Probabilistic OPF Approach for Transmission Expansion Planning in Restructured Power Systems

M. Parsa Moghaddam, H. Abdi, and M. H. Javidi

***Abstract*—Transmission expansion planning (TEP) is one of the most important parts of expansion planning in power systems. Competition in these systems has resulted in essential changes in TEP models and criteria. While methods introduced so far are essentially based on dc load flow, the proposed method utilizes the ac optimal power flow (OPF) in order to model the real world condition and obtaining optimal plans. Furthermore, in order to model the operation and investment costs, transmission tariffs are used. Investigation on 8-bus system confirms the advantages of the proposed method as compared with previously presented approaches.**

***Index Terms*—Transmission expansion planning, competition, electricity market, probabilistic locational marginal price.**

NOMENCLATURE

ℓ	Line number between buses *q* and *r*
G	Set of generators
L	Set of lines
N	Set of network buses
C	Set of PQ buses
M , m	Indices for maximum and minimum limits
c_ℓ	Duration for construction of line ℓ [year]
g	General inflation
b	Profit factor, equal to 1.2
x_ℓ	Impedance of line ℓ [p.u.]
s	Sample number
K , t	Positive numbers [K is app. 100]
α	Variable coefficient
T_ℓ	Transmission tariff of line ℓ [$/MWh]
LMP_k	LMP at k th bus [$/MWh]
LMP_{ave}	Total mean value of LMPs [$/MWh]
σ_k	Standard deviation of pdf of LMPk [$/MWh]
σ^2	Variance of a defined pdf [$/MWh]
$C_i(P_{gi})$	Cost of generated power of bus i [$/h]
P_{gi} , Q_{gi}	Active and reactive generated powers at bus i [MW, MVar]
$P_{loss\,\ell}$	Loss of line ℓ at base case [MW]
P_{dk} , Q_{dk}	Active and reactive loads at bus k [MW, MVar]
$P_{flow\,\ell}$	Power flow of line ℓ [MW]
v_k	Voltage magnitude of bus k [p.u.]
δ_k	Voltage angle of bus k [rd]
AC_ℓ	Annual cost of line ℓ [$]
PVC_ℓ	Present value of construction for line ℓ [$]
PVL_ℓ	Present value of land for line ℓ [$]
PVO_ℓ	Present value of operation for line ℓ [$]
FCR_ℓ	Fixed charge rate of line ℓ
$FCRL_\ell$	Fixed charge rate of land for line ℓ
CRF_ℓ	Capital return factor for line ℓ
TE_ℓ	Total energy transmitted by line ℓ [MWh]
$LTEC_\ell$	Levelized transmitted energy cost for line ℓ [$/MWh]
Y_1, Y_2, Y	Random variables
U	Random number
Z	Normal random variable

I. INTRODUCTION

WORLD-WIDE focus on competition and open access transmission networks has resulted in restructuring of power systems. Different goals such as providing resources, increasing efficiency and customer choice have been considered in numerous countries and therefore, various strategies have been adopted [1], [2]. Power industry and its related aspects have experienced dominant changes, consequently. However, transmission networks, as the interfaces between generation and load sections, have preserved their monopolistic characteristics in most power systems. They play a vital role in order to facilitate competition in the generation and electricity retailing. While reliability and stability of a system as the most important features should be considered in TEP, the plan should also provide fair and no discriminatory access to the system for all consumers.

Furthermore, there are many differences between TEP in vertically integrated utilities (VIUs) and competitive environments. Some of these important differences are as follows:

- In vertically integrated systems, TEP is considered only as a part of general expansion planning for the whole integrated systems, while in competitive environments it is normally an isolated expansion planning for the transmission systems [3].
- Comparing deregulated power systems with vertically integrated ones, there are a lot of uncertainties in input data of the new systems. Therefore, TEP in these

Manuscript received May 27, 2006; revised March 12, 2007.

M. Parsa Moghaddam is with the Electrical Engineering Department, Tarbiat Modares University, Tehran, Iran (e-mail: parsa@modares.ac.ir).

H. Abdi is with the Electrical Engineering Department, Razi University of Kermanshah, Kermanshah, Iran (e-mail: hamdiabdi@gmail.com).

M. H. Javidi is with the Electrical Engineering Department, Ferdowsi University of Mashhad, Mashhad, Iran (e-mail: h-javidi@ferdowsi.um.ac.ir).

