenario i, condition e, and year t

f_{pq}^{tie0} Power flowed in existing line $p-q$ in scenario i, condition e, and year t

θ_{p}^{tie} The angel at bus p in scenario i, condition e, and year t

$P_{G_h}^{tie}$ Power generated by hth generator in scenario i, condition e, and year t

$P_{D_n}^{tie}$ Power consumed by nth demand center in scenario i, condition e, and year t

$\delta_{pq,a}^{tie0}$ Variable used in linearization of power flow in the existing lines, scenario i, condition e, and year t

$\delta_{pq,r,a}^{tie}$ Variable used in linearization of power flow in the rth prospective lines, scenario i, condition e, and year t

Global variables

$n_{pq,r}^{t}$ Binary variable presenting rth transmission lines installed in corridor $p-q$ and year t

y_{hj}^{t} Binary variable presenting jth generating unit installed in bus i and year t

$u_{pq,r,a}^{t}$ Binary variable presenting ath FSC installed in the rth prospective transmission line and year t

$u_{pq,a}^{t0}$ Binary variable presenting ath FSC installed in the existing transmission line between node $p-q$ and year t

Constants

ω^i The weighting factor of scenario i

$\mu^{ti}_{D_{nm}}$ Bid for mth block of nth demand in scenario i and year t

$\mu^{ti}_{G_{hj}}$ Offer for jth block of hth generator scenario i and year t

$c_{pq,r}$ Transposed vector of the investment costs of new transmission lines

c_{hj} Transposed vector of the investment costs of new generating units

α Adjustment factor for costs of planning and operation

x_{pq} Reactance of corridor $p-q$

n^0_{pq} Transmission line in the initial topology

M Big enough positive constant

$f^{\max}_{pq}$ Maximum power flow in one of the lines in corridor $p-q$

$p^{\max}_{G_{hj}}$ Size of jth block of hth generator

$p^{\max}_{G_h}$ Maximum generation of hth generator

k^e_{pq} A binary parameter presenting contingency in condition e

U_e A binary parameter of allocation FSC for existing lines

U_p A binary parameter of allocation FSC for candidate lines

p_a Compensation level of ath FSC for corresponding lines

C_a Ratio of ath FSC's investment cost to investment cost of corresponding line

I Discount rate

t^0 Base year

Sets

E Set of all system conditions, i.e., e_0 normal condition, e_1 contingency occurred on existing lines, and e_2 contingency occurred on prospective lines

e^0_1 Set of all corridors that includes contingency in existing lines

e_1 Set of all corridors that includes contingency in prospective lines

γ_c Set of all scenarios

γ_{N} Set of all nodes of network

γ_k Set of all transmission lines, existing and prospective

γ_r Set of all prospective transmission lines in corridor $p-q$

γ_h Set of all blocks of hth generating unit

γ_{G} Set of indices of the generating units

γ_n Set of all blocks of nth demand

γ_{D} Set of indices of the demands

A Set of all candidate FSCs indexed by a

T Set of all years of the planning horizon

1 Introduction

In the past, centralized models addressed the network expansion problem aimed at minimizing the investment cost (Romero et al. 2002; Rahmani et al. 2013a, b). With restructuring of electricity industry, new expansion models have been introduced. In these models, some issues such as the market participants' strategies [generation companies (GENCOs), load serving entities (LSEs), and transmission companies (TRANSCOs)], congestion, and security criteria are considered as the main components of the long-term planning problem (Khodaei et al. 2010; Alguacil et al. 2003). Therefore, generation and transmission expansion planning considering the entire network social welfare maximization is one of the most challenging and decision-making activity problems in power system (Hooshmand et al. 2012; Roh et al. 2009), and it plays an important role in operation-based tools, which are the core of a power system (Pourakbari-Kasmaei and Rashidi-Nejad 2011).

In a restructured electric industry, generation and transmission expansion are usually handled by a centralized entity (e.g., ISO) to obtain the most economical and reliable expansion (Roh et al. 2009). In other words, transmission systems should be developed to remove transmission congestion and provide fair access for all market participants (Shrestha and Fonseka 2004). Constructing new transmission lines is difficult due to geographical problems, high investment cost, and severe reduction in social welfare (de la Torre et al. 2008).

Power system planning is the science of determining the optimal place, size, and time for adding new facilities to power systems. In the previous literature, different models have been proposed to solve transmission expansion planning (TEP) problem (Rahmani et al. 2013a, b). Orfanos et al. (2013) proposed an efficient approach for probabilistic transmission expansion planning that considers load and wind power generation uncertainties. The Benders decomposition algorithm in conjunction with Monte Carlo simulation is used to tackle the proposed probabilistic TEP. In Akbari and Tavakoli-Bina (2014), TEP is solved using the AC optimal power flow (AC-OPF) to provide accurate picture of power flow compared to the DC optimal power flow. Also, uncertainties about future electricity demand, fuel prices, greenhouse gas emissions, as well as possible disruptions can be incorporated in the planning models (Seddighi and Ahmadi-Javid 2015). Improved heuristic algorithms have been used for the solution of the power system planning. In Georgilakis (2010), market-based transmission expansion planning as a complex mixed integer non-linear programming problem is solved via improved differential evolution algorithm. The main objective is to obtain the optimal decision to minimize the overall generation and transmission cost for market participants considering pricing and investment. The global optimum solution is obtained through the proposed algorithm with some improvements to increase the diversity of population and prevent the premature convergence. In some works, short-term operating problems are incorporated in long-term planning problems. In Koltsaklis and Georgiadis (2015) unit commitment problem is incorporated into the long-term planning horizon to determine the optimal capacity additions, electricity market clearing prices, and daily operational planning of the studied power system. The heuristic-based algorithms, such as simulated annealing and genetic algorithm have been widely used to solve GTEP problem (Da Silva et al. 2000; Sun and Yu 2000; Braga and Saraiva 2005; Kandil et al. 2001). The power system planning models are mixed integer linear programming. Therefore, there is a wide tendency to solve these problems based on mathematical optimization, such as linear programming, Bender's decomposition, and bi-level optimization (Sanchez-Martin et al. 2005; Garver 1970; Lee et al. 1974; Choi et al. 2005a, b; Lu et al. 2005). Some issues such as reliability and security constraints and uncertainties were considered in market-based power system planning (Buygi et al. 2004a, b, c, d), where the stochastic planning is also one of the most important issues in power system planning (Akbari et al. 2011). In some works such as Shayeghi et al. (2008), new points of view have been taken into account, a decimal codification genetic algorithm (DCGA) has been used to consider the inflation rate and load growth factor on network losses, where the social welfare and better expansion planning can be a byproduct.

Nowadays, some short-term practical issues such as transmission switching and installing compensation devices can be considered for better utilization of the existing transmission network, delaying the construction of new lines, and even improving social welfare (Khodaei et al. 2010). In Blanco et al. (2009), a new framework is presented for assessing flexible investment within the transmission expansion planning under uncertainties. In this model, gaining flexibility by investing in FACTS devices, the expansion investments in transmission lines are deferred. In other words, a suitable combination between lines and FACTS devices can lead to flexible investment in small scale, instead of large investments in transmission expansion projects. In Miasaki and Romero (2007), a developed mathematical model of TEP considers the installation of series compensation devices. In this model, the solution obtained by a specialized genetic algorithm supplies the amount and the location where new transmission lines and series compensation devices must be installed. However, installing fixed series compensators (FSCs) in new transmission lines can eliminate the necessity of constructing parallel transmission lines with high investment cost (Rahmani et al. 2013a, b). In other words, FSCs can redistribute the power flow to use the remaining capacity of transmission lines and increase competition between market participants. Considering FSCs in transmission planning results in a different grid topology at much lower cost due to better utilization of the whole transfer capacity of the network, meaning that, with a small investment in FSCs, significant improvement in social welfare can be achieved.

