JOURNAL OF ELECTRIC POWER AND ENERGY CONVERSION SYSTEMS (JEPECS)
JEPECS VOL. 1, NO. 1, PP. 8-15, SPRING 2016
ISSN: 2345-4830 print/2345-4733 online

A Transmission Expansion Planning Model for Maximizing Merchant Investment

Pouria Maghouli[*] and Seyed Ahmadreza Mousavimirkolaei[†]

The unbundling of electricity industry introduced new objectives and requirements in transmission expansion planning. In this paper, a multi-stage transmission expansion methodology is presented using a multi-objective optimization framework for maximizing absorbed merchant investment in the bulk transmission system. Investment cost, congestion cost and merchant investment are considered as three optimization objectives. The genetic based Non-dominated Sorting Genetic Algorithm (NSGA II) is used to to overcome the difficulties in solving the non-convex and mixed integer optimization problem. Then, fuzzy decision is applied to obtain the most preferred solution. The planning methodology is applied to the IEEE 24 bus test system to show feasibility of the proposed algorithm.

Keywords: Fuzzy Satisfying Method, Genetic Algorithm, Merchant Investment, Multi-objective Optimization, NSGA II, Transmission Expansion Planning.

Received June 2015; Revised Nov. 2015; Accepted March 2016.

I INTRODUCTION

The unbundling of electricity business has raised new challenges for transmission planners. As discussed in [1], a sound transmission expansion planning strategy could handle the following challenges and requirements:

- A cost-benefit approach instead of classical least cost approach
- Stakeholders requirements with different and mostly conflicting goals
- Financial and physical uncertainties due to the unbundling process

For handling above requirements, a multi objective framework presented in [1, 2] for modeling transmission expansion problem. By applying a posteriori approach for solving the multi-objective optimization problem, a new framework was presented which could handle different objectives and would enable the planner to find the optimal plan based on a cost-benefit analysis. This framework is used and extended in this paper to deal with a new objective: maximizing Absorbed Merchant Investment.

Just like other infrastructure projects, bulk power transmission system needs a huge investment for reliable operation. Lack of investment to enhance transmission grid will result power outage in large area power outages in Northeast US on August 14 , 2003 which affected more than 20 million consumers, six control areas and shut down 61 GW of generation capacity [3]. Because of budget constraints, regulatory entities such as TransCos and RTOs cannot invest adequately in transmission expansion projects and are more concern about involving private sector for investing in merchant transmission projects.

The transmission network has a vital role in new electricity market because it should provide a nondiscriminatory environment for all market participants. Merchant transmission projects were intended as a market-driven solution to keep the electric market competitive. In general, there are two types of transmission projects: reliability-driven and market-driven projects. Reliability-driven projects are built to maintain system reliability and security based on bulk transmission reliability criteria such as N-1 criterion [4, 5]. Market-driven projects are those which improve market competition and serve load serving entities with cheaper energy. The TransCos are not obliged to invest in market-driven projects and these projects should be addressed by merchant investors. Since merchant investors objective is to maximize their profit, in this paper a multi-objective model is proposed to consider TransCos and merchant investors objectives. Thus the main contribution of this study is to present a novel model for transmission expansion planning problem which can identify profitable plans in a central planning approach and consequently absorbing merchant investment and relaxing budget constraints on regulatory bodies. Three defined objectives in this study are minimizing investment cost and congestion cost (maximizing social welfare); and maximizing absorbed merchant investment. The proposed approach can simultaneously consider different stakeholders objectives and goals such as regulatory objectives and private investors objectives.

This paper is organized as follows. After an overall review of the merchant investment and transmission pricing in Section III, the mathematical formulation and optimization process are presented in Section IV followed by a case study demonstrating the capabilities of the proposed method in Section V. Finally, conclusions are given in Section VI.

---

[*] Ph.D. with the Department of Electrical Engineering, Sharif University of Technology, Tehran, Iran, E-mail: maghuli@gmail.com (Corresponding Author).

[†] Tablie Construction Co., E-mail: ar_musavi@yahoo.com.

Published by Shahed University Publishing Center.

II MERCHANT INVESTMENT

A A. Combined Regulatory-Merchant Mechanism for Transmission Expansion Planning

All the works presented in the literature about transmission expansion planning can be classified into two categories:

- Those which not address merchant investment [6–10]
- Those which consider merchant investment as an option for transmission expansion with in decentralized approach [11–13]

However, there are few works on centralized combined regulatory and merchant investment model for transmission expansion planning. After major blackouts in 2003 that are generally regarded as partially being due to insufficient transmission capacity, centralized planning is currently receiving more attention [14] because this approach can consider bulk transmission reliability and economic performance requirements more efficiently.

Based on the centralized planning approach, addressing regulatory and private sector objectives needs a multi-objective model for considering these conflicting objectives and goals. The planner should address the merchant investors requirements for absorbing more private investment. Thus, a multi-objective model is presented which could detect profitable merchant projects and maximizing merchant investments.