Publisher Item Identifier S 1682-0053(08)1514

systems should be robust against those uncertainties [4]-[5].

- In the new environments, transmission service pricing has more impact on TEP [6].

Different models for solving TEP have been proposed. Generally, planning models are classified into three different categories including mathematical, heuristic and meta-heuristic optimization models [4].

As the TEP problem is stated as a large-scale, non-linear and non-convex optimization problem, heuristic or meta-heuristic optimization algorithms should be applied. This is due to the fact that such algorithms can reach to better solutions as compared with those obtained through classical techniques [7]. Based on the above mentioned description, various methods such as multi-objective planning [8], fuzzy algorithm [9], cooperative game theory [10], multi-agent coalition formation [11], non-linear mixed integer programming [12], genetic algorithm (GA) [7], [13], and locational marginal price (LMP) [5], [14]-[17] have been proposed so far for TEP in competitive environments. It should be noted that due to uncertainties, most publications emphasize on probabilistic approaches for TEP in competitive environments [13], [18].

Since, the pricing system for purchasing and selling the electric energy in competitive markets is based on nodal pricing or LMP, therefore methods based on LMP, which model the real condition of these environments are of more importance. LMP is the price of supplying an additional MW of load at each bus in the system, considering generator and load bidding prices, the transmission system components experiencing congestion, losses and the electrical characteristics of the system.

Generally, the previous methods proposed for TEP in competitive markets have two drawbacks as follows [4]:

- The network modelling does not consider the ohmic losses. Although the dc load flow decreases the calculation time, but the accuracy of optimal plans decreases, seriously. Furthermore, the importance of finding optimal plans in the planning stage, justifies the long time of ac OPF calculations.
- The operation costs are not taken into account by the planning algorithm. Usually these costs are calculated a posterior considering a set of alternative plans that were selected.

In this paper the above mentioned weak points are eliminated in the TEP problem of competitive environments. The case study results show that the location of optimal plans will change in this case.

II. Fundamentals of the Proposed Method

Load, generation costs, bid of generators, power and bids of independent power producers (IPPs) are the main sources of random uncertainties in deregulated power systems. Probabilistic load flow (PLF) is used for modeling these uncertainties in regulated power systems. It models only the technical criteria. However, to achieve the objectives of TEP in deregulated power systems, market based criteria are needed in addition to the technical criteria. Also, to define and compute probabilistic market based criteria, it is need to calculate the pdfs of variables that market performance can be assessed by their analysis.

To facilitate a perfect and fair competition, electricity suppliers and consumers should have no constraint for bidding and offering the energy. Therefore, TEP in competitive electricity markets must encourage the competition and provide fair access to cheap generation.

A good approach to facilitate a fair competition is to expand the network in a way which flats the LMP profile as much as possible. Thus, flatting the LMP profile is selected as planning criterion.

In the proposed method, pdfs of LMPs in all network buses are calculated using OPF based on PLF. As a result, the pdfs of output variables are computed instead of their accurate values.

Then, the buses are divided into source and sink sets based on their LMP mean values. Those buses at which mean of LMPs are smaller than the LMP_{ave} are grouped in the source set and the rest are considered as the set of sink buses.

To reduce the number of lines nominated for expansion planning; only few buses among each of the above mentioned sets are selected to be connected through new lines. The criteria for choosing the nominated buses are as follows

- Buses in the source set

$$LMP_{ave} - LMP_k > \alpha\sigma_k \qquad (1)$$

- Buses in the sink set

$$LMP_k - LMP_{ave} > \alpha\sigma_k \qquad (2)$$

Finally, the option plan for expansion is characterized by new lines that should be constructed between any of the nominated buses from sink and source sets for flatting the LMP profile, as much as possible.

To specify the flatness of a price profile, some indices are defined. In a network with n buses, the pdf of LMPs have been computed for a given pdf for each input. Consider MLMP be a $1\times n$ vector such that its kth element is the mean of LMP at bus k, and VLMP be a $1\times n$ vector such that its kth element is the variance of LMP at bus k. The following parameters can be defined for determining the flatness of price profile [5].

- Mean of MLMP or LMP_{ave}: The less mean of MLMP indicates that cheaper generators are dispatched. This means a better condition for competition.
- Variance of MLMP: the smaller variance of MLMP indicates the flatter price profile and consequently better competition.
- Variance of VLMP: the smaller variance of VLMP indicates the more similar volatility of LMP at different buses and consequently the more similar risk in purchasing the power from different buses.

