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Study of Transmission Expansion Planning with Security Considerations and High Penetration of Wind Energy

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Abstract: Transmission Network Expansion Planning (TNEP) is one of the major components of the electric power industry. In the deregulated power systems, transmission systems provide the required environment for the competition among the power market participants. In this paper a mathematical model and a methodology are presented to solve the TNEP problem with security consideration and high penetration of wind energy and uncertainties such as load and bid of producers in deregulated electricity markets. In proposed model construction cost of new network, congestion cost, paid cost of unsupplied energy and also the cost of security has been considered. Considering the cost of operation in normal mode and also observing the loading rate limits on generators at event are the benefits of proposed method. To expand the transmission network a sample test system with use of appropriate optimization methods in the presence of wind energy and network uncertainties are considered. In this context we will choose the best scenario in terms of economic and technical consideration to be introduced. The Planning methodology has been demonstrated on the modified IEEE 24-bus test system to show the feasibility and capabilities of the proposed algorithm.

Index Terms: Genetic Algorithm, Monte Carlo simulation, multi objective optimization, NSGA II, transmission expansion planning, wind power.

1. Introduction

Restructuring in the power networks imports new objectives and requirements in TNEP. Separation of generation and transmission sector cause an increase uncertainty at input data to TNEP. In general the purpose of TNEP is to provide a network development plan to meet economical power so that the plan maintain or improve the level of network reliability. The purpose of meeting economical power is to minimize investment costs of lines and to go beyond restrictions of transmission network in economic operation of power grid. In the past, economical operation in power grid meant minimizing production cost and in deregulated power grids it mean to create a competitive market to exchange electric energy. If the transmission network is not developed adequately, competition which is the main characteristics of electricity markets is failed. The primary goal of TEP in power systems is to determine an optimal strategy to expand the existing transmission network to meet the demand of possible load growth and the proposed generators, while maintaining reliability and security performance of the power system. The commonly used objective function for TEP is to maximize the social welfare. Deregulation of power system has introduced new objectives and requirements for transmission expansion planning problem. Also, the unbundling of electricity industry introduced new approaches like competition in market. Under these circumstances there is an emerging need for new planning models to cope with restructured electricity industry requirements. In this paper a new model is developed based on optimization process which can consider different stakeholders' objectives and requirements. So the contributions of this paper include is a mathematical model which account of adequacy-security among market

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participants to solve a multi-stage planning problem. Based on Locational Marginal Prices (Lmps), a complete planning framework is proposed including the investment cost, congestion cost and the network adequacy-security considerations. In this paper, first the methods of TNEP is reviewed then the uncertainty in the power system is defined and modeling of wind energy and its effects on the amount of local marginal prices (LMP) are considered and has been applied appropriate model for TNEP with multi-objective and methods to solve it. A complete planning framework is presented and a TNEP is performed on the IEEE 24-bus test system.

2. Overview of Transmission Expansion Planning

TNEP primarily should to determine, when, where and what kind of new lines or transformers should be constructed to minimize operation and investment costs in a given period.

Answering these questions leads to a non-linear and non-convex optimization that variety of methods has been used to solve it. The applied methods for solving TNEP is divided into two categories:

A. Mathematical optimization models

The mathematical optimization models find an optimum expansion plan by using a calculation procedure that solves a mathematical formulation of the problem. Due to the impossibility of considering all aspects of the TNEP problem, the plan obtained is the optimum only under large simplification and should be technically, financially and environmentally verified, among other examination, before the planner makes a decision [1].

Several methods have been proposed to obtain the optimum solution for TNEP problem, mostly using classical optimization techniques like linear programming [2], dynamic programming [3], non-linear programming [4] and mixed integer programming [5].

Usually, big practical obstacles appear to obtain the “optimal” solution when mathematical optimization techniques are used for solving the TNEP, which is non-linear and non-convex in nature [1].

B. Heuristic optimization models

The heuristic methods are the current alternative to the mathematical optimization models. The term ”heuristic“ is used to describe all those techniques that, instead of using a classical optimization approaches, go step-by-step generating, evaluating and selecting expansion options, with or without the user’s help. However, they cannot guarantee in an absolute way, mathematical speaking, the “optimal” transmission expansion. The TNEP has been solved using heuristic models, for example, game theory [6], simulated annealing [7], genetic algorithm [8], expert systems [9] and fuzzy set theory [10].

Detailed description of the proposed algorithms can be seen in [1].

Transmission expansion planning approaches can be classified from different viewpoints. From the viewpoint of power system uncertainties, transmission expansion planning approaches can be classified in:

- Deterministic
- Non-deterministic

In deterministic approaches the expansion plan is designed only for the worst cases of the system without considering the probability of occurrence (degree of occurrence) of them. In non-deterministic approaches the expansion plan is designed for all possible cases which may occur in future with considering the occurrence probability of them. Hence, Non-deterministic approaches are able to take into account the past experience and future expectations.

Uncertainties can be classified in two categories:

- Random
- Non-random uncertainty

Random uncertainties are deviation of those parameters which are repeatable and have a known probability distribution. Hence, their statistics can be derived from the past observations. Uncertainty in load is in this category. Non-random uncertainties are evolution of parameters which are not repeatable and hence their statistics cannot be derived from the past observations. Uncertainty in generation expansion is in this category. Besides the uncertainties, there are imprecision and vague data in expansion planning. Imprecision and vague data are the data which can not be clearly expressed. Importance degree of different criteria in multi objective planning falls in this category.