B Transmission Pricing

Transmission pricing has a vital role in absorbing merchant investment. Incentive-based mechanisms are necessary to promote merchant investment. Optimizing the transmission revenue stream over the life of the project will incentivize the private sector to invest in transmission projects.

According to economic theory, a transmission rate should send the right economic signals to achieve the most efficient use of the transmission grid. Many usage-based [15], market-based [12] and financial-based (FTRs) [16] transmission pricing schemes proposed in the literature which is beyond the scope of this paper. In this paper the well-known MW-Mile methodology [17] is adopted for calculation of transmission revenues while other pricing methods can be incorporated in the proposed transmission expansion algorithm simply.

III PROPOSED STRATEGY

In this paper, it is assumed that the transmission planning is managed by a regulated organization whose main interest is to improve competition among market players or to maximize the social welfare while maintaining the system reliability. Thus, the main objective is to minimize investment and congestion costs. It can be shown that this objective is equivalent to maximizing the social welfare [1, 18].

Besides above objectives, the proposed planning methodology will detect profitable expansion plans and maximize total absorbed merchant investment. This objective can relax budget constraints of the regulatory entity and improve market operation. Using a multi-objective optimization model, a set of non-dominated solutions is generated by the algorithm demonstrating their trade-offs.

Thus, the planner can select the best compromise solution according to different objectives and requirements by the fuzzy satisfying method as a decision making process.

In the next section, first of all the objectives are formulated and then optimization method, fuzzy decision making and the proposed algorithm will be described.

A Minimization of Total Social Cost

The first objective of the proposed strategy is to minimize the Net Present Value (NPV) of the investment cost during the planning horizon. This objective can be formulated as:

$$Min\, f_1 = \sum_{t_y \in T} \sum_{(i,j)\in\Omega_l} \frac{c_{ij} n_{ij}(t_y)}{(1+D)^{(t_y - T_0)}} \tag{1}$$

The second objective is to minimize the NPV of total congestion cost over the planning horizon. Minimizing the congestion cost means improving market performance in deregulated electricity markets. Thus the second objective can be formulated as:

$$Min\, f_2 = \sum_{t_y \in T} \frac{CC(t_y)}{(1+D)^{(t_y - T_0)}} \tag{2}$$

Objectives (1) and (2) are subjected to long-term and short-term constraints. The long-term constraint is as follows [1]:

$$0 \le n_{ij}(t_y) \le \bar{n}_{ij}(t_y) \quad \forall (i,j) \in \Omega_l \tag{3}$$

The short-term constraints are hourly DC load flow constraints:

$$\boldsymbol{s}^T \boldsymbol{f} + \boldsymbol{g} + \boldsymbol{r} = \boldsymbol{d} \tag{4}$$

$$f_{ij} - \gamma_{ij}(n_{ij}^0 + n_{ij})(\theta_i - \theta_j) = 0 \tag{5}$$

$$0 \le \boldsymbol{g} \le \bar{\boldsymbol{g}} \;\;,\;\; 0 \le \boldsymbol{r} \le \boldsymbol{d} \tag{6}$$

$$|f_{ij}| \le (n_{ij}^0 + n_{ij}) \bar{f}_{ij} \tag{7}$$

All variables in (4) are hourly parameters except for the number of added circuits n_{ij}. For the sake of simplicity time indices in (4) are removed.

The market operation should be formulated for calculating annual congestion cost and load curtailments. Considering the Locational Marginal Price (LMP) based market [19] the operator (ISO) would minimize the hourly social cost (HSC) as follows:

$$\text{Min}\, HSC = \sum_{i=1}^{n_g} C_i(g_i(t_h)) - \sum_{j=1}^{n_d} B_j(d_j(t_h)) \tag{8}$$

In one-sided markets, the objective is to minimize the production cost subject to constraints in (4). The production cost can be formulated as a function of generation bids. If incremental costs are used for bidding:

$$\text{Min}\, HSC = \sum_{i=1}^{n_g} g_i(t_h)\left(a_i g_i(t_h) + b_i\right) \tag{9}$$

This optimization is also subjected to the short-term constraints in (3). The congestion cost is defined as the difference between social costs under two dispatching strategies with and without line capacity limits [20]:

$$CC(t_h) = \{\mathrm{Min}\, HSC|_{3.a-3.d}\} - \{\mathrm{Min}\, HSC|_{3.a-3.c}\} \quad (10)$$

The annual congestion costs and load curtailments should be calculated hourly. However, for reducing the computational effort, a simple accurate method will be used based on the Load Duration Curve (LDC) concept [1].

