A Multi-Objective Framework for Transmission Expansion Planning in Deregulated Environments

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***Abstract*—Deregulation of power system has introduced new objectives and requirements for transmission expansion problem. In this paper, a static transmission expansion methodology is presented using a multi-objective optimization framework. Investment cost, reliability (both adequacy and security), and congestion cost are considered in the optimization as three objectives. To overcome the difficulties in solving the nonconvex and mixed integer nature of the optimization problems, the genetic based NSGA II algorithm is used followed by a fuzzy decision making analysis to obtain the final optimal solution. The planning methodology has been demonstrated on the IEEE 24-bus test system to show the feasibility and capabilities of the proposed algorithm. Also, in order to compare the historical expansion plan and the expansion plan developed by the proposed methodology, it was applied to the real life system of northeastern part of Iranian national 400-kV transmission grid.**

***Index Terms*—Fuzzy satisfying method, genetic algorithm, multi-objective optimization, NSGA II, transmission expansion planning.**

I. Nomenclature

f_i	Individual objective of transmission planning.
c_{ij}	Cost of a circuit that may be added to the right-of-way $i-j$.
n_{ij}	Number of new circuits added to the right-of-way $i-j$.
Ω	Set of all existing and new right-of-ways.
f_{ij}	Active power flow in the right-of-way $i-j$.
lmp_i	Locational marginal price at bus i.
p_i	Active generation of GENCO i.
a_i, b_i	Constants of bid function of generator i.
$\boldsymbol{C}_D$	Vector of DISCOs' bids.
$\boldsymbol{P}_D$	Vector of active loads.
ng	Number of GENCOs.
W_0	Total artificial generation (curtailed/shed load) in normal operation without contingencies.
W_1	Total artificial generation (curtailed/shed load) in single contingency condition.
r_k	Artificial generation (curtailed/shed load) at bus k in normal operation.
r_k^{mn}	Artificial generation (curtailed/shed load) at bus k while a line in right-of-way $m-n$ is out of service.
Γ	Set of load buses.
Ψ	Set of selected contingencies.
pf	A large penalty factor.
$\boldsymbol{s}$	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.
γ_{ij}	Susceptance of the circuits in right-of-way $i-j$.
n_{ij}^0	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 $i-j$.
$\bar{\boldsymbol{g}}$	Vector of maximum generation capacities.
θ_i	Voltage angle at bus i.
$\boldsymbol{f}^{mn}$	Vector of active power flow of transmission lines after outage of a line in right-of-way $m-n$.
$\boldsymbol{r}^{mn}$	Vector of artificial generations after outage of a line in right-of-way $m-n$.
$\bar{X}$	A solution (a combination of new branches to be added to the network).
$\mu_{f_i}(\bar{X})$	Satisfaction level of solution $\bar{X}$ with respect to ith objective.
μ_{ri}	Reference level of achievement of ith objective.
d_{ij}	Euclidian distance between solutions i and j.
$\sigma_{\mathrm{share}}, \alpha$	Adjustable parameters in sharing factor calculation.
Φ	Set of nondominated solutions.

Manuscript received June 13, 2008; revised November 02, 2008. First published March 31, 2009; current version published April 22, 2009. Paper no. TPWRS-00469-2008.

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Digital Object Identifier 10.1109/TPWRS.2009.2016499

II. Introduction

THE deregulation of power system has introduced new challenges in the field of transmission expansion planning. The main goal of deregulation can be summarized as defining a competitive market for maximizing the overall social welfare while maintaining power system reliability.

The transmission network has a vital role in new electricity market because it should provide a nondiscriminatory environment for all market participants. Obviously, the current transmission network is not designed to handle market-based power flow patterns and stakeholders' interests [1]. Any new model for transmission expansion planning should be capable of considering the objectives and interests of each stakeholder and also should be based on cost-benefit analysis instead of classical least cost approach.

Moreover, the unbundling process results in increasing uncertainties mainly regarding generation expansion planning [2], [3].