III. TEP Problem Formulation

To formulate the TEP problem in a competitive environment, important features should be simulated and considered in their mathematical forms. The most important parameters are as follows

A. Uncertainties

Generation bid prices and load quantities are the major input uncertainties which have been modelled as normal pdfs.

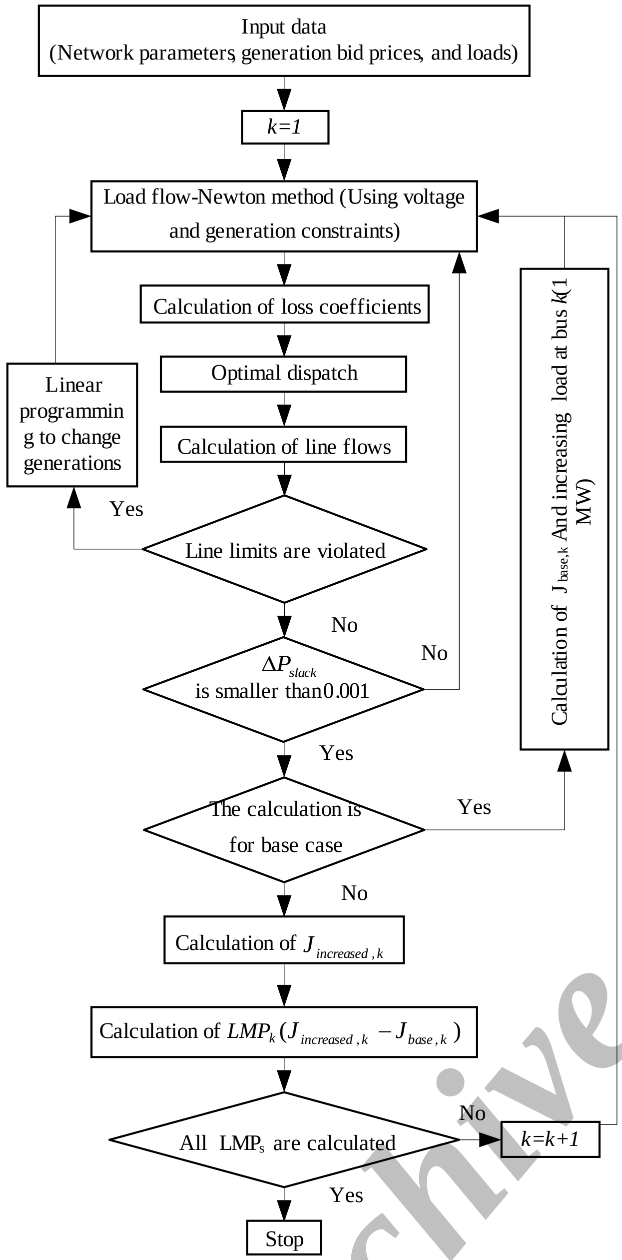

Fig. 1. General structure of the proposed OPF for calculating LMPs.

B. Probabilistic LMP

As explained before, probabilistic LMPs are estimated using PLF. In fact, LMPs are calculated in their probabilistic forms using OPF. To do this, the objective function of costs including generation bids and transmission costs based on transmission tariffs is minimized subject to load, voltage and generation constraints. The objective function and AC OPF are modeled as follow.

$$\text{Min} J_k = \sum_{i=1}^{G} C_i (P_{gi}) + \sum_{\ell=1}^{L} T_\ell P_{flow\ \ell} \tag{3}$$

S.T:

$$\sum_{i=1}^{G} P_{gi} - \sum_{\ell=1}^{L} P_{loss\ \ell} - \sum_{k=1}^{N} P_{dk} = 0 \tag{4}$$

$$P_{gi} - P_{di} - P_i(v, \delta) = 0 \qquad i \in N \tag{5}$$

$$Q_{gi} - Q_{di} - Q_i(v, \delta) = 0 \qquad i \in C \tag{6}$$

$$P_{gi}^m \le P_{gi} \le P_{gi}^M \tag{7}$$

$$Q_{gi}^m \le Q_{gi} \le Q_{gi}^M \tag{8}$$

$$\left| P_{flow\ \ell} \right| < P_{flow}^M \tag{9}$$

$$v_k^m \le v_k \le v_k^M \tag{10}$$

$$\delta_k^m \le \delta_k \le \delta_k^M \tag{11}$$

It should be noted that (4) as the loss equation can be written in terms of voltage and angle. However, presentation of this equation as an individual relation is only for emphasizing on its importance in the proposed model.