According to the reliability constraints, the transmission system should serve the total load of the system without any load curtailment in normal and under n-1 contingency condition [21]. Here only the adequacy criterion is used in the proposed methodology while the n-1 criterion can be easily incorporated in the formulation [2]. For calculating the amount of load curtailment in normal operation, virtual generators are modeled at each load bus. Loads will be curtailed if the re-dispatch of real generators cannot eliminate transmission overloads:

$$LC = \sum_{t_y \in T} \sum_{k \in \Omega_b} r_k(t_y) \quad (11)$$

By defining a large penalty factor (pf) for the LC, final non-dominated solutions will have a zero load curtailment in all expansion plans. Thus, final solutions will be all adequate ones.

B B. Maximizing Absorbed Merchant Investment

The planning strategy should incentivize private sector to invest in transmission expansion projects. This objective could be achieved by considering private investors requirements in transmission planning. Thus the third proposed objective defined in this study is maximizing absorbed merchant investment by searching for profitable expansion projects.

There are many techniques for measuring the profitability of an investment. Rate of Return and Capital Cost Recovery Time are the most convenient ones. In infrastructure projects with long operational life, revenues could not be predicted over the project lifetime because of uncertainties. Thus we use the capital cost recovery time period as the profitability index (CCRT). Therefore, profitable projects are those have a CCRT period smaller than a pre-specified time period, desirable CCRT. The third objective function would be the NPV of the investment cost of profitable projects. The third objective function can be formulated as:

$$\mathrm{Max}\, f_3 = \sum_{t_y \in T} \sum_{(i,j) \in \Omega_f} \frac{c_{ij} n_{ij}(t_y)}{(1+D)^{(t_y - T_0)}} \quad (12)$$

Where Ω_f is the set of profitable transmission lines. The revenue of transmission lines are calculated based on MW-Mile methodology:

$$\mathrm{Re}venue = \sum_{t_y \in T} \frac{f_{ij} \times R_{ij}}{(1+D)^{(t_y - T_0)}} \quad (13)$$

Where R_{ij} is the transmission tariff in \$/MWh-Mile. For each transmission project in a solution, NPV of its revenue will be calculated over the desirable CCRT period and if its total revenue would be larger than its investment cost; this project would be identified as a profitable one.

C Optimization Method

Generally, it is impossible to obtain an optimal solution for all objectives which are defined and optimized in (1), (2), and (9) are optimized. The concept of pareto optimality (also known as non-inferiority or non-dominancy) is used to characterized solutions to multi-objective problems. Qualitatively, a non-dominated solution of a multi-objective problem is the one by which any improvement of one objective function can be achieved only at the expense of degrading the others. A set of non-dominated solutions composes a region which is called non-dominated set or trade-off region [1].

There is a range of mathematical and evolutionary algorithms for finding non-dominated solutions of a multi-objective optimization problem. Genetic algorithm in general, has an inherent capability to handle non-linear, non-convex, and mixed integer optimization problems effectively [22]. The genetic-based NSGA II is one of the best efficient tools to solve complex multi-objective optimization problems [23, 24], and is used in the proposed strategy.

The main idea of NSGA II is to sort a solution population into a number of non-dominated fronts. The detailed description of this algorithm can be found in [1, 2]. For finding adequate solutions through the optimization process, Load Curtailment should be added to all three objectives with a large penalty factor. Also, the third objective (maximizing absorbed merchant investment) should be converted to a minimization objective. Hence, the final objective functions would be:

$$\begin{array}{ll} Min & f_1 + pf.LC \\ Min & f_2 + pf.LC \\ Min & -1 \times f_3 + pf.LC \end{array} \quad (14)$$

Adding the load curtailment to all objective functions will guarantee solutions adequacy i.e. zero load curtailment. Fig. 1 shows the codification of solutions used in this study [25]. In this codification, each solution is represented by a $t \times l$ matrix corresponding to t planning stages and l right-of-ways (existing and new right-of-ways). The matrix values show the number of new lines added to the corresponding right-of-way. For example, Fig. 1 shows that two new circuits are added in right-of-way 1-2 in stage one and one circuit is also added to this right-of-way in stage two.

Since the decision on additional branches in each stage depends on the decision made in the previous stage, in this study, the matrix rows will be joined to form a vector of length in the reproduction process. This technique was shown to have a better convergence behavior in several test runs [1].

D Final Decision Making

The solution to the multi-objective problem is not unique and some kind of subjective judgment by the planner as a decision maker should be added to the quantitative analysis. Because of similarity of fuzzy decision-making to human subjective reasoning, the fuzzy satisfying method is used for selecting the final

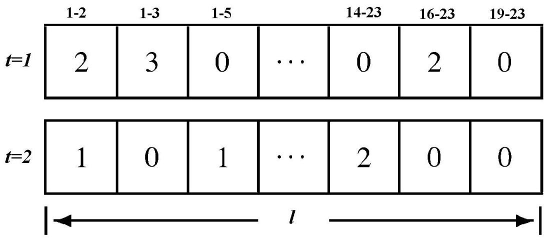


Figure 1: Codification of solutions.

solution in this study [1,2].