A detailed review of different methods proposed for transmission expansion planning can be found in [4] and [5]. This paper focuses on defining a multi-objective framework to handle different stakeholders' objectives with a cost-benefit approach. The issue of uncertainties will not be addressed here. Previous works on defining a multi-objective framework can be classified mainly into two categories: those which convert the problem into a single objective optimization using such techniques as weighted method [6]–[8], and those which use goal programming to solve the multi-objective optimization problem [9]–[11]. Because of nonconvexity feature of the transmission expansion problem, the weighted methods could not guarantee to find the global pareto optimal solutions. Also, goal programming approach needs a prior knowledge about decision maker preferences.

In this paper, a posterior method is proposed to find the pareto optimal region which can show the trade-offs between different objectives. Then, the final decision making will be done by fuzzy satisfying method [12]. To handle nonlinearity and mixed integer nature of the optimization problem, the genetic algorithm based NSGA II [13] method is adopted. This paper is organized as follows: after an overall review of the proposed method in Section II, the mathematical formulation is presented in Section III. An overview of genetic algorithm implementation and fuzzy decision making is presented in Section IV followed by a case study showing the capabilities of the proposed method in Section V. Finally, conclusions are given in Section VI.

III. Overview of the Proposed Method

In this paper a general framework for multi-objective static transmission expansion planning is presented. Minimization of investment cost and congestion cost while satisfying system adequacy and static security requirements are considered.

A. Objectives of Transmission Expansion Planning

Traditionally, the transmission expansion planning problem had been formulated as a single objective problem to minimize construction cost while eliminating any overloads in normal operating conditions [14]. Obviously, minimization of construction cost should be an objective of transmission expansion planning in new environment, too, aiming to minimize the investment budget and transmission tariffs.

As mentioned earlier, deregulation of power system has faced new objectives and goals in the field of network planning such as minimizing congestion cost. Any form of transmission constraints or bottlenecks in transmission network will prevent perfect competition between market participants [15]. Therefore, minimizing the congestion level in transmission network will result in a more competitive electricity market and consequently it maximizes social welfare. The idea of minimizing congestion cost has been used in [15] and [16] to develop a new model for transmission expansion planning in the new electricity industry. Congestion cost is a function of the congestion level and its duration in the network. Thus, calculation of congestion cost needs a time consuming analysis considering different loading patterns of the network such as the time dependant formulation proposed in [15]. Fortunately, because of the ability of multi-objective optimization to handle incommensurable objectives, here we calculate the time independent congestion cost only at the peak load of the network and will try to minimize it as one of the problem objectives.

Practically, the transmission expansion planning process is done in two phases. In phase I, a mathematical optimization model is used to construct an optimal adequate network, and in phase II, using the expansion plan obtained in the first phase, new circuits are added to the network and other modifications are applied in order to satisfy dynamic and static security constraints and allowable short circuit levels. Since the security of power system has an increasing important role in power system operation [17], [18], it should be addressed in planning phase like what has been done in [17]. Postponing security analysis to the second phase of planning process will result in an expansion plan which will not be optimal. In other words, if the required investment cost to construct a secure network is much more than the investment needed for an adequate network (which is the case in many situations), the final expansion plan will differ significantly from the one obtained in phase I and thus, the final plan will certainly be a nonoptimal one.

In this paper, satisfying static security constraints has been considered as the third objective in phase I of planning process. For limiting computational efforts to an acceptable level, the so called dc model of the network has been used. Also, it has been assumed that the transmission network is managed and expanded by a regulated entity (a transmission provider) who aims to maximize social welfare and satisfy system reliability. Moreover, the electric energy market has been modeled as an LMP based market.

B. Multi-Objective Optimization

Multi-objective optimization is an appropriate tool for handling different incommensurable objectives with conflicting/supporting relations or not having any mathematical relation with each other. Generally, it is impossible to obtain an optimal solution at which all such objectives are optimized. Thus, the concept of pareto optimality (also known as noninferiority or nondominancy) is used to characterized solutions to the multi-objective problem. Qualitatively, a noninferior solution of a multi-objective problem is one where any improvement of one objective function can be achieved only at the expense of degrading the others. A set of all nondominated solutions composes a region which is called nondominated set or trade-off region. Mathematically, none of the solutions in the trade-off region has a priority with respect to other solutions. Therefore, obtaining a final solution is left to the decision maker with its own preferences. There are different methods for handling multi-objective optimization problems which generally can be classified as priori and posterior methods [13]. In priori methods, a relative preference vector needs to be supplied without any knowledge of possible consequences and trade-offs between objectives. Thus, the preferences may result in an infeasible solution and otherwise the optimal solution obtained by these methods is highly subjective to the particular decision maker. In contrast to the priori methods, in posterior methods, first the set of pareto optimal solutions will be found and using the trade-offs between objectives, decision maker can find the best solution applying an appropriate decision making method.