Several flexible AC transmission systems (FACTS) can be used to redistribute the power in the transmission system but among them FSCs are cost-effective and more suitable for redistributing the power in transmission system (Rahmani et al. 2013a, b). In Rahmani et al. (2013a, b), besides considering some of the benefits and drawbacks of FSCs, the effects of their installation on planning project, in monopoly environment, have been investigated. In deregulated environment, ISO can install FSCs along with transmission planning for better utilization of existing transmission infrastructures and lowering the overall transmission investments. However, these problems have feasible solutions, and with technological advances in protection system, there is no fear of using series compensation in a transmission system.

In this paper, a dynamic (multi-year) model for the transmission expansion problem considering inclusion of FSCs in a pool-based electric energy market is presented. In this model, the network topology, generator offers, and demand bids are taken into account. Moreover, the improvement of social welfare as a result of transmission expansion planning via inclusion of FSCs is investigated. FSCs as a short-term solution for the power system problems are integrated in the multistage transmission expansion planning, when the horizon of planning is divided in several stages (Escobar et al. 2004). In each planning stage, FSCs can be integrated into the system to increase competition between market participants as well as to lower the necessity of constructing many transmission lines, which results in a significant decrease in both the investment cost and the construction time.

This paper proposes a mixed integer linear programming for multi-period framework in which market-based GTEP along with FSC allocation is considered. The main contributions of this paper are as follows:

1. To consider integrated generation and transmission expansion planning. In this paper new generating units are constructed so that the profits of LSEs and GENCOs are maximized.
2. To propose a robust mixed-integer linear programming model for multi-period GTEP. In this model three operating periods are incorporated with different

lifetime design: (a) hourly market structure (b) short-term planning related to FSC lifetime, and (c) long-term transmission expansion planning.

The rest of this paper is organized as follows. Section 2 presents the model features. In Sect. 3 the mathematical model for dynamic generation-transmission expansion planning incorporating FSC is described. Section 4 describes some metrics to analyze the solution of expansion with respect to using FSCs. The proposed methodology is applied to case studies in Sect. 5. Section 6 provides the concluding remarks.

2 Model Features

2.1 Market Model

The proposed model is a perfectively competitive energy market-based GTEP model with allocation of FSCs, where GENCOs and LSEs make their offers and bids in an electricity pool. It is assumed that no market power can be applied in this system and GENCOs and LSEs submit their offers and bids according to their true cost and utility functions, respectively. The ISO will coordinate expansion of the transmission system and generating units considering offers and bids of market participants (De la Torre et al. 2008). The main objective of GENCOs and LSEs is to obtain maximum profit through an optimal power systems planning, while the objective of ISO is maximizing the social welfare (Buygi et al. 2004a; Fang and Hill 2003). Indeed, an expansion in transmission network may influence the profit of market participants.

This model maximizes the social welfare and ensures proper operation of the system in normal and contingency conditions for each demand scenario. The aims of the proposed model are to simultaneously construct transmission lines as well as to generate units and allocate FSCs to satisfy the future increases in energy demand while a reliable operation of the system in normal and contingency conditions is ensured.

2.2 Load Behavior

According to Fig. 1, the annual load duration curve is used with multiple demand blocks to model demand behavior during one typical year of network operation and it is extended to whole planning horizon. Each demand block is considered as a scenario that represents hours with the same amount of demand and the amount of demand level as demand coefficient is used as the weight of each scenario in the objective function. Therefore, social welfare is maximized through all scenarios.

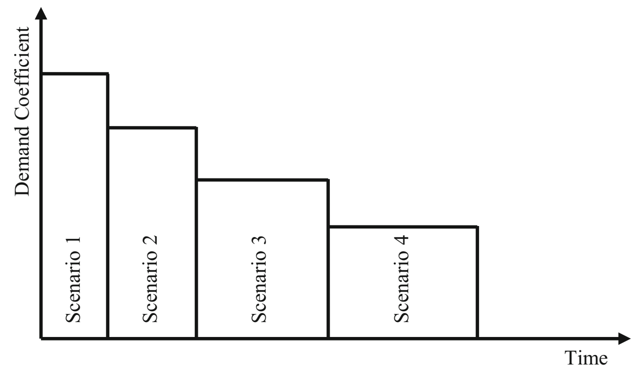

Fig. 1 Annual load duration curve

3 Mathematical Modeling

This section presents multi-period GTEP with allocation of FSC in a competitive pool-based market environment. The aims of the proposed model are to determine when and where new facilitates should be installed. New facilities support future increases in demand and also ensure reliable operation of the power system under normal and contingency conditions. For the sake of simplicity, the model is prepared in three sections; objective function by (1), contingency-independent constraints by (2)–(11), and contingency-dependent constraints by Eqs. (12)–(37).

$$\max\left\{\sum_{\forall t\in T}\left(\sum_{\forall i\in\gamma_i} w^i\left(\sum_{\forall n\in\gamma_D}\sum_{\forall m\in\gamma_n}\frac{\mu^{ti}_{D_{nm}}p^{tie}_{D_{nm}}}{(1+I)^{t-t_0}}-\sum_{\forall h\in\gamma_G}\sum_{\forall j\in\gamma_h}\frac{\mu^{ti}_{G_{hj}}p^{tie}_{G_{hj}}}{(1+I)^{t-t_0}}\right)\right)\right.$$
$$-\alpha\left(\sum_{t=t_0+1}^{T}\sum_{\forall r\in\gamma_k}\frac{c_{pq,r}\left(n^t_{pq,r}-n^{t-1}_{pq,r}\right)}{(1+I)^{t-t_0}}+\sum_{\forall r\in\gamma_k}c_{pq,r}\left(n^{t_0}_{pq,r}\right)\right.$$
$$+\sum_{t=t_0+1}^{T}\sum_{\forall r\in\gamma_k}\frac{c_{hj}\left(y^t_{hj}-y^{t-1}_{hj}\right)}{(1+I)^{t-t_0}}+\sum_{\forall r\in\gamma_k}c_{hj}\left(y^{t_0}_{hj}\right)$$
$$+C_a\left(\sum_{t=t_0+1}^{T}\left(\sum_{\forall(pq)\in\gamma_k}\frac{c_{pq}n^0_{pq}\left(u^{(t)0}_{pq,a}-u^{(t-1)0}_{pq,a}\right)}{(1+I)^{t-t_0}}\right.\right.$$
$$\left.+\sum_{\forall r\in\gamma_k}\frac{c_{pq,r}\left(u^t_{pq,r,a}-u^{t-1}_{pq,r,a}\right)}{(1+I)^{t-t_0}}\right)$$
$$\left.\left.\left.+\sum_{\forall(pq)\in\gamma_k}c_{pq}n^0_{pq}\left(u^{(t_0)0}_{pq,a}\right)+\sum_{\forall r\in\gamma_k}c_{pq,r}\left(u^{t_0}_{pq,r,a}\right)\right)\right)\right\}$$
$$\text{Subject to:} \tag{1}$$

$$\sum_{a\in A}u^{(t)0}_{pq,a}\le U_e;\quad\{\forall(pq)\in\gamma_k,\forall(t)\in T\} \tag{2}$$