In the fuzzy satisfying method, a strictly monotonically decreasing and continuous membership function for representing the satisfaction level is assigned to each objective [26]. The value of membership function indicates what extend a solution is satisfying the decision maker about the objective f_i. The decision maker is fully satisfied with the objective value of $f_i(X)$ if $\mu_{f_i}(X) = 1$, and not satisfied at all if $\mu_{f_i}(X) = 0$.

This membership function can be defined linearly as:

$$\mu_{f_i}(X) = \begin{cases} 0 & f_i(X) > f_i^{\max} \\ \dfrac{f_i^{\max} - f_i(X)}{f_i^{\max} - f_i^{\min}} & f_i^{\min} \le f_i(X) \le f_i^{\max} \\ 1 & f_i(X) < f_i^{\min} \end{cases} \tag{15}$$

After defining each membership function, the decision maker is asked to choose the desirable level of achievement (satisfaction level/ reference value) of each objective μ_{ri} . The final solution is obtained using a decision analysis technique such as the distance metric method:

$$\min_{X \in \Phi} \sum_{i=1}^{3} |\mu_{ri} - \mu_{fi}(X)|^p \tag{16}$$

where $1 \le p < \infty$. This formulation would minimize the p-norm deviations from satisfaction levels. The trade-off between objectives that derived by NSGA II could help the decision maker to select reasonable satisfaction levels while this information will not be available if a priori method is used for solving the multi-objective problem. By applying methods like the one in [27], planners can incorporate stakeholders relative importance and their preferences in the decision making process.

E Proposed Algorithm

Initially, the first population which is a set of randomized alternative solutions is produced. For each alternative in the population, the NPV of investment, congestion costs and load curtailment will be calculated through the planning horizon using a series of standard quadratic optimizations. Also, for each candidate line in each solution, the NPV of its revenue is calculated over the desired capital cost recovery time period. In each solution, all candidates which their total revenue is larger than their investment cost will be identified as profitable candidates. The NPV of sum of profitable candidates investment cost would be the absorbed merchant investment of that solution.

The NSGA II sorts the solutions according to their objective values, reproduces them using the best ones, and sends the new population to the next iteration. The iterative process will be terminated if it reaches the maximum number of allowed iterations or it cannot find any new non-dominated solution in a predefined number of successive iterations.

Finally, the planner will be asked to define his/her satisfaction levels and by applying the fuzzy satisfying method, the final solution will be obtained. As it can be seen in the above process, the proposed algorithm searches the solution space to find cost effective, market driven and profitable solutions simultaneously. Thus, the final solution would satisfy different stakeholders requirements and goals. Please note that other objectives such as maximization of consumers or producers surplus [28] or cost of transmission losses [29] could be easily incorporated into the algorithm. These objectives could be added as new ones or combined with the first objective that presented in this study.

IV CASE STUDY

The proposed algorithm was implemented in MATLAB environment with the MATPOWER optimal power flow functions. The planning horizon is assumed to be 15 years divided into three five-year stages. It is also assumed that GENCOs bid functions (incremental costs) will not change during the planning horizon (this assumption may not be valid for a practical network but the issue of bid forecasting is beyond the scope of this report).

The proposed method is applied to the IEEE 24-bus test shown in Fig. 2. Network data of this system can be found in [2, 30]. Revenue rate of transmission lines is define according to their investment cost and by assuming the rate of return of 16%. It is assumed that the system should be expanded for future conditions with the generation and load demand increased by 2.2 times their original values, i.e., load level of 6720 MW and generation level of 7490 MW. These conditions correspond to load incremental rate of 5% per year within 15 years planning horizon.

It is assumed that the candidate branches can be constructed in all 34 existing right-of-ways plus 10 new right-of-ways which their data can be found in [2]. The parameters of new branches in the existing right-of-ways are the same as the parameters of the existing branches in those right-of-ways. Up to three and up to two branches can be installed in the existing and in the new corridors, respectively, limited by environmental considerations. In substations up to four power transformers can be installed. It is also assumed that the desirable capital cost recovery time period is 6 years based on industry experience [12]. Considering objective functions defined in (14) and with population size of 200 and after 185 iterations (these parameters are tuned after several runs of the developed program in MATLAB), 187 non-dominated solutions were found by the proposed algorithm. Fig. 3 shows these non-dominated solutions. Due to difficulty of effectively displaying a non-dominated set in a three dimensional space, three trade-off graphs are used.