In this paper, a two stage posterior method is proposed for static transmission expansion planning in a deregulated environment. One of the important advantages of the proposed method is its flexibility. Obtaining a set of pareto optimal solutions instead of one optimal solution, which is the case in single objective formulation, represents more flexibility to the planner as a decision maker to select a satisfying final plan.

C. *Final Decision Making*

Due to subjective imprecise nature of the decision maker's judgment, the fuzzy satisfying method has been applied here to select the preferred solution among nondominated solutions obtained in stage one of the optimization. The decision maker will be asked to determine its imprecise goals for each objective called satisfying levels. Using a decision analysis technique, the final solution will be found. Since the trade-offs between each objective are determined in the first stage, one can expect a much reasonable judgment from decision maker comparing to prior or interactive methods.

IV. Mathematical Formulation

A. *Objectives*

The construction cost minimization can be formulated as

$$\text{Min } f_1 = \sum_{(i,j)\in\Omega} c_{ij} n_{ij}. \tag{1}$$

Considering the locational marginal price (LMP) based market [16], the objective of minimizing total congestion cost can be formulated as

$$\text{Min} f_2 = \sum_{(i,j)\in\Omega} f_{ij}(\text{lmp}_j - \text{lmp}_i). \tag{2}$$

LMPs are the Lagrange multipliers or shadow prices of the power flow constraints. For a given operating point (here the peak load) they can be computed through an optimization with following objective function:

$$\text{Min} \left(\sum_{i=1}^{\text{ng}} p_i \times (a_i p_i + b_i) - C_D^T P_D \right). \tag{3}$$

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 [17]:

$$\begin{aligned} \text{Min } f_3 &= W_0 + W_1 \\ W_0 &= \sum_{k\in\Gamma} r_k W_1 = \sum_{mn\in\Psi} \sum_{k\in\Gamma} r_k^{mn}. \end{aligned} \tag{4}$$

While there have been many works trying to propose a probabilistic reliability criteria for transmission planning such as [19], in this paper, the NERC definition of security (single contingency security or N-1) has been considered [20]. In [19] a single objective model of the transmission expansion problem using the traditional objective function of minimizing investment cost has been proposed with new constraints on system reliability indexes. These indexes were calculated using probabilistic reliability assessment techniques but the admissible level of these indexes were not discussed.

The above formulation can easily be modified to incorporate contingencies probabilities and cost of load shedding but here only the classic security criteria will be used. Although for limiting the computational time in large scale transmission planning an appropriate method of contingency selection might be applied [21], in the case study presented in Section V the full single contingency enumeration has been applied.

Note that the formulation presented in (4) has two advantages: first, the optimization problem will be always feasible due to the presence of the loss of load and second, defining the reliability criteria as an objective will allow the decision maker to run a cost-benefit analysis.

The reliability criteria presented above can be considered either as an objective or as a constraint. In this paper, the triple and the double objective models will be considered.

In the triple objective case, the adequacy criterion will be treated as a constraint. To implement this model, the amount of curtailed load in base case should be added to the objectives with a large penalty factor. Thus, the formulation will be

$$\begin{aligned} \text{Min } f_1 &= \sum_{(i,j)\in\Omega} c_{ij} n_{ij} + pf \times W_0 \\ \text{Min } f_2 &= \sum_{(i,j)\in\Omega} f_{ij}(\text{lmp}_j - \text{lmp}_i) + pf \times W_0 \\ \text{Min } f_3 &= \sum_{l\in\Psi} \sum_{k\in\Gamma} r_k^l + pf \times W_0. \end{aligned} \tag{5}$$

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:

$$\begin{aligned} \text{Min } f_1 &= \sum_{(i,j)\in\Omega} c_{ij} n_{ij} + pf \times (W_0 + W_1) \\ \text{Min } f_2 &= \sum_{(i,j)\in\Omega} f_{ij}(\text{lmp}_j - \text{lmp}_i) + pf \times (W_0 + W_1). \end{aligned} \tag{6}$$

Here, the trade-off between investment cost and security criterion could not be calculated.