From the viewpoint of power system horizons, transmission expansion planning approaches can be classified in:

- Static
- Dynamic

In static planning, only a single time period is considered as a planning horizon. In contrast, dynamic planning considers the planning horizon by separating the period of study into multiple stages. for static planning, the planner searches for an appropriate number of new circuits that should be added into each branch of the transmission system and in this case, the planner is not interested in scheduling when the new lines should be constructed and the total expansion investment is carried out at the beginning of the planning horizon. Many research works regarding the static TNEP are presented in [11]-[21] that are solved using a variety of the optimization techniques.

In contrast, time-phased or various stages are considered in dynamic planning while an optimal expansion schedule or strategy is considered for the entire planning period. Thus, multi-stage transmission expansion planning is a larger-scale and more complex problem as it deals with not only the optimal quantity, placement and type of transmission expansion investments but also the most suitable times to carry out such investments. Therefore, the dynamic transmission expansion planning inevitably considers a great number of variables and constraints that consequently require enormous computational effort to achieve an optimal solution, especially for large-scale real-world transmission systems. Many research works regarding the dynamic TNEP [22]-[25] have presented some of the dynamic models that have been developed.

From the viewpoint of power system structures, transmission expansion planning approaches can be classified in:

- Regulated
- Deregulated power systems

The main objective of expansion planning in regulated power systems is to meet the demand of loads, while maintaining reliability and service quality of power system. In this environment uncertainty is low but in deregulated power system The main objective of expansion planning is competition among market actors. In this environment uncertainty is high. Many models presented for TNEP problem, in addition to the investment cost, operation cost of network that obtained from optimal power flow, can be considered. Obviously, considering the cost of potential outages caused by probable events in objective function with existing uncertainty existing in system makes a perfect model.

3. Wind Energy Model

Wind generation levels are growing in power systems around the world in response to increase pressure to reduce CO_2 levels and dependence on fossil fuels.

Nowadays in many countries, wind energy as a promising and popular source of electrical energy has been considered a substitution candidate for conventional fossil energy resources. Wind power is expected to have a significant portion in total electrical energy production for the years to come [26]. In countries where this energy could not yet find its place in electrical industry, there is a trial to develop it using the incentive policies such as Renewable Portfolio Standard (RPS). Renewable policies such as fixed tariff in countries such as Germany, Denmark and Spain have made rapid progress of this energy [27].

With increment in the penetration of wind energy in power systems, the necessity of considering its impacts on transmission expansion planning studies, especially for large scale wind farms, is inevitable.

Changeability and uncontrollability in wind farm generation and being far from the demand center can be recounted as the biggest obstacles for efficient use of the wind energy. Due to the intermittent and stochastic nature of wind resource, wind energy brings great challenges to power system operation and planning [27]. One of the impediments to large-scale use of wind generation within power system is its variable and uncertain real-time availability. Due to the low marginal cost of wind power, its output will change the merit order of power markets and influence the Local Marginal Price (LMP). For the large scale of wind power, LMP calculation can't ignore the essential variable and uncertain nature of wind power.

Wind speed affects the output of wind turbine generator and it fluctuates significantly during the operating period of wind turbine generators. Due to unsteady wind speed, the power output of wind turbine generator may vary between zero to its rated output and hence leads to fluctuations in the power flow in the network. As both accurate wind speeds and precise WTG outputs are difficult to forecast, they can be better modeled probabilistically. Weibull distributions have been widely used to represent the wind speed [28], [29]. the shape parameter and scale parameter of the distribution function can be derived from the mean and standard deviation of wind speed [30].

The probability density function of wind speed at a certain location is generally described by a Weibull distribution, as in (1):

$$f_U(U) = \begin{cases} 0 & U < 0 \\ \frac{K}{C}\left(\frac{U}{C}\right)^{K-1} e^{-\left(\frac{U}{C}\right)^K} & U \geq 0 \end{cases} \tag{1}$$

According to [2], [3] parameters are obtained from the mean value and variance value of wind speed.

$$\mu_U = C\Gamma\left(1+\frac{1}{K}\right) \tag{2}$$

$$\sigma_U^2 = C^2\left[\Gamma\left(1+\frac{2}{K}\right)-\left[\Gamma\left(1+\frac{1}{K}\right)\right]^2\right] \tag{3}$$

According to [31], the Rayleigh distribution can be used as an alternative, by fixing $K = 2$. Under this assumption, the mean value of the wind speed is easily obtained, as in (4):

$$\mu_U = \frac{\sqrt{\pi}}{2}C \tag{4}$$

According to [30], the power curve of a wind turbine can be modeled by means of a function split into four different parts, such as in (5):

$$P = \begin{cases} 0 & U \le U_{CI} \\ P_R \dfrac{U^2 - U_{CI}^2}{U_R^2 - U_{CI}^2} & U_{CI} < U \le U_R \\ P_R & U_R < U \le U_{CO} \\ 0 & U_{CO} < U \end{cases} \tag{5}$$