The trade-offs depicted in Fig. 3 could help the decision maker

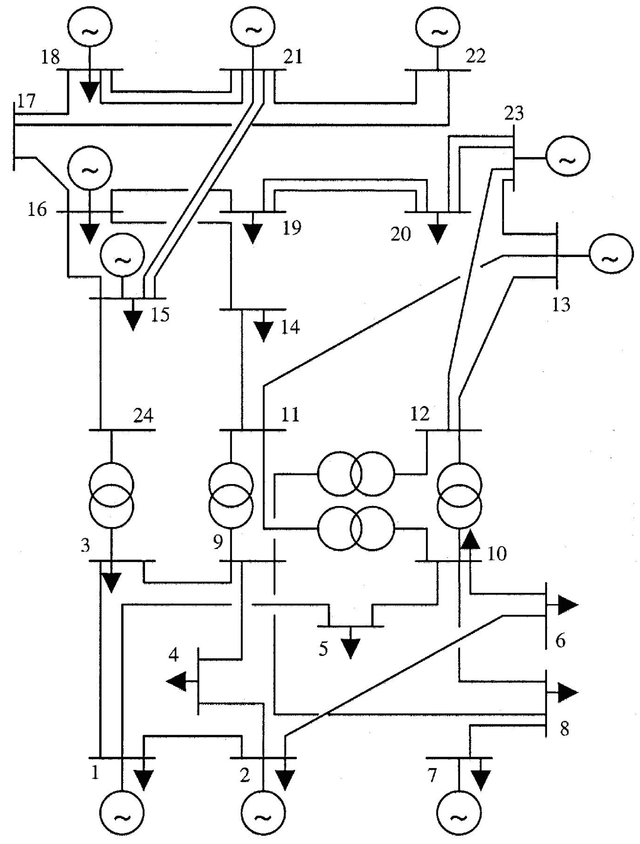
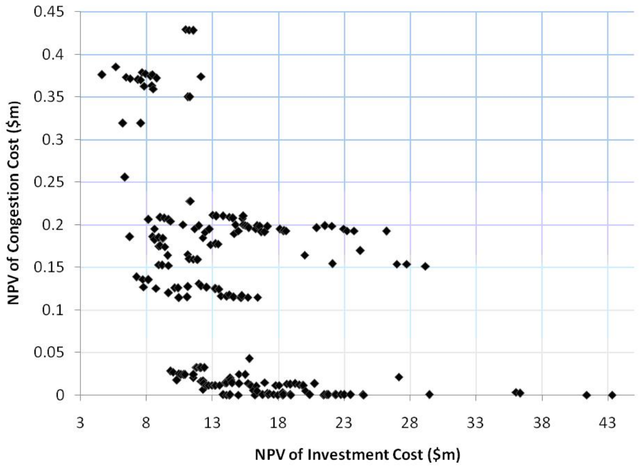
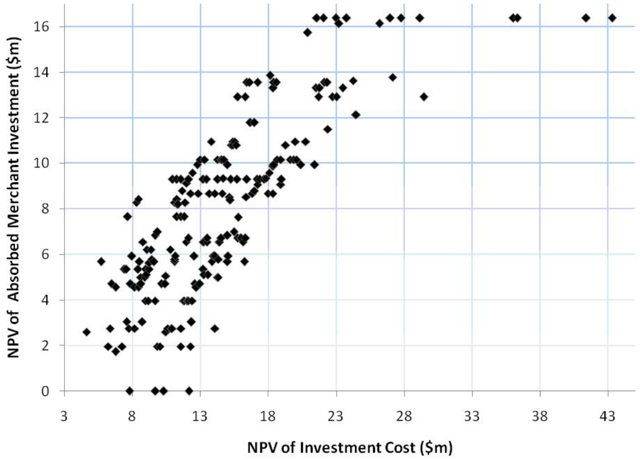


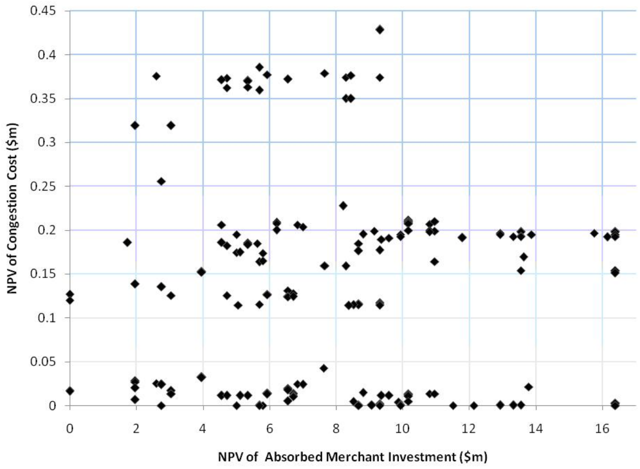
Figure 2: IEEE 24 bus test system.



(a) Trade-off between NPV of investment cost and congestion cost



(b) Trade-off between NPV of investment cost and absorbed merchant investment



(c) Trade-off between NPV of absorbed merchant investment and congestion cost.