B. Constraints

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:

$$\begin{aligned}
&\boldsymbol{s}^{\boldsymbol{T}}\boldsymbol{f}+\boldsymbol{g}+\boldsymbol{r}=\boldsymbol{d}\\
&f_{ij}-\gamma_{ij}\left(n_{ij}^{0}+n_{ij}\right)(\theta_i-\theta_j)=0\\
&|f_{ij}|\le (n_{ij}^{0}+n_{ij})\bar{f}_{ij}\\
&0\le g\le \bar{g}, 0\le r\le d\\
&0\le n_{ij}\le \bar{n}_{ij}\quad \forall (i,j)\in\Omega.
\end{aligned}\tag{7}$$

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 mn are as follows:

$$\begin{aligned}
&\boldsymbol{s}^{\boldsymbol{T}}\boldsymbol{f}^{mn}+\boldsymbol{g}^{mn}+\boldsymbol{r}^{mn}=\boldsymbol{d}\\
&0\le \boldsymbol{g}^{mn}\le \bar{\boldsymbol{g}},\quad 0\le \boldsymbol{r}^{mn}\le \boldsymbol{d}\\
&f_{ij}^{mn}-\gamma_{ij}^{mn}\left(n_{ij}^{0}+n_{ij}-1\right)\left(\theta_i^{mn}-\theta_j^{mn}\right)=0\quad ij=mn\\
&|f_{ij}^{mn}|\le \left(n_{ij}^{0}+n_{ij}-1\right)\bar{f}_{ij}\quad ij=mn\\
&f_{ij}^{mn}-\gamma_{ij}^{mn}\left(n_{ij}^{0}+n_{ij}\right)\left(\theta_i^{mn}-\theta_j^{mn}\right)=0\quad ij\neq mn\\
&|f_{ij}^{mn}|\le \left(n_{ij}^{0}+n_{ij}\right)\bar{f}_{ij}\quad ij\neq mn.
\end{aligned}\tag{8}$$

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. These lines can be selected as credible contingencies using a contingency screening method.

For calculating the amount of load shedding, the priority of load buses for load curtailment has been considered the same in the network. Load will be curtailed if the re-dispatching of generators can not eliminate overloads in transmission system.

C. Fuzzy Satisfying Decision Making

After determination of nondominated set, it is desirable to obtain a flexible and realistic solution that represents a trade-off between different objectives [22]. While there are many methods for selecting a compromise solution among a set of solutions, as will be discussed in Section V, a fuzzy approach is of great interest because of its simplicity and similarity to human reasoning. The fuzzy sets are defined by membership functions which represent the degree of membership in a fuzzy set using values from 0 to 1. The membership value "0" indicates incompatibility with the set, while "1" means full compatibility. In fuzzy satisfying method, a strictly monotonically decreasing and continuous membership function is assigned to each objective. The assigned membership function is 1 at the minimum of objective and 0 at its maximum [12]. The value of the membership function indicates to what extend a solution is satisfying the objective f_i. The decision maker is fully satisfied with objective value of $f_i(\bar{X})$ if $\mu_{f_i}(\bar{X})=1$ and not satisfied at all if $\mu_{f_i}(\bar{X})=0$. There are some types of strictly monotonically decreasing and continuous functions which can be used as membership functions such as linear, convex exponential and hyperbolic types. Here, the linear type has been used for all objectives as follows:

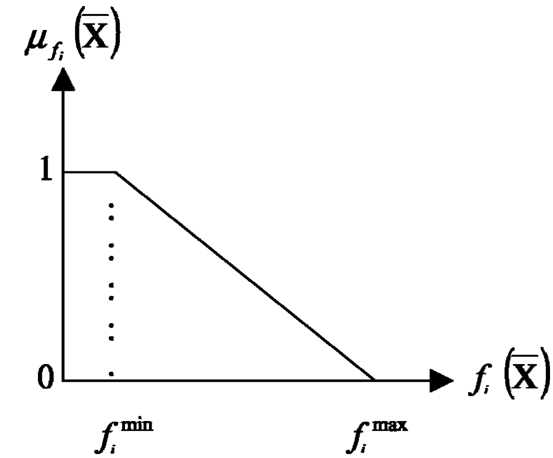

Fig. 1. Linear type membership function.