In Figure 1, function of output power of wind turbine for 20000 random wind speed with Rayleigh distribution is given and in Figure 2 its probability density function is shown.
For a wind farm, which is composed of n wind turbines, it can be written as in (6):

$$\begin{aligned} P_R \mid_{WF} &= nP_R \mid_{WT} \\ U_{CI} \mid_{WF} &= U_{CI} \mid_{WT} \\ U_R \mid_{WF} &= U_R \mid_{WT} \\ U_{CO} \mid_{WF} &= U_{CO} \mid_{WT} \end{aligned} \tag{6}$$

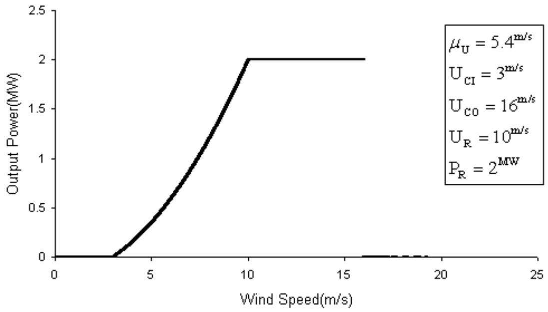


Figure 1. Output power of a wind turbine.

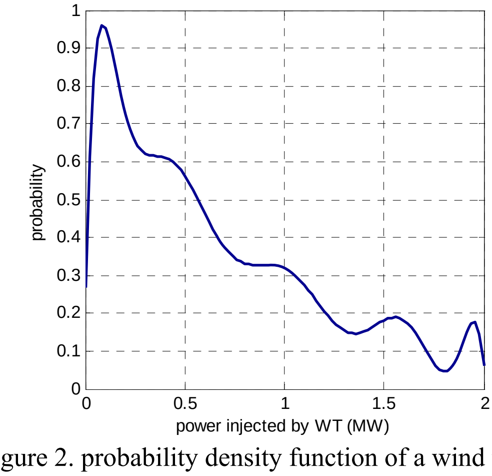


Figure 2. probability density function of a wind turbine.

4. Monte Carlo Simulation

Monte Carlo is the art of approximating an expectation by the sample mean of a function of simulated random variables [32]. Consider a random variable X having probability mass function or probability density function $P(X)$ which is greater than zero on a set of values χ. if X is discrete, then the expected value for target function $F(X)$ of X is:

$$E(F) = \sum_{x \in \chi} F(x)P(x) \tag{7}$$

Now, if we were to take an *n*-sample of $X's$, $(x_1, x_2, ..., x_n)$, and we computed the mean of $F(X)$ over the sample, then we would have the Monte Carlo estimate of $E(F)$:

$$E(F) = \frac{1}{N}\sum_{i=1}^{N} F(x_i) \tag{8}$$

Also we would have the estimate of variance of $F(X)$:

$$V(E(F)) = \frac{1}{N-1}\sum_{i=1}^{N}(F(x_i) - E(F))^2 \tag{9}$$

Except for computational burden, MC simulation is a reliable method.

5. Objective Function of TNEP

Several targets have been introduced for the development of transmission network. Some of these objectives have been used in classical methods and regarding their importance, they still exist in the new methods. Alongside these objectives, new objective functions have also been introduced which only are conceived in restructuring networks. All of objective functions have not equal importance or do not apply in restructuring networks, such as operation cost of plants that are otherwise defined in the new structure, Or network losses that have low importance in network planning. In this section dose not aim at defining new objectives but to formulating a model with multi-objective functions.

A. Minimizing the investment cost

Due the high volume of investment required for lines and lack of financial resources in infrastructure sector, which is the problem of almost all countries and transmission companies, minimizing investment costs of lines have always been noticed as the most important objective in TNEP.

The construction cost minimization can be formulated as in (10):

$$\min \; f_1 = \sum_{(i,j)\in\Omega} c_{ij} n_{ij} \tag{10}$$

B. Minimizing the congestion cost

Congestion is a situation when the demand for transmission capacity exceeds the transmission network capabilities. Obviously that overload of the branches is not a new problem, however this can cause problems in the new network that its most important problem is the Low level of market competitiveness. Congestion in transmission lines makes an imperfect market which means reduction of social welfare and imposing additional costs on the users of the network.

The congestion cost minimization can be formulated as in (11):

$$\min \; f_2 = \sum_{(i,j)\in\Omega} f_{ij}(lmp_j - lmp_i) \tag{11}$$

Local marginal prices are obtained from another optimization. In section (7) the way of calculating LMP of network buses are explained regarding network uncertainties which are wind generation energy, bid of generators and load.