Figure 3: Non-dominated solutions.

to find the best compromise solution. Fig 3-a shows that for an specific amount of investment cost (e.g. between \$13M up to \$23M), there are two sets of solutions, those with very low absorbed merchant investment and others with an acceptable level of absorbed merchant investment. Thus, the planner as a decision maker, based on its own requirements and objectives, can find the most appropriate solution. For applying the fuzzy satisfying method presented in section IV, the planner should select maximum and minimum for each objective. These values could be easily obtained from non-dominated solutions. For example: Fig. 3 obviously indicates that it is obvious that the minimum of congestion cost and absorbed merchant investment is zero. Also the planner should select its desirable satisfaction levels. Assume that the planner selects the following satisfaction levels (reference values) for each objective:

- $\mu_{r1} = 0.8$ for minimizing of investment cost
- $\mu_{r2} = 0.4$ for minimizing of congestion cost
- $\mu_{r3} = 0.8$ for maximizing absorbed Merchant investment

With the above reference levels and using the 2-norm method (p=2 in (16), the final solution could be obtained by applying the fuzzy satisfying method. This optimal solution is presented in Tables 1 and 2. Please note that above reference levels means that the planner is more concern about merchant investment than congestion cost. In the final solution, six new branches are proposed while four of them are profitable. Table II shows that the final solution needs \$18.1M investment while only the 23%

Table 1: Optimal Solution (New Propoosed Branches).

Stage 1	Stage 2	Stage 3
8-9	14-16, 6-8 and 16-17	1-5 and 2-6

Table 2: Overall Optimal Solution (Objective Values (Million $).

NPV of Investment Cost	NPV of Congestiont	NPV of Absorbed Merchant Investment
18.1	0.2	13.8

of this investment should be supplied by the regulatory entity (18.1-13.8 = $4.3M). For analyzing the performance of the proposed method, a double objective case optimization has been conducted considering only the investment cost and congestion cost. The results of this optimization are shown in Fig. 4. It can be seen that by increasing the investment, congestion cost will decrease steadily. Now, for comparing the results of both optimization, assume that the planner is interested in solutions with zero congestion cost i.e. a full competitive market. Analyzing the solutions represented in Fig. 3 and 4 shows that the minimum investment cost for a solution with zero congestion cost is as presented in Table 3 for triple and double objective cases. The results presented in Table 3 shows that with three objectives defined in (14), $16.2M of investment required to have a transmission network without any congestion while in double objectives case, the required investment cost is $13.6M. But in three objectives case, $5.7M of this investment will be absorbed from the private sector. In other words, the regulatory body (TransCo or RTO) should invest only 16.2-5.7=$10.5M while in the double objective case the regulator should invest 13.6 M$. Thus, the proposed strategy can save about $3.1M of the regulatory budget (13.6-10.5=$3.1M). This is a direct consequence of considering private sector objectives and requirements in the optimization model. Results presented in Table 3 shows that the required regulatory budget will decrease from $13.6M to $10.5M (30% saving) by considering the merchant investment in the planning process.

V CONCLUSIONS

In this paper, a new strategy for transmission expansion planning is proposed based on central planning approach with different objectives. In this study, the objective of the private sector, i.e. profitability of merchant transmission projects is formulated and incorporated in the planning process by applying a multi-objective optimization method. By applying a posterior method for solving this optimization, the proposed strategy can find out trade-offs between costs and benefits of alternative solutions. In contrast to the other methods presented in the literature, the proposed strategy considers both regulatory and private sector requirements in the planning process simultaneously. Minimization of Investment Cost and Congestion Cost and maximization of Absorbed Merchant Investment is used as objective functions in this study while other objectives or risk indices can easily be incorporated into the method. By defining a profitability index, the proposed method can search the solution space for finding the most profitable expansion projects. A specialized genetic algorithm (NSGA II) was used to solve the mathematical model of the expansion planning problem followed by a fuzzy decision making method for determining the best compromise solution which suits the planners preferences and requirements. The results obtained form the test system show the excellent performance of the proposed methodology. There are several ways for expanding the proposed algorithm such as incorporating risk analysis or probabilistic reliability assessment which is under development by the authors.

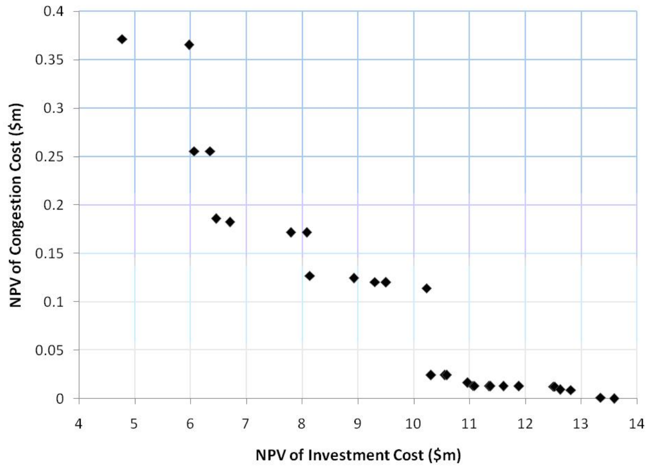


Figure 4: Trade-off between NPV of investment cost and Congestion Cost in double objectives case

Table 3: Fnal Solution with Zero Congestion Cost.