$$\boldsymbol{\mu}_{f_i}(\bar{X})=\begin{cases}0 & f_i(\bar{X})>f_i^{\max}\\ \frac{f_i^{\max}-f_i(\bar{X})}{f_i^{\max}-f_i^{\min}} & f_i^{\min}\le f_i(\bar{X})\le f_i^{\max}\\ 1 & f_i(\bar{X})<f_i^{\min}\end{cases}.\tag{9}$$

Fig. 1 illustrates the graph of this membership function. Note that selection of different types of membership function for different objectives can influence the final solution. For example, using a "convex exponential" function for one of the objectives' membership function will provide a priority for minimizing that objective relative to the other objectives because this function will assign a smaller membership function in the vicinity of $f_i^{\max}$ comparing to linear type.

After defining each membership functions, the decision maker will be asked to choose the desirable level of achievement of each objective. Desirable levels of achievement are named reference levels of achievement and are shown by μ_{ri}. Now, the final solution can be obtained using a decision analysis technique. In this paper, two methods called "minimax" [12], and a distance metric method [13] have been applied to represent a conservative and nonconservative behavior of a decision maker, respectively.

Using the minimax formulation (conservative approach), the final solution can be found by solving the following optimization problem:

$$\max_{\bar{X}\in\Phi}(\max_{i}|\mu_{ri}-\mu_{fi}(\bar{X})|).\tag{10}$$

Applying the distance metric method, the final solution can be obtained by solving the following optimization problem:

$$\min_{\bar{X}\in\Phi}\sum_{i=1}^{3}|\mu_{ri}-\mu_{fi}(\bar{X})|^{p}\tag{11}$$

where $1\le p<\infty$. It can be seen that this formulation tries to minimize the p-norm deviations from the reference membership values. Since $|\mu_{ri}-\mu_{fi}(\bar{X})|$ has a value between 0 and 1, a larger p means to be less sensitive to reference values.

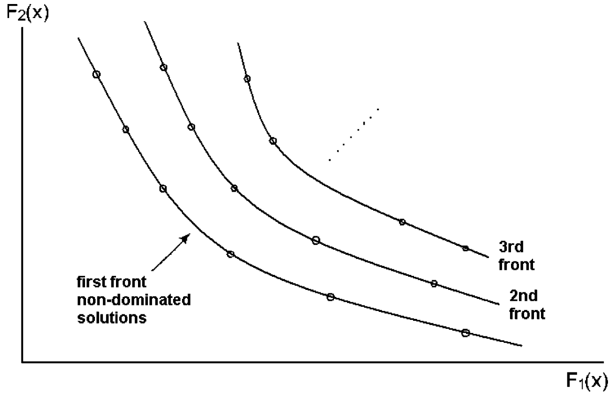

Fig. 2. Classification of a population to k nondominated fronts.

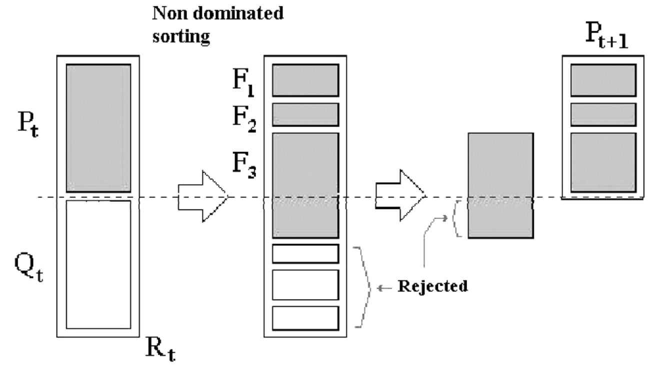

Fig. 3. NSGA II procedure.

Note that if the fuzzy satisfying method is used interactively or as a priori method in multi-objective optimization, the reference membership values (μ_{ri}) should be unattainable goals to guarantee finding a nondominated solution [23], while this is not the case in the proposed algorithm because the nondominated solutions (Φ) are found in the first stage.