C. Maximizing of network reliability

One of the major reasons of network expansion in practice is maintaining and enhancing network reliability. Single contingency security is the most applied criteria for evaluating reliability of transmission network, which has also been accepted by NERC. According to this criteria, power system, in addition to normal mode at the time losing a components have to meet the user's needs without any overload, unauthorized voltage drop and load curtailment. Adequacy and security criteria can be considered as constraints. However, here these criteria are modeled as an objective function applying the idea of artificial generation at each load bus. So, the mathematical formulation of the third objective function, providing static security, is as follows [33]:

$$\begin{aligned} &\min\ f_3 = W_0 + W_1 \\ &W_0 = \sum_{k\in\Gamma} r_k\ ,\ W_1 = \sum_{mn\in\Psi}\sum_{k\in\Gamma} r_k^{mn} \end{aligned} \tag{12}$$

In this paper objective function of network reliability is considered as minimizing the amount of load curtailment in normal mode and single contingency (N-1). Therefore the network security criteria is noticed as an objective function but not a constrain. The amount of load curtailment in normal mode must be zero thus, the amount of load curtailment with a large penalty factor could be added to the objective function. The objective functions formulating as in (13):

$$\begin{aligned} &\min\ f_1 = \sum_{(i,j)\in\Omega} c_{ij} n_{ij} + \alpha \sum_{k\in\Gamma} r_k \\ &\min\ \mathrm{f}_2 = \sum_{(\mathrm{i},\mathrm{j})\in\Omega} \mathrm{f}_{\mathrm{ij}} (\mathrm{lmp}_{\mathrm{j}} - \mathrm{lmp}_{\mathrm{i}}) + \alpha \sum_{\mathrm{k}\in\Gamma} \mathrm{r}_{\mathrm{k}} \\ &\min\ \mathrm{f}_3 = \sum_{\mathrm{mn}\in\Psi}\sum_{\mathrm{k}\in\Gamma} \mathrm{r}_{\mathrm{k}}^{\mathrm{mn}} \end{aligned} \tag{13}$$

The pf factor should be large enough to ensure that all pareto optimal solutions found by the algorithm have zero load curtailment in normal operation. In double objective case, it is assumed that the planner is only interested in secure solutions. Thus, the reliability criteria will be treated as a constraint as follows:

$$\begin{aligned} &\min\ f_1 = \sum_{(i,j)\in\Omega} c_{ij} n_{ij} + pf \times (\sum_{k\in\Gamma} r_k + \sum_{mn\in\Psi}\sum_{k\in\Gamma} r_k^{mn}) \\ &\min\ f_2 = \sum_{(i,j)\in\Omega} f_{ij} (lmp_j - lmp_i) + pf \times (\sum_{k\in\Gamma} r_k + \sum_{mn\in\Psi}\sum_{k\in\Gamma} r_k^{mn}) \end{aligned} \tag{14}$$

The constraints of the above multi-objective optimization problem are mainly those of dc optimal power flow in normal and contingency operating conditions as follows:

$$\begin{aligned} &s^T f + g + r = d \\ &f_{ij} - \gamma_{ij} (n_{ij}^0 + n_{ij})(\theta_i - \theta_j) = 0 \\ &\left| f_{ij} \right| \le (n_{ij}^0 + n_{ij}) \overline{f}_{ij} \\ &0 \le g \le \overline{g}\ ,\quad 0 \le r \le d \\ &0 \le n_{ij} \le \overline{n}_{ij} \quad \forall (i,j) \in \Omega \end{aligned} \tag{15}$$

The constraints of the modified network topology related to outage of every branch in Ψ must be added to the previous constraints. The constraints of the modified network topology related to the outage of line are as follows:

$$
\begin{array}{ll}
s^T f^{mn} + g^{mn} + r^{mn} = d & \\
0 \le g^{mn} \le \bar{g} \;,\quad 0 \le r^{mn} \le d & \\
f_{ij}^{mn} - \gamma_{ij}^{mn} (n_{ij}^0 + n_{ij} - 1)(\theta_i^{mn} - \theta_j^{mn}) = 0 & ij = mn \\
\left| f_{ij}^{mn} \right| \le (n_{ij}^0 + n_{ij} - 1)\bar{f}_{ij} & ij = mn \\
f_{ij}^{mn} - \gamma_{ij}^{mn} (n_{ij}^0 + n_{ij})(\theta_i^{mn} - \theta_j^{mn}) = 0 & ij \ne mn \\
\left| f_{ij}^{mn} \right| \le (n_{ij}^0 + n_{ij})\bar{f}_{ij} & ij \ne mn
\end{array}
\tag{16}
$$

Parameters with subscript mn denote the modified branch susceptances and bus voltage angles after outage of one of the lines in right-of-way mn

6. Calculate The Local Marginal Prices in The Presence Uncertainties of Network

Market operating point is determined for the operator to minimize costs or increase social welfare by using optimization tools and considering existing various constrains.

Providing electrical energy at a special point depends on three factors:

- Marginal cost of generators
- operating point of the system
- Transmission network constraints

The local marginal prices are obtained from the following optimization:

$$
\begin{array}{l}
\min \quad J = \sum_{i=1}^{ng} p_{G_i} (a_i p_{G_i} + b_i) \\
s.t: \quad B\delta - P_G + P_D = 0 = b \\
\qquad -p_\ell^{\max} \le p_\ell \le p_\ell^{\max} \\
\qquad p_G^{\min} \le P_G \le p_G^{\max}
\end{array}
\tag{17}
$$

The lagrangian is formulated as in (18):

$$
\begin{array}{l}
\psi(P_{G_i}, \lambda, \eta, \varphi, \gamma, \varsigma) = \\
\sum_{i=1}^{N} (p_{G_i} \times (a_i p_{G_i} + b_i)) - \lambda^T (B\delta - P_G + P_D - b) \\
\quad -\eta^T (H\delta - p_\ell^{\max}) - \varphi^T (-H\delta - p_\ell^{\max}) \\
\quad -\gamma^T (P_G - p_G^{\max}) - \varsigma^T (-P_G + p_G^{\min})
\end{array}
\tag{18}
$$

That, λ, η, φ, γ, ς are Lagrange multipliers of the associated constraints that obtained from Kuhn Tucker conditions.