NPV Value (M$)	Three Objective Cases	Two Objective Case
Investment	16.2	13.6
Congestion	0.0	0
Absorbed Merchant	5.7	Not Applicable

VI APPENDIX

The symbols which were used in the paper, is illustrated in Table. A-1.

REFERENCES

[1] P. Maghouli, S. H. Hosseini, M. Oloomi and M. Shahidehpour, *" A Scenario-based multi-objective model for multi-stage transmission expansion planning,"* IEEE Trans. Power Systems, vol. 26, no. 1, pp. 470-478, Feb. 2011.

[2] P. Maghouli, S. H. Hosseini, M. Oloomi and M. Shahidehpour, *" A multi-objective framework for transmission expansion planning in a deregulated environment,"* IEEE Trans. Power Systems, vol. 24, no. 2, pp. 1051-1061, May 2009.

[3] W. Hogan, J. Rosellon and I. Vogelsang, *"Toward a combined merchant-regulatory mechanism for electricity transmission expansion,"* Journal of Regulatory Economics, vol. 38, no. 2, pp. 113-143, 2010.

[4] I. da Silva, R, Romero and C. A. Murari, *"Transmission Network Expansion Planning with Security Constraints,"* presented at the IEE Proc. On Generation, Transmission and Distribution, no.6, pp. 828-836, November 2005.

[5] H. Zhang, V. Vital, G.T. Heydt and J. Quintero, *"A mixed-integer linear programming approach for multi-stage security-constrained trans-*

Table A-1: List of Main Symbols.

Symbol	Quantity
c_{ij}	Cost of a circuit added to the right-of-way $i-j$.
n_{ij}	Number of new circuits added to the right-of-way $i-j$.
n^o_{ij}	Number of existing circuits in right-of-way $i-j$.
$\bar{n}_{ij}$	Maximum number of new branches which can be added to the right-of-way $i-j$.
t_y	Yearly time index.
t_h	Hourly time index.
T_0	Base year.
D	Annual discount rate.
T	Planning horizon.
CC	Congestion cost.
r_k	Curtailed load at bus k.
LC	Amount of load curtailment.
R_{ij}	Revenue rate of branch $i-j$ ($/MWh-Mile)
f_{ij}	Active power flow in a branch in the right-of-way $i-j$.
$\bar{f}_{ij}$	Maximum capacity of a branch in the right-of-way $i-j$.
γ_{ij}	Susceptance of a branch in right-of-way $i-j$.
C_i	Cost function of GENCO i.
B_j	Utility (benefit) function of DISCO j.
g_i	Amount of power generated by GENCO i.
d_j	Amount of power consumed by DISCO j.
$a_i,\ b_i$	Constants of bid function (incremental cost) of GENCO i.
n_g	Number of GENCOs.
n_d	Number of DISCOs.
μ_{ri}	Reference level of satisfaction of ith objective.
μ_{fi}	Satisfaction level of the ith objective.
Ω_l	Set of existing and new right-of-ways.
Ω_b	Set of load buses.
Ω_f	Set of profitable branches.
$\boldsymbol{s}$	Node-branch incidence matrix.
$\boldsymbol{f}$	Vector of active power flows.
$\boldsymbol{g}$	Vector of generated active powers.
$\boldsymbol{r}$	Vector of load curtailments.
$\boldsymbol{d}$	Vector of predicted loads.
Φ	Set of non-dominated solutions.
X	A solution (a combination of new branches to be added to the network).

mission expansion planning," IEEE Trans. Power Systems, vol. 27, no. 2, pp. 1125-1133, May 2012.

[6] R. Fang and D. J. Hill, *"A new strategy for transmission expansion in competitive electricity markets,"* IEEE Trans. Power Systems, vol. 18, no. 1, pp. 374-380, February 2003.

[7] CIGRE TF 38.05.10, *"Optimal network structure in an open market environment,"* November 2001.

[8] M. Oloomi, H. M. Shanechi, G. Balzer, M. Shahidehpour and N. Pariz, *"Network planning in unbundled power system,"* IEEE Trans. Power Systems, vol. 21, no. 3, pp. 1379-1387, August 2006.

[9] P. S. Martin, A. Ramos and J. F. Alonso, *"Probabilistic midterm transmission planning in a liberalized market,"* IEEE Trans. Power Systems, vol. 20, no. 4, pp. 2135-2142, November 2005.

[10] M. Rahmani, R. Romero and M.J. Rider, *"Strategies to reduce the number of variables and combinatorial search space for multistage transmission expansion planning problem,"* IEEE Trans. Power Systems, vol. 28, no. 3, pp. 2164-2173, August 2013.

[11] R. Fischer and K. S. Joo, *"Economic evaluation of transmission expansion for investment incentives in a competitive electricity market,"* International Journal of Control, Automation and systems, vol. 6, no. 5, pp. 627-638, Oct. 2008.