$$u^{(t)0}_{pq,a}-u^{(t-1)0}_{pq,a}\ge 0;\quad\{\forall(pq)\in\gamma_k,\forall(t)\in T\} \tag{3}$$

$$\sum_{a\in A}u^t_{pq,r,a}\le U_p n^t_{pq,r};\quad\{\forall(pq)\in\gamma_k,\forall(t)\in T\} \tag{4}$$

$$u_{pq,r,a}^{t} - u_{pq,r,a}^{t-1} \geq 0; \quad \{\forall (pq) \in \gamma_k, \forall (t) \in T\} \tag{5}$$

$$\left| u_{pq,a}^{(t)0} - u_{pq,r,a}^{t} \right| \leq 1 - n_{pq,r}^{t}; \quad \{\forall (pq) \in \gamma_k, r = 1, \forall a \in A, \forall (t) \in T\} \tag{6}$$

$$\left| u_{pq,r-1,a}^{t} - u_{pq,r,a}^{t} \right| \leq 1 - n_{pq,r}^{t}; \quad \{\forall (pq) \in \gamma_k, \forall a \in A, \forall (t) \in T\} \tag{7}$$

$$n_{pq,r-1}^{t} - n_{pq,r}^{t} \geq 0; \quad \{\forall (pq) \in \gamma_k, \forall (t) \in T\} \tag{8}$$

$$n_{pq,r}^{t} - n_{pq,r}^{t-1} \geq 0; \quad \{\forall (pq) \in \gamma_k, \forall (t) \in T\} \tag{9}$$

$$y_{hj}^{t} - y_{hj}^{t-1} \geq 0; \quad \{\forall j \in \gamma_h, \forall i \in \gamma_c, \forall (t) \in T\} \tag{10}$$

$$\left(\sum_{t \in T} \sum_{r \in \gamma_k} n_{pq,r}^{t} + n_{pq}^{0} - 1 \right) \geq 0; \quad \{\forall (pq) \in \gamma_k, \forall (t) \in T\} \tag{11}$$

$$\sum_{t \in (t_1, t_2, \ldots, t_\eta)} \sum_{r \in \gamma_k} n_{pq,r}^{t} = 0; \quad \{\forall (pq) \in \gamma_k\} \tag{12}$$

$$\sum_{\forall p = s} f_{pqr}^{tie} - \sum_{\forall q = s} f_{pqr}^{tie} + \sum_{\forall (pq) \in \gamma_k} f_{pq}^{te0} + \sum_{\forall h \in \gamma_G} p_{G_h}^{tie} = \sum_{\forall n \in \gamma_D} p_{D_n}^{tie}, \quad \{\rho_s^{ie}, \forall i \in \gamma_c, \forall s \in \gamma_N, \forall e \in E, \forall (t) \in T\} \tag{13}$$

$$x_{pq} f_{pq}^{tie0} - \sum_{a \in A} \delta_{pq,a}^{tie0} = n_{pq}^{0} (\theta_p^{tie} - \theta_q^{tie}); \{\forall (pq) \in \gamma_k, \forall i \in \gamma_c, \forall e \in E, \text{ for } (pq) \neq e_l^0, \forall (t) \in T\} \tag{14}$$

$$x_{pq} f_{pq}^{tie0} - \sum_{a \in A} \delta_{pq,a}^{tie0} = (n_{pq}^{0} - 1)(\theta_p^{tie} - \theta_q^{tie}); \quad \{\forall (pq) \in \gamma_k, \forall i \in \gamma_c, \forall e \in e_1, \text{ for } (pq) = e_l^0, \forall (t) \in T\} \tag{15}$$

$$\left| f_{pq}^{tie0} \right| \leq n_{pq}^{0} f_{pq}^{\max}; \quad \{\forall i \in \gamma_c, \forall e \in E, \forall (pq) \in \gamma_k, \text{ for } (pq) \neq e_l^0, \forall (t) \in T\} \tag{16}$$

$$\left| f_{pq}^{tie0} \right| \leq (n_{pq}^{0} - 1) f_{pq}^{\max}; \{\forall i \in \gamma_c, \forall e \in e_1, \forall (pq) \in \gamma_k, \text{ for } (pq) = e_l^0, \forall (t) \in T\} \tag{17}$$

$$\left| f_{pq}^{tie0} - \frac{\delta_{pq,a}^{tie0}}{x_{pq} p_a} \right| \leq (n_{pq}^{0})(1 - u_{pq,a}^{t0}) f_{pq}^{\max}; \quad \{\forall i \in \gamma_c, \forall e \in E, \forall (pq) \in \gamma_k, \text{ for } (pq) \neq e_l^0, \forall (t) \in T\} \tag{18}$$

$$\left| f_{pq}^{tie0} - \frac{\delta_{pq,a}^{tie0}}{x_{pq} p_a} \right| \leq \left(n_{pq}^{0} - 1 \right) \left(1 - u_{pq,a}^{(t)0} \right) f_{pq}^{\max}; \quad \{\forall i \in \gamma_c, \forall e \in e_1, \forall (pq) \in \gamma_k, \text{ for } (pq) = e_l^0, \forall (t) \in T\} \tag{19}$$

$$\left| \frac{\delta_{pq,a}^{tie0}}{x_{pq} p_a} \right| \leq \left(n_{pq}^{0} \right) \left(u_{pq,a}^{(t)0} \right) f_{pq}^{\max}; \quad \{\forall i \in \gamma_c, \forall e \in E, \forall (pq) \in \gamma_k, \text{ for } (pq) \neq e_l^0, \forall (t) \in T\} \tag{20}$$

$$\left| \frac{\delta_{pq,a}^{tie0}}{x_{pq} p_a} \right| \leq \left(n_{pq}^{0} - 1 \right) \left(u_{pq,a}^{(t)0} \right) f_{pq}^{\max}; \quad \{\forall i \in \gamma_c, \forall e \in e_1, \forall (pq) \in \gamma_k, \text{ for } (pq) = e_l^0, \forall (t) \in T\} \tag{21}$$

$$\left| x_{pq} f_{pq,r}^{tie} - \sum_{a \in A} \delta_{pq,a,r}^{tie} - \left(\theta_p^{tie} - \theta_q^{tie} \right) \right| \leq M \left(1 - n_{pq,r}^{t} \right), \quad \{\forall (pq) \in \gamma_k, \forall i \in \gamma_c, \forall r \in \gamma_r, \forall e \in E, \text{ for } (pq) \neq e_l, \forall (t) \in T\} \tag{22}$$

$$\left| x_{pq} f_{pq,r}^{tie} - \sum_{a \in A} \delta_{pq,a,r}^{tie} - \left(\theta_p^{tie} - \theta_q^{tie} \right) \left(1 - k_{pq}^{e} \right) \right| \leq M \left(1 - n_{pq,r}^{t} \right), \quad \{\forall (pq) \in \gamma_k, \forall i \in \gamma_c, \forall e \in e_2, \text{for } (pq) = e_l, \forall (t) \in T\} \tag{23}$$

$$\left| f_{pq,r}^{tie} \right| \leq \left(n_{pq,r}^{t} \right) f_{pq}^{\max}, \quad \{\forall i \in \gamma_c, \forall (pq) \in \gamma_k, \forall e \in E, \text{ for } (pq) \neq e_l, \forall (t) \in T\} \tag{24}$$