General structure of the proposed OPF for calculating LMPs is presented in Fig. 1. Its main features are as follows

Modeling line resistance and transmission tariffs in LMP calculations.

LMP_k is calculated by subtracting base case cost from increased cost ($J_{increased,k}$ - $J_{base,k}$), instead of using differentiation function, which is very complex, when the AC OPF is used.

Using the well known loss coefficient method developed by Kron and adopted by Kirchmayer for loss calculation [19].

Using the linear programming based on utilizing generation shift factors for adjusting flows in overloaded lines [20]

C. Transmission Tariffs

Justification of costs is very important in competitive environments. Therefore, transmission costs must be taken into account. In this paper for modelling the construction, operation, and maintenance costs of transmission lines, transmission tariffs are used. Transmission tariff is calculated according to the levelized transmitted energy cost (LTEC) as follows.

$$AC_\ell = (1+g)^{c_\ell} (PVC_\ell FCR_\ell + PVL_\ell FCRL_\ell + PVO_\ell CRF_\ell) \tag{12}$$

$$TE_\ell = 8760\ P_{flow\ \ell}^M \tag{13}$$

$$LTEC_\ell = \frac{AC_\ell}{TE_\ell} \tag{14}$$

$$T_\ell = b\ LTEC_\ell \tag{15}$$

At first, the annual cost of line ℓ is calculated using (12) based on economic parameters. Then, $LTEC_\ell$ is calculated dividing the annual cost by total energy transmitted for line ℓ. Finally, the transmission tariff for line ℓ is obtained using (15).

IV. The Proposed Algorithm

The proposed algorithm for TEP in competitive electricity markets is depicted in Fig. 2.

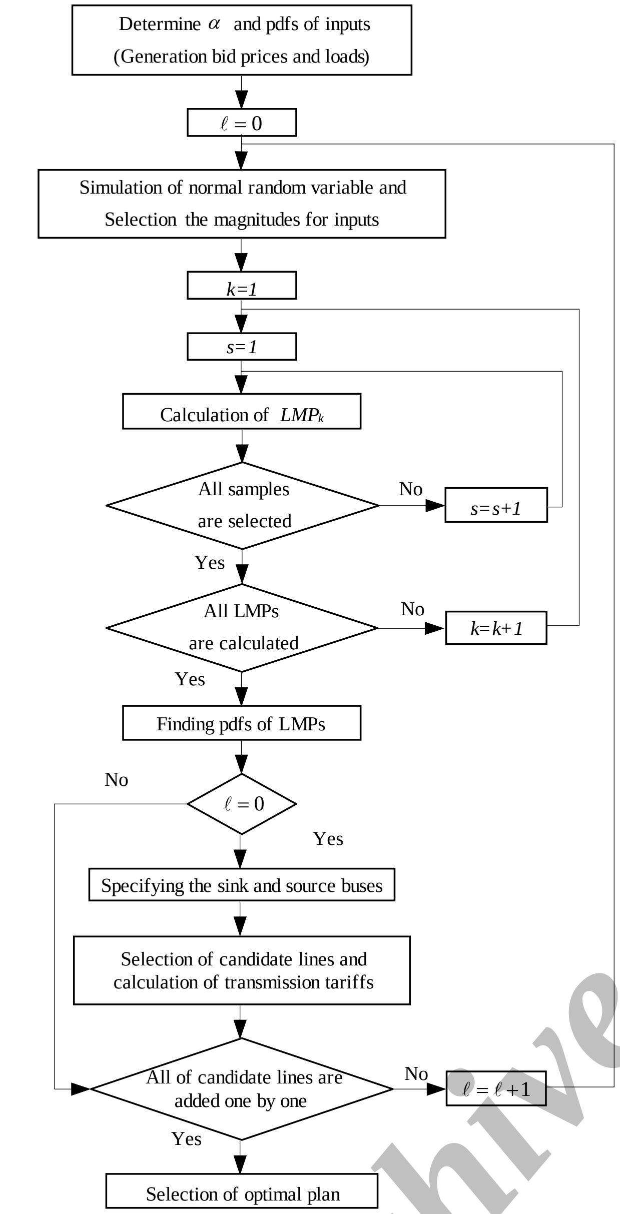

Fig. 2. Flowchart of the proposed algorithm.