[12] H. Salzar, C. C. Liu and R. F. Chu, *"Market-based rate design for recovering merchant investment,"* IEEE Trans. Power Systems, vol. 25, no. 1, pp. 305-312, February 2010.

[13] P. Buijs and R. Belmans, *"Transmission investments in a multilateral context,"* IEEE Trans. Power Systems, vol. 27, no. 1, pp. 475-483, February 2012.

[14] Z. Xu, Z. Y. Dong and K. P. Wong, *"Transmission planning in a deregulated environment,"* presented at the IEE Proc. on Generation, Transmission and Distribution, no.3, pp. 326-334, May 2006.

[15] J. Pan, Y. Teklu, S. Rahman and K. Jun, *"Review of usage-based transmission cost allocation methods under open access,"* IEEE Trans. Power Systems, vol. 15, no. 4, pp. 1218-1224, November 2000.

[16] P. Joskow and J. Tirole, *"Merchant transmission investment,"* Journal of Industrial Economics, vol. 53, no. 2, pp. 233-264, Jun 2005.

[17] C. O. Ahiakwor, U. C. Chukwu and D. O. Dike, *"Optimal Transmission Line Pricing Algorithm for a Restructured Power System,"* presented at the Conf. PES, IEEE Press, April 2008.

[18] G. B. Shrestha and P. A. J. Fonseka, *"Optimal transmission expansion under different market structures,"* IET Generation, Transmission and Distribution, vol. 1, no.5, pp. 697-706, May 2007.

[19] M. Oloomi, G. Balzer, H. M. Shanechi and M. Shahidehpour, *"Market-Based Transmission Expansion Planning,"* IEEE Transaction on Power Systems, vol. 19, no. 4, pp. 2060-2067, November 2004.

[20] G. B. Shrestha and P. A. J. Fonseka, *"Congestion-driven transmission expansion in competitive power markets,"* IEEE Trans. Power Systems, vol. 19, no. 3, pp. 1658-1665, August 2004.

[21] NERC Planning Standard, 1997.

[22] R. A. Gallego, A. Monticeilli and R. Romero, *"Comparative studies on non-convex optimization methods for transmission network expansion planning,"* IEEE Trans. Power Systems, vol. 13, no. 3, pp. 822-828, August 1998.

[23] K. Deb, A. Pratap, A. Agarwal and T. Meyarivan, *"A fast and elitist multi-objective genetic algorithm: NSGA II,"* IEEE Trans. Evolutionary Computation, vol. 6, no. 2, pp. 182-197, April 2002.

[24] P. K. Shukla and K. Deb, *"On finding multiple pareto-optimal solutions using classical and evolutionary generating methods,"* European Journal of Operational Research, vol. 181, pp. 1630-1652, September 2007.

[25] A. H. Escobar, R. A. Gallego and R. Romero, *"Multistage and coordinated planning of the expansion of transmission systems,"* IEEE Trans. Power Systems, vol. 19, no. 2, pp. 735-744, May 2004.

[26] M. Sakawa and H. Yano, *"An interactive fuzzy satisfying method for multi-objective nonlinear programming problems with fuzzy parameters,"* Fuzzy Sets and Systems, vol. 30, no. 3, pp. 221-238, May 1989.

[27] M. Oloomi, H. M. Shanechi, G. Balzer, M. Shahidehpour and N. Pariz, *"Network planning in unbundled power system,"* IEEE Trans. Power Systems, vol. 21, no. 3, pp. 1379-1387, August 2006.

[28] E. E. Sauma and S. S. Oren, *"Economic criteria for planning transmission investments in restructured electricity markets,"* IEEE Trans. Power Systems, vol. 22, no. 4, pp. 1394-1405, November 2007.

[29] N. Alguacil, A. L. Motto and A. J. Conejo, *"Transmission expansion planning: a mixed-integer LP approach,"* IEEE Trans. Power Systems, vol. 18, no. 3, pp. 1070-1077, August 2003.

[30] Reliability test system task force of the application of probability methods subcommittee, *"IEEE Reliability Test System,"* IEEE Transactions on Power Apparatus and Systems, vol. PAS-98, no. 6, pp. 2047-2054, Nov./Dec. 1979.

Pouria Maghouli received the B.Sc, M.Sc and Ph.D. degrees in electrical engineering from Sharif University of Technology, Tehran, Iran, in 2001, 2004 and 2010 respectively. Currently he joined the Electrical Engineering Department of the Shahed University, Tehran, Iran.

His research interests include restructured power system planning and operation, smart grids and power system protection and security.

Seyed Ahmadreza Mousavimirkolaei received the B.Sc in electrical engineering from Sharif University of Technology in 2001 & M.Sc in industrial engineering from Khatam University in 2010. After graduation he joined Tablieh Construction Company as electrical manager. His research interests include power system economics, investment in infrastructure projects and financial instruments.