$$\left| f_{pq,r}^{tie} \right| \leq \left(1 - k_{pq}^{e} \right) \left(n_{pq,r}^{t} \right) f_{pq}^{\max}, \quad \{\forall i \in \gamma_c, \forall (pq) \in \gamma_k, \forall e \in e_2, \text{ for } (pq) = e_l, \forall (t) \in T\} (24) \tag{25}$$

$$\left| f_{pq,r}^{tie} - \frac{\delta_{pq,r,a}^{tie}}{x_{pq} p_a} \right| \leq \left(1 - u_{pq,r,a}^{t} \right) f_{pq}^{\max}, \quad \{\forall i \in \gamma_c, \forall (pq) \in \gamma_k, \forall e \in E, \text{ for } (pq) \neq e_l, \forall (t) \in T\} \tag{26}$$

$$\left| f_{pq,r}^{tie} - \frac{\delta_{pq,r,a}^{tie}}{x_{pq} p_a} \right| \leq \left(1 - k_{pq}^{e} \right) \left(1 - u_{pq,r,a}^{t} \right) f_{pq}^{\max}, \quad \{\forall i \in \gamma_c, \forall (pq) \in \gamma_k, \forall e \in e_2, \text{ for } (pq) = e_l, \forall (t) \in T\} \tag{27}$$

$$\left| \frac{\delta_{pq,r,a}^{tie}}{x_{pq} p_a} \right| \leq \left(u_{pq,r,a}^{t} \right) f_{pq}^{\max}, \quad \{\forall i \in \gamma_c, \forall (pq) \in \gamma_k, \forall e \in E, \text{for } (pq) \neq e_l, \forall (t) \in T\} \tag{28}$$

$$\left| \frac{\delta_{pq,r,a}^{tie}}{x_{pq} p_a} \right| \leq \left(1 - k_{pq}^{e} \right) u_{pq,r,a}^{t} f_{pq}^{\max}, \quad \{\forall i \in \gamma_c, \forall e \in \gamma_e, \text{ for } (pq) = e_l, \forall (pq) \in \gamma_k, \forall e \in e_2, \forall (t) \in T \tag{29}$$

$$p_{G_h}^{tie} = \sum_{\forall j \in \gamma_h} p_{G_{hj}}^{tie}; \quad \{\forall h \in \gamma_G, \forall i \in \gamma_c, \forall (t) \in T\} \tag{30}$$

$$0 \le p_{G_{hj}}^{tie} \le y_{hj}^{t} p_{G_{hj}}^{\max}; \quad \{\forall j \in \gamma_h, \forall i \in \gamma_c, \forall(t) \in T\} \tag{31}$$

$$0 \le p_{G_h}^{tie} \le p_{G_h}^{\max}; \quad \{\forall h \in \gamma_G, \forall i \in \gamma_c, \forall(t) \in T\} \tag{32}$$

$$p_{D_n}^{tie} = \sum_{\forall m \in \gamma_n} p_{D_{nm}}^{tie}; \quad \{\forall n \in \gamma_D, \forall i \in \gamma_c, \forall(t) \in T\} \tag{33}$$

$$0 \le p_{D_{nm}}^{tie} \le p_{D_{nm}}^{\max}; \quad \{\forall m \in \gamma_n, \forall i \in \gamma_c, \forall(t) \in T\} \tag{34}$$

$$\left|\theta_p^{tie} - \theta_q^{tie}\right| \le \bar{\theta}; \quad \{\forall(pq) \in \gamma_k, \forall i \in \gamma_c, \forall(t) \in T\} \tag{35}$$

$$\left|\theta_p^{tie} - \theta_q^{tie}\right| \le \bar{\theta} + M k_{pq}^{e}; \quad \{\forall i \in \gamma_c, \forall e \in e_1, \forall(pq) \in \gamma_k, \forall(t) \in T\} \tag{36}$$

$$\left|\theta_p^{tie} - \theta_q^{tie}\right| \le \bar{\theta} + M\left(1 - n_{pq,r}^{t}\right), \quad \{\forall i \in \gamma_c, \forall e \in e_0, \forall(pq) \in \gamma_k, \forall(t) \in T\} \tag{37}$$

$$\left|\theta_p^{tie} - \theta_q^{tie}\right| \le \bar{\theta} + M\left(1 - n_{pq,r}^{t}\left(1 - k_{pq}^{e}\right)\right), \quad \{\forall i \in \gamma_c, \forall e \in e_2, \forall(pq) \in \gamma_k, \forall(t) \in T\} \tag{38}$$

3.1 Objective Function of Proposed Model

In (1), the total social welfare is maximized under normal and contingency conditions and is weighted for different scenarios over the planning horizon. Total social welfare is comprised of two main terms: (a) market social welfare (i.e., the aggregated demand bid function minus the aggregated generator offer function) and (b) investment costs of new lines and FSCs. The market social welfare is considered for one typical operation year, while investments are considered over the planning horizon. Therefore, α simulates the ratio between the investments and the annual scenario-weighted social welfare and makes them comparable using $\frac{I(1+I)^{t-t_0}}{(1+I)^{t-t_0}-1}$. In Rahmani et al. (2013a, b), a global investment cost has been considered for FSCs in US\$/MW that contains the cost of capacitors. To calculate the C_a, as a constant coefficient, the cost of FSCs is divided by the cost of the line as follows:

$$C_a = \frac{\text{FSC investment cost per km}}{\text{Line investment cost per km}}. \tag{39}$$

The third term of the objective function stands for calculating the cost of FSCs, multiplying C_a by transmission line investment cost for the existing and candidate lines. The objective function is subjected to the following constraints.

3.2 Contingency Independent Constraints

3.2.1 FSC Installation Constrains

Constraints (2) and (4) ensure that one of the FSCs with equal compensation level can be installed in the existing and prospective transmission lines, respectively. Constraints (3) and (5) guarantee that an installed FSC remains operative during the whole planning horizon. Due to lack of information for the line lengths in the system data, FSCs are installed in the lines with a reactance greater than 0.05 pu. Therefore, U_e and U_p, as binary parameters, are set to 1 if the reactance of the corresponding line is greater than 0.05 pu.

Constraints (6) and (7) enforce installing the same FSCs in the existing and prospective lines for power flow balancing in parallel lines. Constraint (6) is applied to the corridors with the existing lines in base topology, i.e., $n_{pq}^{0} \ge 1$. Constraint (6) ensures that no FSC is installed in candidate lines without installing FSC in similar existing lines. In addition, note that constraint (7) enforces the same FSCs installation in similar prospective lines in a corridor.

3.2.2 Prospective Line Installation Constraints

Constraint (8) guarantees installing prospective lines sequentially. Constraints (9) and (10) guarantee that an installed line and generating unit remain operative during the planning horizon. Constraint (11) expresses that by a line outage, sum of the other lines (existing and prospective) in corridor $p-q$ must be greater than or equal to zero. Constraint (12) enforces that no new lines can be built during the first η years of the planning horizon.

3.3 Contingency-Dependent Constraints

3.3.1 Power Flow Constraints

Constraint (13) satisfies power balance in all nodes under normal and contingency conditions and in scenario i. ρ_s^{ie}, as a dual variable of the power balance constraint, is the nodal price at bus s in scenario i, in normal condition of the system. Constraints (14) and (15) enforce the Kirchhoff's voltage law (KVL) to non-outage existing transmission lines under all conditions, and existing transmission lines in contingency conditions, respectively, in scenario i.