Bus LMP is defined as the amount of the additional cost for providing 1 MW power in the same bus, hence it can be written:

$$
\left. \frac{\partial J(P_G)}{\partial b} \right|_{\text{optimal point}} = \left. \frac{\partial \psi(P_G, \lambda, \eta, \varphi, \gamma, \varsigma)}{\partial b} \right|_{\text{optimal point}} = \lambda^* \tag{19}
$$

Therefore, according to the definition of LMP, LMP of bus i is equal to the shadow price of power flow equation of bus i.

7. Optimization with Multi-Objective Functions

A multi-objective optimization problem has a number of objective functions which are to be minimized or maximized. Optimization problems including multi-objective functions do not have a unique response. The response of this kind of optimization problems consist of a set pareto responses.

$$\begin{array}{lll} Min / Max & f_m(x), \quad m = 1,2,...,M & \\ s.t & g_j(x) \geq 0, \qquad j = 1,2,...,J & \\ & h_k(x) = 0, \qquad k = 1,2,...,K & \\ & x_i^{(L)} \leq x_i \leq x_i^{(U)}, \quad i = 1,2,...,n & \end{array} \tag{20}$$

optimization problems with multi-objective function has not a unique response, Genetic algorithms, having global search capabilities, have been extensively used in several works in recent years for tackling the nonlinear, non-convex, and mixed integer optimization problem of transmission expansion planning. Generally, genetic algorithm (GA) starts with a set of initial solutions (initial population) which is randomly selected from the feasible solution space. Assigning fitness to each solution and consequently ranking them, the population evolves through several operations such as reproduction, crossover and mutation to obtain the final optimal solution. A detail comparison of the genetic algorithm with other evolutionary algorithms used for solving classic transmission expansion planning problem can be found in [34]. Regarding useful properties of genetic algorithm for solving multi-objective optimization problems such as the ability to handle non-convex problems comparing to mathematical methods, the "Elitist Non-dominated Sorting Genetic Algorithm" (NSGA II) [35] has been chosen here for solving the proposed multi-objective optimization problem. The basic idea of the NSGA II algorithm is to classify a population of solutions into the number of non-dominated fronts in which the first front (level 1) is a set of non-dominated solutions in the entire population, the second front (level 2) is a set of non-dominated solutions in the population ignoring the first level and so on until the entire population has been classified into k levels. This idea is depicted in Figure 3 where three levels have been showed. This ranked population is then reproduced through crossover and mutation operators. In the selection phase, an individual's non-domination rank biases the probability of being selected for reproduction. The solutions in the first level front have highest priority, and then those in the second level and so forth. The coding, crossover, and mutation procedures are the same as those used in single objective optimizations [34]. Figure 4 shows the procedure of one iteration of NSGA II [36]. First, a set of new alternatives is produced from previous population (P_t) then, the combined population $R_t = P_t \cup Q_t$ with size $2N$ is sorted and classified to different non-dominated levels N is the size of first population. Since all previous solutions are included in the process, elitism is guaranteed.

The new population (P_{t+1}) is composed of the first, the second, and other non-dominated levels until all N population slots are filled. To obtain a set of diverse solutions, a shared fitness value is assigned to each solution in the first front. The diversity is maintained by degrading the assigned dummy fitness based on the number of neighboring solutions. This fitness assignment procedure also applies in the second level non-dominated solutions in such a way that the smallest shared fitness value of the first front solutions be a little larger than the largest shared fitness value of the second front solutions. This procedure continues until the whole solutions have been assigned a shared fitness value [37].

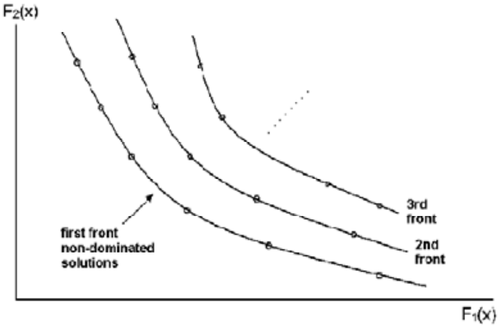


Figure 3. Classification of a population to *k* non-dominated fronts.

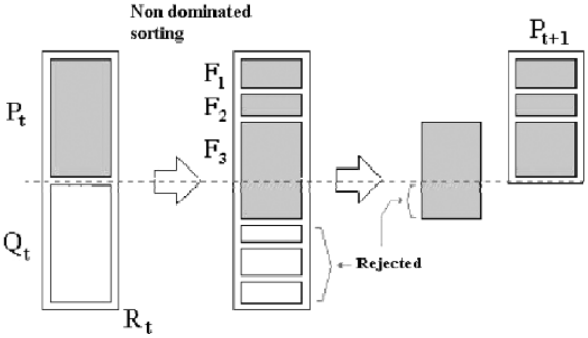


Figure 4. NSGA II procedure.