It should be noted that the algorithm is continued till the mean value of LMP of each bus is converged to a limit value. Therefore, the number of samples is variable with a range from 150 to 500.

Also, simulating normal random variables and selecting the magnitudes for input pdfs are performed applying the method as described in [21].

V. Case Study

The proposed algorithm has been applied to a typical 8-bus and standard IEEE 30 bus networks [5], [22]. The 8-bus network structure and its related parameters are presented in Appendix. However, R and X parameters of the lines have been modified to be more realistic. Also, the related parameters of IEEE 30 bus network are presented in [22].

A. 8- Bus Network

Using the random generated samples from the pdfs of loads and generation bid prices, MLMP and VLMP vectors, and LMP_{ave} for the base case are found in \$/MWh as follows:

$$MLMP = [18.905\ 24.531\ 18.629\ 22.082\ 17.233\ 18.354\ 23.149\ 25.326]$$

$$VLMP = [10.100\ 10.782\ 12.607\ 8.9144\ 12.505\ 9.727\ 13.426\ 14.815]$$

$$LMP_{ave} = 21.0261$$

By comparing MLMP values at any bus in the network with LMP_{ave}, the sink and source buses and therefore, candidate lines are specified.

- Set of source buses $\{1,\ 3,\ 5,\ 6\}$.
- Set of sink buses $\{2,\ 4,\ 7,\ 8\}$.
- Transmission line candidates

$$\{1\text{-}2, 1\text{-}4, 1\text{-}7, 1\text{-}8, 3\text{-}2, 3\text{-}4, 3\text{-}7, 3\text{-}8, 5\text{-}2, 5\text{-}4, 5\text{-}7, 5\text{-}8, 6\text{-}2, 6\text{-}4, 6\text{-}7, 6\text{-}8\}$$

Finally, based on the proposed algorithm, the optimal candidate lines for expansion are specified as $\{1\text{-}8,\ 3\text{-}4,\ 5\text{-}4 \text{ and } 6\text{-}8\}$ (Table I).

It should be considered that as much as α is smaller, the candidate set of expansion buses will be bigger (Table II).

B. IEEE 30 Bus Network

Using the described method, MLMP and VLMP vectors, and LMP_{ave} for the base case are found in \$/MWhr as:

$$MLMP = [18.09\ 18.87\ 14.26\ 20.69\ 13.58\ 21.32\ 14.58\ 15.12\ 23.42\ 18.11\ 22.34\ 15.94\ 16.24\ 12.79\ 15.30\ 18.75\ 24.30\ 20.58\ 22.72\ 16.83\ 16.93\ 24.82\ 19.75\ 21.11\ 20.63\ 30.66\ 19.38\ 23.34\ 23.17\ 27.94]$$

$$VLMP = [12.02\ 10.43\ 17.98\ 13.45\ 23.53\ 15.92\ 18.72\ 16.82\ 14.16\ 12.65\ 12.24\ 25.63\ 12.98\ 25.89\ 16.98\ 19.62\ 14.97\ 12.80\ 16.92\ 27.07\ 27.90\ 15.07\ 12.09\ 25.98\ 26.09\ 26.98\ 17.01\ 29.42\ 17.09\ 29.81]$$

$$LMP_{ave} = 19.7233$$

- Set of source buses

$$\{1,\ 2,\ 3,\ 5,\ 7,\ 8,\ 10,\ 12,\ 13,\ 14,\ 15,\ 16,\ 20,\ 21,\ 27\}$$

- Set of sink buses

Error! Objects cannot be created from editing field codes.

- Transmission line candidates

$\{1\text{-}4,\ 1\text{-}6\ ,...,27\text{-}30\}$. This set has 225 members.

Finally, based on the proposed method, the optimal candidate lines for TEP are found as:

$$\{1\text{-}24,\ 2\text{-}19,\ 3\text{-}18,\ 5\text{-}26,\ 7\text{-}25,\ 8\text{-}11,\ 10\text{-}23,\ 12\text{-}6,\ 13\text{-}19, 14\text{-}28,\ 15\text{-}17,\ 16\text{-}30,\ 20\text{-}23,\ 21\text{-}17,\ 27\text{-}11\}$$

To investigate the validity of the proposed algorithm, all possible candidates in the 8- bus network are selected in another approach without applying any screening procedure (Table I). The results confirm that none of the optimal candidates are among those filtered candidates. The major conclusions of the proposed method are as follows:

TABLE I
FINAL RESULTS

Line	Mean of MLMP ($/MWh)	Variance of MLMP ($/MWh)	Variance of VLMP ($/MWh)
1-2	20.9538	3.9800	49.5549
1-4	20.9925	3.9086	4.8503
1-7	21.0588	4.9366	6.6343
1-8	20.9125	3.8316	2.0108
3-2	21.1863	3.8372	7.6887
3-4	20.6038	3.9237	4.4382
3-7	21.5088	4.4816	42.9999
3-8	20.7663	4.8428	10.6796
5-2	20.3250	2.7620	3.6992
5-4	20.2713	2.8295	2.0665
5-7	20.8450	3.9317	1.5732
5-8	20.4113	2.2360	0.8331
6-2	20.9863	3.1817	3.4456
6-4	21.3688	4.2670	4.1954
6-7	21.0525	4.1499	2.2607
6-8	20.5338	2.7085	0.9166
Other feasible candidate lines			
1-3	21.8143	5.2022	1.0007
1-5	21.9547	5.0124	8.0076
1-6	21.0207	4.5565	13.8966
2-4	21.6741	5.4219	0.4531
2-7	21.6109	5.3909	0.2233
2-8	21.6573	5.1677	0.3987
3-5	21.4084	4.8034	1.2227
3-6	21.6183	5.0499	2.1217
4-7	21.0039	3.2660	44.5071
4-8	21.5231	6.5671	13.9812
5-6	21.3273	4.1896	0.4850
7-8	21.9871	6.9801	10.2214

TABLE II
DIFFERENT VALUES OF α AND OPTIMAL OPTIONS FOR TEP

α		0.0	0.25	0.50	0.75	1.0
Sink buses	All feasible candidates	1, 3, 5, 6	1, 3, 5, 6	1, 3, 5, 6	5, 6	5
Source buses		2, 4, 7, 8	2, 4, 7, 8	2, 7, 8	2, 8	2
Candidate lines	28	16	16	12	4	1
Optimal options for each sink bus	1-8, 3-4, 5-4, 6-8	1-8, 3-4, 5-4, 6-8	1-8, 3-4, 5-4, 6-8	1-8, 3-8, 5-2, 6-8	5-2, 6-8	5-2

TABLE III
LOADS DATA (PF=0.95)

Load No.	Bus No.	Load (MW)(μ , σ^2)
1	2	(300, 10)
2	3	(300, 12)
3	4	(300, 15)
4	6	(300, 5)
5	8	(250, 9)

optimal candidates are among those filtered candidates. The major conclusions of the proposed method are as follows:

Comparing the results with those which are obtained by previous algorithms [5], it can be observed that considering ac OPF and transmission tariffs, change not only the LMP values but also the final optimum plans. Furthermore, simplifying the models chosen for optimization procedure will result in finding sub-optimal or even non-optimal solutions.

Choosing appropriate values for α and number of samples, the calculation time can be reduced significantly, while it does not affect the final solutions. According to

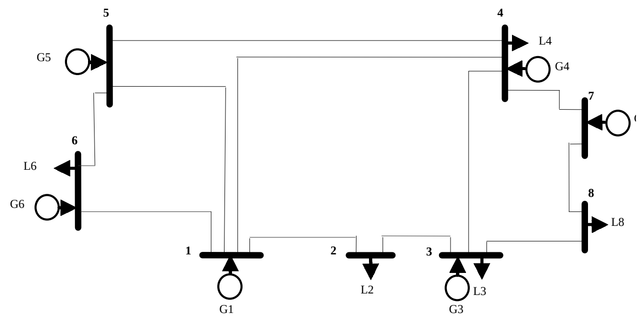

Fig. 3. Case study network.

TABLE IV
GENERATORS DATA

Gen. No.	Bus No.	P_{max} (MW)	Q_{max} (MVAr)	Bid ($/MWh)
1	1	100	50	(15, 1.8)
2	3	520	300	(30, 1.5)
3	4	250	150	(30, 2)
4	5	600	400	(10, 3)
5	6	400	200	(20, 2.1)
6	7	200	150	(20, 1.5)

TABLE V
ECONOMIC PARAMETERS

Description	Qty. for 1 sample line 230 kV
Construction cost of line	50,000 $/Km
Price of land	25,000 $/Km in width of right of way
Operation cost of line	1,000 $/Km per year
Inflation rate	0.15
Duration for line construction	1 Year

TABLE VI
LINES DATA (R, X IN P.U. ON 100 MVA BASE)