In constraints (14) and (15), FSC reduces line reactance as follows:

$$f_{pq}^{tie0} = \frac{n_{pq}^{0}\left(\theta_p^{tie} - \theta_q^{tie}\right)}{x_{pq}\left(1 - \sum_{s \in S} p_a u_{pq,a}^{t0}\right)}. \tag{40}$$

Equation (40) can be re-rewritten as follows:

$$x_{pq} f_{pq}^{tie0} - x_{pq} f_{pq}^{tie0} \sum_{s \in S} p_a u_{pq,a}^{t0} = n_{pq}^{0}\left(\theta_p^{tie} - \theta_q^{tie}\right). \tag{41}$$

Multiplying a binary variable, $u_{pq,a}^{t0}$, and a continuous variable, f_{pq}^{tie0}, makes (41) nonlinear; therefore, to linearize

(41), a new continuous variable, $\delta_{pq,a}^{tie0} = x_{pq} p_a f_{pq}^{tie0} u_{pq,a}^{t0}$, is used. Finally, linear form of (40) can be expressed considering (14)–(21) to study the effect of FSCs on planning problem under all system conditions. Constraints (16)–(21) are used to apply the power flow in the existing transmission lines under all system conditions and scenario i. Constraints (16) and (17) enforce maximum permissible power flow in the existing transmission lines in normal and contingency condition, respectively. It must be noted that (16) enforces power flow limitation on non-outage existing transmission lines under all conditions and (17) limits the power flow in the existing transmission lines in corridors that contingency has occurred. Note that $u_{pq,a}^{t0}$ cannot be greater than zero, unless n_{pq}^{0} is greater than zero. Considering $u_{pq,a}^{t0}$ in constraints (18)–(21), two cases are considered under normal and contingency conditions.

1. $u_{pq,a}^{t0} = 1$: constraints (18) and (19) apply $f_{pq,a}^{tie0} = \frac{u_{pq,a}^{t0}}{x_{pq} p_a}$.
2. $u_{pq,a}^{t0} = 0$: constraints (20) and (21) guarantee $\delta_{pq,a}^{tie0} = 0$; therefore, power flow limitation is applied normally.

Constraints (22)–(29) similar to (16)–(21) are linear form of the following nonlinear equation:

$$f_{pq,r}^{tie} = \frac{(\theta_p^{tie} - \theta_q^{tie})}{x_{pq}(1 - \sum_{s \in S} p_a u_{pq,a}^{t})}. \tag{42}$$

Constraint (22) enforces KVL to the prospective transmission lines under normal and contingency conditions and scenario i. In addition, constraint (23) applies KVL to the prospective transmission lines in corridor where contingency has occurred. M is assumed as a big value that ensures the constraint is relaxed when $n_{pq,r} = 0$; but when $n_{pq,r} = 1$, this value is not important and KVL is enforced for the corresponding transmission line.

Constraints (24) and (25) express the power flow limits. In constraints (25), (27), and (29), to model line contingency in condition e and scenario i, a binary parameter, k_{pq}^{ε}, is defined. It can be seen that, when k_{pq}^{ε} is 1, node p will be isolated from node q.

3.3.2 Generation (Consumption) Limit Constraints

Constraints (30) and (33) represent the total power generated by each generator and the total power consumed by each consumer, respectively. Constraints (31) and (34) determine the size of the blocks of the generators and the demands in each scenario, respectively. Constraint (32) enforces generator output to generate within a certain range of maximum and minimum output power.

3.3.3 Voltage Angle Constraints

Constraints (35)–(38) limit voltage angle difference between nodes connected by existing and prospective transmission lines. In (36) and (38), k_{pg}^{e} is set to be one if contingency occurs in the existing and prospective corresponding lines.

These models can be solved by any commercial solver that deals with a mixed integer linear program. In this paper the CPLEX optimizer within GAMS is used to solve the proposed models (Brooke et al. 2003).

4 Metrics for Transmission Incorporating FSC

In this section, a set of metrics is considered to calculate the benefit changes for each entity created by investment on new facilities. The change in social welfare is determined by three metrics (λ_1, λ_1') given in the following two equations:

$$\lambda_1 = \frac{\mathrm{SW}^{\mathrm{GTEP}} - \mathrm{SW}^{B}}{\sum_{\forall t \in T} \sum_{\forall r \in \gamma_k} \left(c_{pq,r} n_{pq,r}^{t} + c_{hj} y_{hj}^{t} \right) / (1+I)^{t-t_0}} \tag{43}$$

$$\lambda_1' = \frac{\mathrm{SW}^{\mathrm{FSC,GTEP}} - \mathrm{SW}^{B}}{\sum_{\forall t \in T} \left(\sum_{\forall r \in \gamma_k} \left(c_{pq,r} n_{pq,r}^{t} + c_{hj} y_{hj}^{t} + C_a c_{pq,r} u_{pq,r,a}^{t} \right) + \sum_{\forall (pq) \in \gamma_k} C_a c_{pq} n_{pq}^{0} u_{pq,a}^{t0} \right) / (1+I)^{t-t_0}} \tag{44}$$

where $\mathrm{SW}^{\mathrm{GTEP}}$ and $\mathrm{SW}^{\mathrm{FSC,GTEP}}$ are the optimal social welfare considering GTEP without and with FSCs incorporation, respectively. SW^{B} is the aggregated social welfare for the base topology. λ_1 shows the improvement of the optimal social welfare for each dollar invested in transmission expansion, while λ_1' expresses the improvement of the optimal social welfare for each dollar invested in transmission expansion as well as installing FSCs. It is clear that investing in new facilities is reasonable if metrics

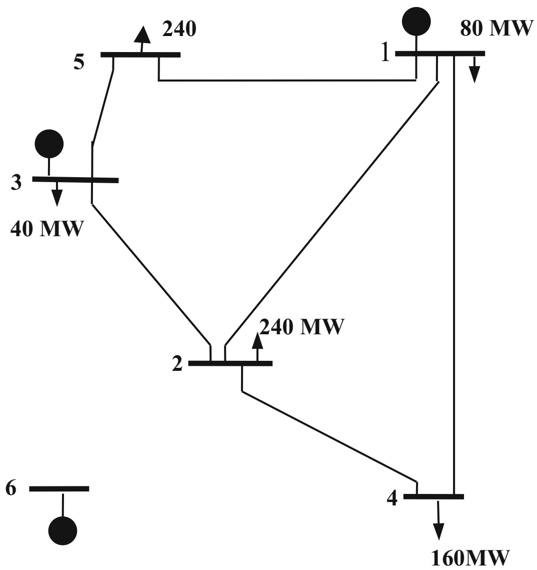

Fig. 2 Garver system

(43)–(44) are greater than one. Similarly, metrics (43)–(44) can be defined to measure the change in welfare obtained by the generators (λ_2, λ_2'), the demands (λ_3, λ_3'), and the market operator (λ_4, λ_4') for each situation. Note that all metrics can be obtained in terms of declared surplus, resulting from clearing market.

ISO can use FSC through GTEP for increasing utilization of the existing lines, which results in lowering transmission and generating investment. Therefore, from an operation point of view, this paper proposes a metric (defined as (45)) which takes into account the effect of new facilities in congestion of existing lines.

$$\mu = \sum_{\forall pq \in \gamma_l} \frac{f_{pq}^{\max} - |f_{pq}|}{f_{pq}^{\max}} \quad (45)$$

Similar to (43) and (44), metric (45) can also be defined for GTEP considering FSC using μ'. In fact, metrics μ and μ' are defined to investigate the effect of FSC through GTEP on congestion of the existing lines. The small value of the metric shows that the lines carry more power, resulting in better utilization of the existing lines.