8. Applied model to the IEEE 24 bus system

For implementing the algorithm a ten years planning period with the load rate of 8% is considered. Thus the load network at the end of horizon planning is increased 2.2 times which would be 4242 MW and the amount of generation would be 4540 MW and it is also assumed that there are 10 right-of-way candidates for line constructing. There is a wind farm with 1000 MW rated power in bus 6. The transmission expansion planning algorithm was applied to the modified IEEE 24-bus test system shown in Figure 5.

The proposed algorithm was implemented in MATLAB environment using MATPOWER optimal power flow functions. Network data for this system can be found in [38] and other data such as investment costs are given in the Appendix. It was 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 8% per year with a ten-year planning horizon. It was also assumed that the candidate branches can be constructed in all 34 existing right-of-ways plus ten new right-of-ways which their data can be found in the Table (1). Regarding random bid of generators and wind power generation LMP of buses are calculated with stochastic optimal power flow and Monte-Carlo simulation. The flowchart of procedure has been shown in Figure 6.

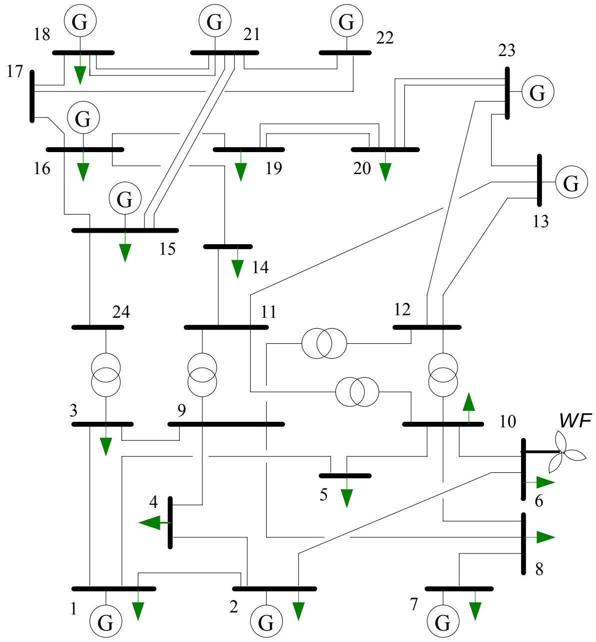


Figure 5. Modified IEEE 24 bus test system.

Loads of system and bid of generators are as normal distribution function and the wind speed is as Rayleigh distribution function. Following steps are done to calculate the LMP of buses in each iteration of Monte-Carlo simulation:

- The network load is determined.
- The proposed cost of generators is determined.
- Wind speed and consequently its power can be determined.
- The optimal power flow is done and amount of λ for each bus determined and saved and finally the amount of LMP of each bus according to the Monte Carlo simulation are obtained as follow:

$$X = \frac{1}{NS}\sum_{k=1}^{NB}\sum_{i=1}^{NS}\lambda_{k,i} \tag{21}$$

Table 1. Investment costs of branches in new right of ways (modified IEEE 24 bus test system)

From	to	Investment cost (10^3 $)	From	to	Investment cost (10^3 $)
1	8	35	13	14	62
2	8	33	16	23	86
6	8	18	16	23	114
6	7	50	19	23	84
7	2	25	20	22	36

According to (18), *X* is the vector of LMP of buses, *NS* is the number of iteration and *NB* is the number of buses. In Table (2) and Figure 7 the amount of LMP of buses for modified IEEE 24 bus test system calculated and is shown.

After 80 iteration and initial population of 100, non-dominated solutions were found by the proposed algorithm.