Line	R(p.u.)	X(p.u.)	Limit (MW)	Tariff ($/MWh)
1-2	0.01675	0.06750	400	1.236
1-4	0.01122	0.09520	190	1.014
1-5	0.01340	0.05400	390	1.014
2-3	0.02364	0.09864	130	1.825
3-4	0.01770	0.12000	230	1.289
4-5	0.01340	0.11260	330	1.198
5-6	0.00680	0.05134	350	0.960
6-1	0.02400	0.15280	250	1.582
7-4	0.03480	0.22156	250	2.293
7-8	0.00800	0.06040	340	1.163
8-3	0.03240	0.20628	240	2.224

calculations, the most suitable number of samples is around 250 and the best quantity for α is about 0.25.

Partial changes in some parameters such as power and profit factors may lead to essential changes in LMPs profile and consequently in final optimum plans.

It should be noted that a complete discussion on the numerical results of both case study models are presented in [22].

VI. CONCLUSIONS

Expansion planning for networks in competitive environments relies seriously on parameters which are not deterministic. In such power systems, there may be many uncertainties about load and generation in the network. Therefore, probabilistic and heuristic methods instead of classic approaches may be applied to get better solutions.

In this paper a new algorithm for TEP has been proposed. While the method uses pdfs of the parameters

TABLE VII
CANDIDATE LINES DATA

Line	R(p.u.)	X(p.u.)	Limit (MW)	Length (km)	Tariff ($/MWh)
1-3	0.03757	0.25370	140	330	4.689
1-7	0.03600	0.22840	185	400	4.275
1-8	0.03015	0.25200	190	450	4.683
2-4	0.01273	0.10697	200	190	1.878
2-5	0.02345	0.09450	390	250	1.267
2-6	0.02100	0.19985	185	350	3.740
2-7	0.02111	0.08505	400	315	1.557
2-8	0.03540	0.22710	140	300	4.237
3-5	0.01822	0.15232	190	270	2.830
3-6	0.03240	0.21636	180	360	3.954
3-7	0.02950	0.18925	140	250	3.351
4-6	0.02700	0.17460	180	300	3.259
4-8	0.02310	0.19600	190	350	3.642
5-7	0.03600	0.22840	185	400	4.275
5-8	0.02700	0.25695	320	450	2.780
6-7	0.09850	0.40950	225	500	4.394
6-8	0.03600	0.23920	180	200	2.197

instead of their accurate values, the priority criteria for the expansion plan is based on LMPs at different buses. This is due to the fact that as much as LMP values are uniform in a network, the competition is more fair and non-discriminatory.

The investigation confirms that modelling ac OPF and transmission tariffs in the TEP problem of competitive environments changes the optimal plans, basically. Also, while the method benefits acceptably calculation time, the results are reliable and optimal.

APPENDIX

Network Data

The data of the case study network which is depicted in Fig. 3 are presented in Table III to Table VII.

REFERENCES

[1] L. Philipson and H. L. Willis, *Understanding Electric Utilities and Deregulation*, Marcel Dekker Inc., New York, USA. 1999.

[2] G. Rothwel and T Gomez, *Electricity Economics: Regulation and Deregulation*, IEEE Press, 2003.

[3] H. Kim, S. Moon, J. Choi, C. Lee, J. Wang, and R. Billinton, "Transmission system expansion planning of KEPCO system using fuzzy set theory," in *Proc. Power Engineering Society Summer Meeting*, vol. 1, pp. 535-540, 2002.

[4] G. Latorre, R. D. Cruz, J. M. Areiza, and A. Villegas, "Classification of publication and models on transmission expansion planning," *IEEE Trans. Power Systems*, vol. 18, no. 2, pp. 938-946, May 2003.

[5] M. O. Buygi, H. M. Shanechi, and M. Shahidepour, "Transmission planning in deregulated environments," *Int. J. of Eng., Trans. A: Basics*, vol. 15, no. 3, pp. 245-255, Sep. 2002.

[6] J. G. Slootweg, "Applicability of engineering design concepts to power system planning and operation," in *Proc. Int. Conf. on Electric Utility Deregulation and Restructuring and Power Technology*, pp. 566-571, 2000.

[7] H. A. Gill and E. L. Silva, "A reliable approach for solving the transmission network expansion planning problem using genetic algorithms," *Electric Power Systems Research*, vol. 58, no. 1, pp. 45-51, May 2001.