5 Case Studies

5.1 Introduction

The Garver and IEEE 24-bus systems are used as case studies. In this paper, three types of FSCs with different compensation percentages can be installed in a transmission line as $P_1 = 20\%$ with $C_1 = 10\%$, $P_2 = 30\%$ with $C_2 = 15\%$, and $P_3 = 50\%$ with $C_3 = 20\%$ (Rahmani et al. 2013a, b). Based on the pool-based market structure,

Table 1 Generators and demands data for Garver system

Bus	Generators data				Demands data	
	Unit	Offer (MW)	Price ($/MWh)	Investment cost ($/kw/year)	Bid	Prices ($/MW)
1	UE1	150	10	Existing unit	80	30, 28, 26, 24, 20
	U1	150	13	70		
	U2	150	16	60		
	U3	150	19	50		
2	U4	50	15	45	240	34, 32, 30, 28, 25
	U5	50	17	40		
	U6	50	20	35		
3	UE2	120	20	Existing unit	40	20, 16, 14, 12, 10
	UE3	120	22	Existing unit		
	UE4	120	25	Existing unit		
	U7	120	28	85		
	U8	120	30	50		
4	–	–	–		160	30, 27, 24, 21, 17
5	–	–	–		240	34, 30, 26, 24, 18
6	U5	100	8	Existing unit	–	–
	U6	100	12	Existing unit		
	U7	100	15	Existing unit		
	U8	100	17	Existing unit		
	U9	100	19	Existing unit		
	U10	100	21	Existing unit		

Table 2 Characteristics of the different scenarios

Scenario	Weight	Demand coefficient
1	0.4120	0.47
2	0.3597	0.85
3	0.1172	1.20
4	0.1111	1.70

generators' offering blocks and demands' bidding blocks are submitted by generating units and demands, respectively, to attain their maximum profits. GTEP will be solved considering submitted bidding and offering data to maximize the social welfare. Here, linear cost functions are used for modeling generators' operation costs that contain a set of blocks. The constant marginal cost is assumed for each block. Each generating unit submits one block of the offered power to the market and the price declared is the marginal cost corresponding to that block. Different scenarios are assigned in which different levels of demand are consumed for a number of hours during the target year. The main difference among the scenarios is the level of demand. Each scenario is weighted in the objective function to correctly consider their relative relevance. The weight of each scenario is calculated by dividing the number of hours a scenario occurs by the total number of hours for the whole year. Moreover, size of each demand blocks is different in every scenario (De la Torre et al. 2008; Aguado et al. 2012). In this paper, an annual growth of generation and demand of 3.1% and annual growth of offer and bids of 5% are considered (Aguado et al. 2012).

5.2 Garver's System

Figure 2 shows the initial topology of Garver's system. This system has six transmission lines and six buses with three generators and five loads. The base data of the Garver's system are given in (Garver 1970). The planning horizon and discount rate are 15 years and 10%, respectively. The bidding blocks for existing and new generators and demands are shown in Table 1. According to Table 1, seven generating units are considered to be installed.

Table 2 shows the weight of each scenario and corresponding demand coefficient. According to this table, scenario 1 has a weight of 0.412 with demand coefficient of 0.47 that means in 41.2% of the hours of a year, the amount of load level for corresponding scenarios is 47% of its peak load.

The proposed method is applied to the Garver's system for the following cases.

Case 1 Solving the proposed method without considering FSC.

In this case, proposed model is solved considering $u^t_{pq,r,a} = 0$ and $u^{t0}_{pq,a} = 0$. The optimal solution provides the following lines and generating units with present value of the investment costs of \$263 M.

- Year 1: lines $n_{2-6} = 3, n_{1-5} = 2, n_{4-6} = 2$ and generating units U1, U2, and U4,
- Year 2: generating unit U5,
- Year 4: line $n_{4-6} = 1$.

As expected, new lines connect inexpensive generator in node 6 to the nodes with high demand (2 and 4).

Table 3 presents economic results of expansion in case 1. Note that, in all cases, the total social welfare is obtained summing up surpluses of the generators, consumers, and planner while subtracting investment cost of new facilities.

Case 2 Solving the proposed method along with FSC allocation.

In this case, proposed model is solved and the following results are obtained.

- Year 1: lines $n_{2-6} = 2, n_{1-5} = 2, n_{4-6} = 1$ and generating units U1, U2, and U4,
- Year 2: generating unit U5,
- Year 4: line $n_{4-6} = 1$,
- Year 14: $u_{3-4,1,3} = 1$, $u_{2-6,2,3} = 1$, and $u_{2-6,3,3} = 1$,

where $u^0_{p-q,a}$ and $u_{p-q,r,a}$ show the a_{th} installed FCS in existing line and r_{th} prospective line in corridor $p - q$, respectively. The present value of investment cost is \$223 M. Table 4 shows the economic results of expansion along with FSC for the market participants. Comparing Tables 3 and 4, it can be observed that optimal allocation of FSCs increases the total social welfare by up to \$61 M.

Table 5 shows metrics presented in Sect. 4 for cases 1 and 2.

Table 3 Results for Garver system (case 1)

	Income and cost/payment (M\$)		Profits (M\$)
Generators	Income	1006	238
	Cost	763	
Demands	Income	1679	672
	Payment	1009	
Merchandising surplus	—		0
Total SW	—		648

Table 4 Results for Garver system (case 2)

	Income and cost/payment (M$)		Profits (M$)
Generators	Income	1088.7	260
	Cost	757.7	
Demands	Income	1653	672
	Payment	1085.5	
Merchandising surplus	—		0.28
Total SW	—		709

Table 5 Economic metrics for Garver system

Metric for	Social welfare	Generator	Consumer	Operator surplus
Value				
Case 1	$\lambda_1 = 2.332$	$\lambda_2 = 0.012$	$\lambda_3 = 2.32$	$\lambda_4 = -0.01$
Case 2	$\lambda'_1 = 3.119$	$\lambda'_2 = 0.065$	$\lambda'_3 = 3.18$	$\lambda'_4 = -0.0016$

According to Table 5, FSC installation through GTEP significantly increases surplus of market beneficiaries (generators and consumers), especially social welfare, while operator surplus is decreased. Installing FSC reduces merchandizing surplus and also reduces transmission congestion and accordingly leads to more identical LMP prices across transmission system. Operating metrics calculated for cases 1 and 2 are $\mu = 5.8123$ and $\mu' = 5.7089$, respectively. Therefore, it can be observed that the metrics, calculated in case 2, are decreased compared to case 1, reflecting a reduction in congestion.

5.3 IEEE 24-Bus System

The IEEE 24-bus system consists of 24 buses, 41 corridors for adding the new circuits, and 7551 MW demand for base topology, where its base data are available in (Fang and Hill 2003). Single line diagram of IEEE 24-bus system is illustrated in Fig. 3.

For long-term expansion planning in IEEE 24-bus, four scenarios are assigned. Generators will offer 4 blocks and consumers will bid 3 blocks, both with equal sizes, which are presented in Table 6. Moreover, the same as the first case study, different scenarios are considered. In this case study, planning horizon spans 10 years to decrease computational efforts. However, this planning horizon is reasonable. The proposed method is applied to an IEEE 24-bus system for the following cases.

Case 1 Similar to the first case study, proposed method is solved without considering FSC.

The optimal solution provides the following new lines with a present value of investment costs equal to $102 M.