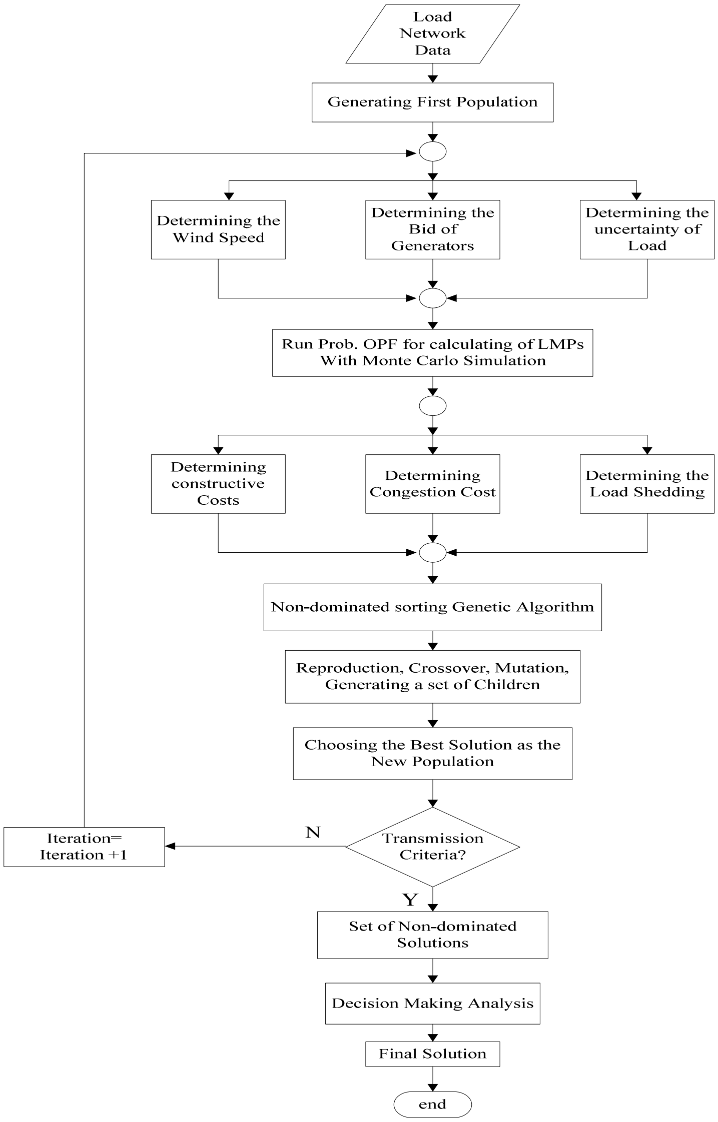


Figure 6. Flowchart of proposed methodology.

Table 2. Lmp calculated in modified IEEE 24 bus test system

BUS	LMP ($/h)	BUS	LMP ($/h)
1	56.3169	13	58.6915
2	56.5817	14	67.3583
3	52.6700	15	44.2975
4	57.2618	16	44.5828
5	59.8611	17	40.5909
6	60.5628	18	41.5488
7	46.1486	19	52.5032
8	58.4498	20	54.0081
9	57.8183	21	42.4102
10	59.0814	22	41.6976
11	61.6508	23	54.8289
12	57.8578	24	47.4390

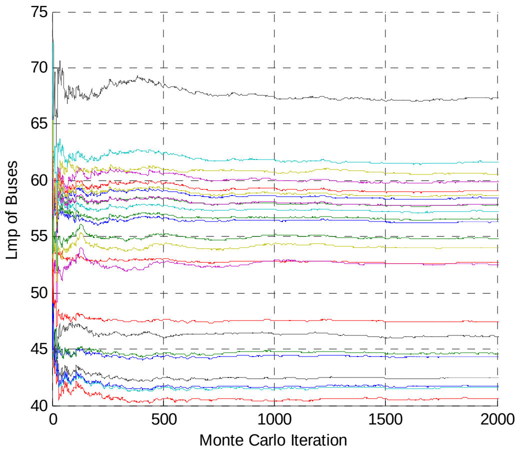
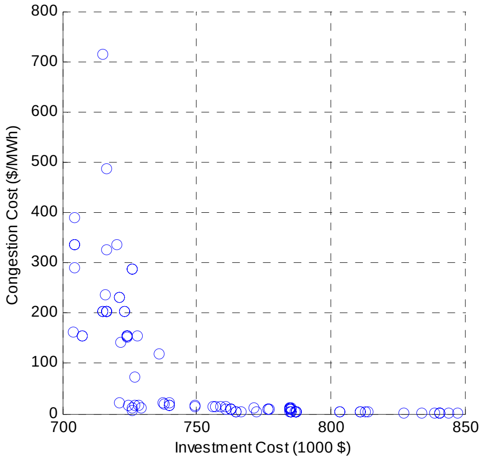
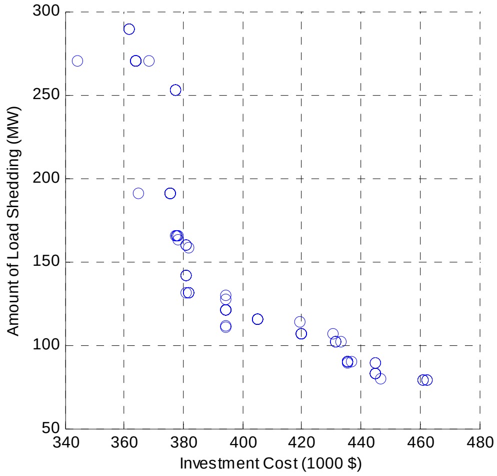


Figure 7. LMP calculated in Monte Carlo iterations.

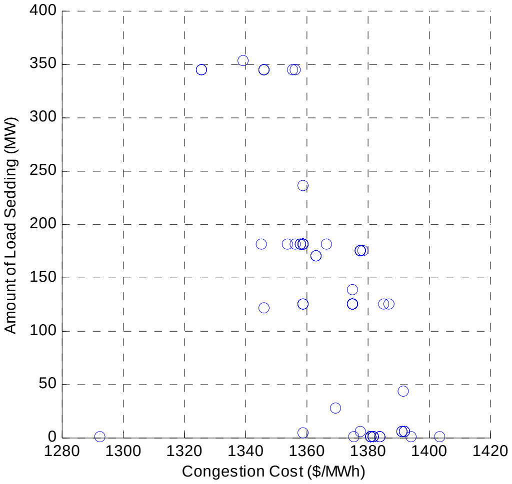
Figure 8, shows these non-dominated solutions. Due to difficultly of effectively displaying a non-dominated set in three dimensional space, three trade-off graphs were used.



(a)



(b)



(c)

Figure 8. Non-dominated solutions (Modified IEEE 24-bus test system).
(a) Trade-off between congestion cost and investment cost. (b) Trade-off between amount of load shedding and investment cost. (c) Trade-off between congestion cost and Investment cost.