[8] Z. A. Styczynski, "Power network planning using game theory," in *Proc. IEEE Electrical and Computer Engineering*, vol. 1, pp. 607-613, 1990.

[9] H. Sun and D. C. Yu, "A multiple objective optimization model of transmission enhancement planning for independent transmission company," in *Proc. IEEE Power Engineering Society Transmission and Distribution Conf.*, pp. 2033-2038, *2002*.

[10] J. Contreras and F. F. Wu, "Coalition formation in transmission expansion planning," *IEEE Trans. Power Systems*, vol. 14, no. 3, pp. 1142-1152, Aug. 1999.

[11] J. Yen, Y. H. Yan, B. J. Wang, P. K. H. Sin, and F. Wu, "Multi agent coalition formation in power transmission planning," in *Proc. IEEE Electrical and Computer Engineering Conf.*, vol. 4, pp. 433-443, Jan 1998.

[12] 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, Feb. 2003.

[13] T. Torre, J. W. Feltes, T. Gomez, and H. M. Merril, "Deregulation, privatization and competition: transmission planning under uncertainty," *IEEE Trans. Power Systems*, vol. 14, no. 2, pp. 460-465, May 1999.

[14] L. Chen, H. Suzuki, T. Wachi, and Y. Shimura, "Components of nodal prices for electric power systems," *IEEE Trans. Power Systems*, vol. 17, no. 1, pp.41-49, Feb.2002.

[15] L. Chen, Y. Tada, H. Okamoto, R. Tanabe, and A. Ono, "Optimal operation solutions of power systems with transient stability constraints," *IEEE Trans. Circuits and Systems-I*, vol. 48, no. 3, pp. 327-339, Mar. 2001.

[16] Y. Y. Hong and C. Y. Hsiao, " Locational marginal price forecasting in deregulated electric markets using a recurrent neural network," in *Proc. Power Engineering Society Winter Meeting*, vol. 2, pp. 539-544, 2001.

[17] Y. Y. Hong and C. Y. Hsiao, "LMP forecasting in deregulated electricity markets using artificial intelligence," *IEE Proc. on. Generation, Transmission and. Distribution*, vol. 149, no. 5, pp. 621-626, Sep. 2002.

[18] X. Y. Chao, X. M. Feng, and D. J. Slump, "Impact of deregulation on power delivery planning," in *Proc. IEEE Power Engineering Society Transmission and Distribution Conf.*, vol. 1, pp. 340-344, Apr. 1999.

[19] H. Saadat, *Power System Analysis*, McGraw-Hill, New York, US, 1999.

[20] A. J. Wood and B. F. Wollenberg, *Power Generation Operation and Control*, John Wiley & Sons, New York, US, 1974.

[21] S. M. Ross, *First Course in Probability*, Prentice Hall, New York, US, 2002.

[22] H. Abdi, *Transmission Expansion Planning Based on Competitive Electricity Markets*, Ph.D. Thesis, Faculty of Engineering, Tarbiat Modares University, Tehran, Iran, 2006.

M. Parsa Moghaddam received his B.Sc. degree from Sharif University of Technology, Tehran, Iran in 1980, M.Sc. degree from Toyohashi University of Technology, Japan in 1985; and Ph.D. degree from Tohoku University, Japan in 1988 all in Electrical Engineering.

Currently, he is an Associate Professor in the Department of Electrical Engineering, Tarbiat Modares University, Tehran, Iran.

He is a member of IEEE Power Engineering Society and his research interests include power system planning and control, optimization and restructuring.

H. Abdi received his B.Sc. degree from Tabriz University, Tabriz, Iran in 1995, M.Sc. and Ph.D. degrees from Tarbiat Modares University, Tehran, Iran in 1999, and 2006 all in Electrical Engineering.

Currently, he is an Assistance Professor in the Department of Electrical Engineering, Razi University, Kermanshah, Iran.

His research interests include power market simulation, transmission expansion planning and design of electrical and control systems for industrial plants.

M. H. Javidi received his B.Sc. degree in Electrical Engineering from Tehran University, Tehran, Iran in 1980, M.Sc. degree from Nagoya University, Japan in 1985; and Ph.D. degree from McGill University, Montreal, Canada in 1994.

He is an associate professor in the Department of Electrical Engineering, Ferdowsi University of Mashhad, Mashhad, Iran. He is also a member and the secretary of the regulatory board for electricity in Iran.

His research interests include power system operation and planning, restructuring and market design, and Artificial Intelligence.