- Year 1: generating unit U3,
- Year 4: line $n_{3-24} = 1$,

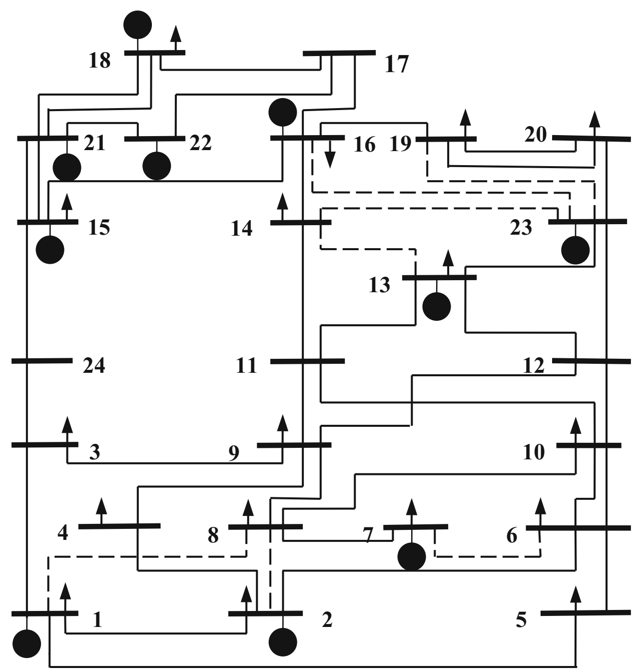

Fig. 3 IEEE 24-bus system

- Year 10: lines $n_{3-24} = 1$, $n_{2-8} = 2$, $n_{2-4} = 1$.

Table 7 presents the results of expansion of IEEE 24-bus in case 1.

Case 2 Solving the proposed method considering FSC allocation.

In this case 1, the transmission line, generating unit and several FSCs are installed in existing and prospective transmission lines as follows.

- Year 1: FSC in existing line $u^0_{3-24,1} = 1$, generating unit U3,
- Year 4: FSC in existing line $u^0_{8-10,3} = 1$,

Table 6 Offers and bids data, second case study

Bus no.	Generation				Consumer	
	Unit	Offer (MW/block)	Offer price [$/MWh]	Investment cost ($/kw/year)	Bid (MW/block)	Bid price [$/MWh]
1		495	10, 13, 15, 17	Existing unit	–	–
2		144	15, 18, 21, 25	Existing unit	97	38, 35, 32
3		–	–		180	40, 37.5, 35
4		–	–		74	26, 20.8, 18.2
5		–	–		71	44, 41, 39
6	U1	50	14	45	136	20, 16, 14
7		225	13, 16.3, 19.5, 22	Existing unit	125	38, 35, 32
8	U2	50	13	50	171	38, 35, 32
9		–	–		175	40, 37.5, 35
10		–	–		195	26, 20.8, 18.2
13		443.25	10, 13, 15, 17	Existing unit	265	44, 41, 39
14	U3	40	15	40	194	20, 16, 14
15		161.25	15, 18, 21, 25	Existing unit	317	38, 35, 32
16		116.25	13, 16.3, 19.5, 22	Existing unit	100	40, 37.5, 35
18		300	10, 13, 15, 17	Existing unit	–	–
19		–	–		181	26, 20.8, 18.2
20		–	–		128	44, 41, 39
21		300	15, 18, 21, 25	Existing unit	–	–
22		225	13, 16.3, 19.5, 22	Existing unit	–	–
23		144	10, 13, 15, 17	Existing unit	108	20, 16, 14

Table 7 Economic results for IEEE 24-bus, case 1

	Income and cost/payment (M$)		Profits (M$)
Generators	Income	7906	1446
	Cost	6453.9	
Demands	Income	13,589.1	5639.3
	Payment	7949.8	
Merchandising surplus	—		73.4
Total SW	—		7055.3

Table 8 Economic results for IEEE 24-bus, case 2

	Income and cost/payment (M$)		Profits (M$)
Generators	Income	7550	1342
	Cost	6501	
Demands	Income	13,599.2	5748.6
	Payment	7850.3	
Merchandising surplus	—		26
Total SW	—		7096

Table 9 Metrics for IEEE 24-bus

Metric for	Social welfare	Generator	Consumer	Merchandising surplus
Value				
Case 1	$\lambda_1 = 0.395$	$\lambda_2 = 0.354$	$\lambda_3 = 0.40$	$\lambda_4 = -0.39$
Case 2	$\lambda'_1 = 1.05$	$\lambda'_2 = 0.734$	$\lambda'_3 = 2.07$	$\lambda'_4 = -1.75$

- Year 10: transmission line $n_{3-24} = 1$; FSC in existing line $u^0_{8-9,1} = 1$; FSC in prospective line $u_{3-24,1} = 1$.

The present value of the investment cost is equal to \$71 M. Two new lines between nodes 2 and 3, considered in case 1, are removed from the list of new transmission lines while the total investment is decreased. Table 8 shows the economic results of TEP and FSC allocation. From Table 8, an increase in total net social welfare can be seen. Due to using FSCs, difference between locational prices is diminished, resulting in a decrease in merchandising surplus.

Table 9 shows metrics presented in Sect. 4 for each case.

According to Table 9, although merchandising surplus has a considerable decrease, the total social welfare, generator and consumer surpluses are increased. Therefore, installing FSCs can be beneficial for a system as a whole. Decreasing merchandising surplus shows that locational marginal prices are closer together. Results of operating metrics presented in Sect. 3 for cases 1 and 2 are $\mu = 34.1$ and $\mu' = 33.86$, respectively. Comparing operating metrics shows that FSCs cause better utilization of existing facilities.

According to the aforementioned results, it can be seen that using new facilities by the ISO not only increases the total social welfare but also increases the flexibility of the network to response part of demand growth without new transmission lines. Therefore, it is beneficial for the market operator to optimally install the FSCs.

6 Conclusion

In this paper a dynamic generation-transmission expansion planning (GTEP) model along with FSC allocation in a competitive market environment has been proposed. In the proposed model, inclusion of FSC has been considered to make better utilization of the transmission facilities and reduce the overall investment. It has been shown that installing FSCs not only improves the market but also enhances operational performance of the transmission network and redistributes active power more efficiently while improving the total social welfare. This fact has been shown for Garver and IEEE 24 bus systems. Results show that FSCs allocation reduces the number of new facilities and, hence, results in a significant improvement in social welfare. Integration of FSCs reduces operating index. This fact shows an improvement in existing transmission network efficiency and consequently reducing the necessity of installing new facilities.