According to these figures, it is clear that reduce the investment cost on the one hand and reduce congestion and increased reliability on the other hand have a contradictory relationship. Figure 8(a) shows that for having a network with no curtailment, it is necessary to invest more than 430 thousand $. These information can be extracted from the relation between the objective functions, can significantly help the planner to select an appropriate response. Consequently the implementation of the model presented in (11) at modified IEEE 24 buses is shown in Figure 9.

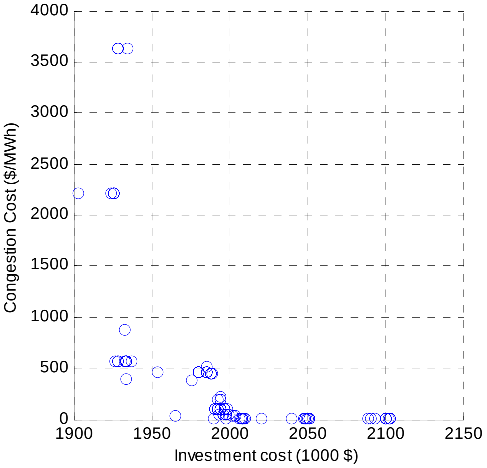


Figure 9. Non-dominated solutions in double objective model (Modified IEEE 24-bus test system).

In this figure all of non-dominated solutions have single contingency condition and only the relation between investment cost and congestion cost are presented. As can be seen in Figure 9, the relationship between objective functions was quite clear and congestion decreased with increasing investment.

In this model there are only two objective functions. To select the optimal design, here a simple ranking method could be used based on the incremental cost-benefit (ICB) ratio concept. Comparing non-dominated solutions with the base case, the ICB of each solution can be defined as:

$$ICB_i = \frac{\Delta CC_i}{\Delta Inv_i} \tag{22}$$

where ΔCC_i is the difference between congestion cost of the base case and solution i and ΔInv_i is the difference between investment cost of the base case and solution i (as the base case condition means zero investment so, $\Delta Inv_i = Inv_i$).

Among the non-dominated solutions depicted in Figure 9, the solution with 1.97 million $ investment cost has the largest ICB. Congestion cost of this solution is 400 $/h and its implementation requires installing new lines or transformers that shown in Table (3).

Table 3. New lines or transformers that should added to system (Obtained from simulation)

corridor	**number**	**corridor**	**number**
1-8	2	14-23	2
2-8	2	16-23	1
6-7	1	19-23	2
7-2	1	10-22	2

9. Conclusion

Requirements of the new deregulated environment make it necessary to revise classic approaches of the transmission expansion planning problem. This paper presented a multi-objective model to cope with new challenges introduced by the deregulation. The main advantages of the proposed algorithm are: it allows the planner to use a cost-benefit approach instead of the least cost planning procedure, it defines a model to handle different stakeholders' preferences, and finally it incorporates the static security analysis in the first stage of planning which results in a more optimal solution in contrast to those leaving this analysis to the second phase. Also, this method produces a set of optimal solutions, in contrast to single objective methods, which yields more flexibility in planning process.

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NOMENCLATURE

$f_U(U)$	Probability density function of wind speed.
U	Wind Speed.
K	Shape parameter of weibull distribution function.
C	Scale parameter of weibull distribution function.
μ_U	Mean of wind speed.
σ_U^2	Variance of wind speed.
Γ	Legendre gamma function.
P	Output power of wind turbine.
P_R	Rated power of wind turbine.
U_{CO}	Cut-out wind speed.
U_{CI}	Cut-in wind speed.
U_R	Rated wind speed.
n	Number of wind turbine.
f_i	Individual objective of transmission planning.
c_{ij}	Investment cost to build candidate circuit.
n_{ij}	Number of new circuit added to the right-of-way $i-j$.
Ω	Set of all new right-of-ways.
f_{ij}	Active power flow in the right-of-way $i-j$.
lmp_i	Local marginal price at bus i.
W_0	Total curtailed (shed load) in normal operation.
W_1	Total curtailed (shed load) in single contingency condition.
r_k	Curtailed load at bus k in normal operation.
r_k^{mn}	Curtailed load at bus k while a line in right-of- way $m-n$ is out of service.
Υ	Set of load buses.
Ψ	Set of selected contingencies.
pf	A large penalty factor.
s	Node-branch incidence matrix.
f	Vector of active power flows.
g	Vector of generated active powers.
r	Vector of load curtailments.
d	Vector of predicted loads.
n_{ij}^0	The number of circuits added in right-of-way $i-j$.

$\overline{n}_{ij}$	Maximum number of circuits that can be added in right-of-way $i-j$.
γ_{ij}	Susceptance of the circuits in right-of-way $i-j$.
$\overline{g}$	Vector of maximum generation capacities.
θ_i	Voltage angle at bus i.
f^{mn}	Vector of active power flow of transmission lines.
P_{G_i}	Active Power generation of generator i.
a_i, b_i	Constant of bid function of generator i.
B	Linear Jacobian matrix of network.
δ	Vector of voltage angle of buses.
P_G	Vector of active power generation.
P_D	Vector of active loads.
p_ℓ	Vector of power transmission lines.
$p_\ell^{\max}$	Vector of line limits.
$P_G^{\min}$	Vector of minimum generation of generators.
$P_G^{\max}$	Vector of maximum generation of generators.