References

Aguado JA, de la Torre S, Contreras J, Conejo AJ, Martínez A (2012) Market-driven dynamic transmission expansion planning. Electr Power Syst Res 82:88–94. doi:10.1016/j.epsr.2011.09.001

Akbari T, Tavakoli-Bina M (2014) A linearized formulation of AC multi-year transmission expansion planning: a mixed-integer linear programming approach. Electric Power Systems Research 114:93–100. doi:10.1016/j.epsr.2014.04.013

Akbari T, Rahimikian A, Kazemi A (2011) A multi-stage stochastic transmission expansion planning method. Energy Convers Manag 52:2844–2853. doi:10.1016/j.enconman.2011.02.023

Alguacil N, Motto AL, Conejo AJ (2003) Transmission expansion planning: a mixed-integer LP approach. IEEE Trans Power Syst 18:1070–1077. doi:10.1109/TPWRS.2003.814891

Blanco GA, Olsina FG, Ojeda OA, Garses FF (2009) Transmission expansion planning under uncertainty—the role of FACTS in providing strategic flexibility. In: IEEE Bucharest PowerTech Conference, pp 1–8. doi: 10.1109/PTC.2009.5282080

Braga ASD, Saraiva JT (2005) A multiyear dynamic approach for transmission expansion planning and long-term Marginal costs computation. IEEE Trans Power Syst 20:1631–1639. doi:10.1109/TPWRS.2005.852121

Brooke A, Kendrick D, Meeraus A, Raman R (2003) GAMS/CPLEX 9.0. User Notes, GAMS Development Corp., Washington, DC, 2003

Buygi MO, Balzer G, Shanechi HM, Shahidehpour M (2004a) Market-based transmission expansion planning. IEEE Trans Power Syst 19:2060–2067. doi:10.1109/TPWRS.2004.836252

Buygi MO, Shahidehpour M, Shanechi HM, Balzer G (2004) Market based transmission planning under uncertainties. In: International conference on probabilistic methods applied to power systems 2004, pp 563–568

Buygi MO, Balzer G, Shanechi HM, Shahidehpour M (2004) Market based transmission expansion planning: fuzzy risk assessment. In: Proceedings of the 2004 IEEE international conference on electric utility deregulation, restructuring and power technologies, vol 2, pp 427–432. doi:10.1109/DRPT.2004.1337997

Buygi MO, Balzer G, Shanechi HM, Shahidehpour M (2004) Market based transmission expansion planning: stakeholders' desires. In: Proceedings of the 2004 IEEE international conference on electric utility deregulation, restructuring and power technologies, vol 2, pp 433–438. doi:10.1109/DRPT.2004.1337998

Choi J, El-Keib AA, Tran T (2005a) A fuzzy branch and bound-based transmission system expansion planning for the highest satisfaction level of the decision maker. IEEE Trans Power Syst 20:476–484. doi:10.1109/TPWRS.2004.840446

Choi J, Tran T, El-Keib AA, Thomas R, Oh H, Billinton R (2005b) A method for transmission system expansion planning considering probabilistic reliability criteria. IEEE Trans Power Syst 20:1606–1615. doi:10.1109/TPWRS.2005.852142

Da Silva EL, Gil HA, Areiza JM (2000) Transmission network expansion planning under an improved genetic algorithm. IEEE Trans Power Syst 16:930–931. doi:10.1109/59.871750

de la Torre S, Conejo AJ, Contreras J (2008) Transmission expansion planning in electricity markets. IEEE Trans Power Syst 23:238–248. doi:10.1109/TPWRS.2007.913717

Escobar AHH, Gallego RAA, Romero R (2004) Multistage and coordinated planning of the expansion of transmission systems. IEEE Trans Power Syst 19:735–744. doi:10.1109/TPWRS.2004.825920

Fang R, Hill DJ (2003) A new strategy for transmission expansion in competitive electricity markets. IEEE Trans Power Syst 18:374–380. doi:10.1109/TPWRS.2002.807083

Garver L (1970) Transmission network estimation using linear programming. IEEE Trans Power Appar Syst PAS 89:1688–1697. doi:10.1109/TPAS.1970.292825

Georgilakis PS (2010) Market-based transmission expansion planning by improved differential evolution. Electr Power Energy Syst 32:450–456. doi:10.1016/j.ijepes.2009.09.019

Hooshmand R, Hemmati R, Parastegari M (2012) Combination of AC transmission expansion planning and reactive power planning in the restructured power system. Energy Convers Manag 55:26–35. doi:10.1016/j.enconman.2011.10.020

Kandil MS, El-Debeiky SM, Hasanien NE (2001) A hybrid mathematical and rule-based system for transmission network planning in a deregulated environment. Power Eng Soc Summer Meet 3:1451–1456. doi:10.1109/PESS.2001.970289

Khodaei A, Shahidehpour M, Kamalinia S (2010) Transmission switching in expansion planning. Power Syst IEEE Trans 25:1722–1733. doi:10.1109/TPWRS.2009.2039946

Koltsaklis NE, Georgiadis MC (2015) A multi-period, multi-regional generation expansion planning model incorporating unit commitment constraints. Appl Energy 158:310–331. doi:10.1016/j.apenergy.2015.08.054

Lee STY, Hicks KL, Hnyilicza E (1974) Transmission expansion by branch-and-bound integer programming with optimal cost–capacity curves. Power Appar Syst IEEE Trans PAS 93:1390–1400. doi:10.1109/TPAS.1974.293869

Lu M, Dong ZY, Saha TK (2005) A framework for transmission planning in a competitive electricity market. In: Transmission and distribution conference and exhibition: Asia and Pacific, IEEE/PES, 2005, pp 1–6. doi:10.1109/TDC.2005.1547025

Miasaki CT, Romero R (2007) A specialized genetic algorithm applied to transmission expansion planning model with allocation of series compensation devices. Controle Autom 18:210–222. doi:10.1590/S0103-17592007000200007

Orfanos GA, Georgilakis PS, Hatziargyriou ND (2013) Transmission expansion planning of systems with increasing wind power integration. IEEE Trans Power Syst 28:1355–1362. doi:10.1109/TPWRS.2012.2214242

Pourakbari-Kasmaei M, Rashidi-Nejad M (2011) An effortless hybrid method to solve economic load dispatch problem in power systems. Energy Convers Manag 52:2854–2860. doi:10.1016/j.enconman.2011.02.018

Rahmani M, Romero R, Rider MJ (2013a) Strategies to reduce the number of variables and the combinatorial search space of the multistage transmission expansion planning problem. IEEE Trans Power Syst 28:2164–2173. doi:10.1109/TPWRS.2012.2223241

Rahmani M, Vinasco G, Rider MJ, Romero R, Pardalos PM (2013b) Multistage transmission expansion planning considering fixed series compensation allocation. IEEE Trans Power Syst 28:3795–3805. doi:10.1109/TPWRS.2013.2266346

Roh JH, Shahidehpour M, Wu L (2009) Market-based generation and transmission planning with uncertainties. Power Syst IEEE Trans 24:1587–1598. doi:10.1109/TPWRS.2009.2022982

Romero R, Monticelli A, Garcia A, Haffner S (2002) Test systems and mathematical models for transmission network expansion planning. IEE Proc Gener Transm Distrib 149:27–36. doi:10.1049/ip-gtd:20020026

Sanchez-Martin P, Ramos A, Alonso JF (2005) Probabilistic midterm transmission planning in a liberalized market. IEEE Trans Power Syst 20:2135–2142. doi:10.1109/TPWRS.2005.856984

Seddighi AH, Ahmadi-Javid A (2015) Integrated multiperiod power generation and transmission expansion planning with sustainability aspects in a stochastic environment. Energy 86:9–18. doi:10.1016/j.energy.2015.02.047

Shayeghi H, Jalilzadeh S, Mahdavi M, Hadadian H (2008) Studying influence of two effective parameters on network losses in transmission expansion planning using DCGA. Energy Convers Manag 49:3017–3024. doi:10.1016/j.enconman.2008.06.013

Shrestha GB, Fonseka PAJ (2004) Congestion-driven transmission expansion in competitive power markets. IEEE Trans Power Syst 19:1658–1665. doi:10.1109/TPWRS.2004.831701

Sun H, Yu DC (2000) A multiple-objective optimization model of transmission enhancement planning for independent transmission company (ITC). Power Eng Soc Summer Meet IEEE 4:2033–2038. doi:10.1109/PESS.2000.866959