V. Application of NSGA II Method

Genetic algorithms, having global search capabilities, have been extensively used in several works in recent years for tackling the nonlinear, nonconvex, 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 [24]. Regarding useful properties of genetic algorithm for solving multi-objective optimization problems such as the ability to handle nonconvex problems comparing to mathematical methods, the "Elitist Nondominated Sorting Genetic Algorithm" (NSGA II) [13] has been chosen here for solving the proposed multi-objective optimization problem.

A. NSGA II Method

The basic idea of the NSGA II algorithm is to classify a population of solutions into the number of nondominated fronts in which the first front (level 1) is a set of nondominated solutions in the entire population, the second front (level 2) is a set of nondominated 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 Fig. 2 where three levels have been showed. This ranked population is then reproduced through crossover and mutation operators. In the selection phase, an individual's nondomination 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 [24].

Fig. 3 shows the procedure of one iteration of NSGA II [25]. 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 nondominated levels (N is the size of first population). Since all previous solutions are included in the process, elitism is guaranteed. The new population $(\mathrm{P_{t+1}})$ is composed of the first, the second, and other nondominated 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 nondominated 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.

Unlike standard NSGA II formulation [25], in this paper, for calculating the shared fitness values, the following sharing function is used because this formulation was shown to have better performance than the "crowding distance" method in several test runs:

$$\mathrm{sh}(d_{ij}) = \begin{cases} 1 - \left(\frac{d_{ij}}{\sigma_{\mathrm{share}}}\right)^{\alpha} & d \le \sigma_{\mathrm{share}} \\ 0 & \text{otherwise.} \end{cases} \quad (12)$$

A zero sharing value, $\mathrm{sh}(d_{ij}) = 0$, means that the i and j solutions are far away from each other adequately, depending on the value of σ_{share}, or they have no sharing effect on each other. While a sharing value near 1 means these two solutions are completely close to each other. In order to determine the fitness value of solution i in the front k, the sharing values for all the solutions in the front k must be calculated. The fitness value of solution i is then found by dividing the dummy fitness value of the k th front by the niche count of solution i. The niche count of solution i is calculated as follows:

$$nc_i = \sum_{j \in \mathrm{K}, j \neq i} \mathrm{sh}(d_{ij}) \quad (13)$$

where K is the set of solutions in the kth front. The niche count (nc_i), in some sense, denotes the number of solutions in the neighborhood of the i th solution. Some methods for calculating the parameters such as σ_{share} can be found in [13]. These shared fitness values will be used in the reproduction process (constructing Q_t). Therefore, it is more probable to select a solution with a larger fitness value than others as a parent of new generation. A detail comparison of the NSGA II algorithm with other ones can be found in [13], [26], and [27].

B. Proposed Algorithm

The block diagram of the proposed algorithm is shown in Fig. 4. Either reaching the maximum number of allowed iterations or finding no other new nondominated solution in a predefined number of successive iterations has been considered as the termination criterion.

As illustrated in Fig. 4, each alternative will be analyzed to determine its investment cost, congestion cost, and its amount of load shedding needed for adequate and secure operation. Congestion cost of each alternative is calculated by solving a standard quadratic optimization problem. For calculating the amount of load shedding, a standard quadratic optimization problem should be performed for each pre-selected contingency. Outputs of these optimizations will be used to sort alternatives in different nondominated fronts. Then, a new population will be reproduced from the best ones using the techniques described in the previous section. Finally, fuzzy satisfying decision making is used to determine the best compromising solution.

VI. Case Study

A. IEEE 24-Bus Test System

The transmission expansion planning algorithm was applied to the IEEE 24-bus test shown in Fig. 5. The proposed algorithm was implemented in MATLAB environment using MATPOWER optimal power flow functions. Network data for this system can be found in [28] 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 Appendix.

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 existing and in new corridors, respectively, limited by environmental considerations. In substations, up to four power transformers can be installed. In this case study, only the whole sale electricity market has been considered (fixed loads) and all single contingencies have been evaluated.

For the above conditions with population size of 200 and after 96 iterations, 121 nondominated solutions were found by the proposed algorithm. Fig. 6 shows these nondominated solutions. Due to difficulty of effectively displaying a nondominated set in three-dimensional space, three trade-off graphs were used. Note that the solutions which appear dominated in each of these graphs, are indeed nondominated when considering the third objective not displayed in that graph. Fig. 6(a) and (b) shows a

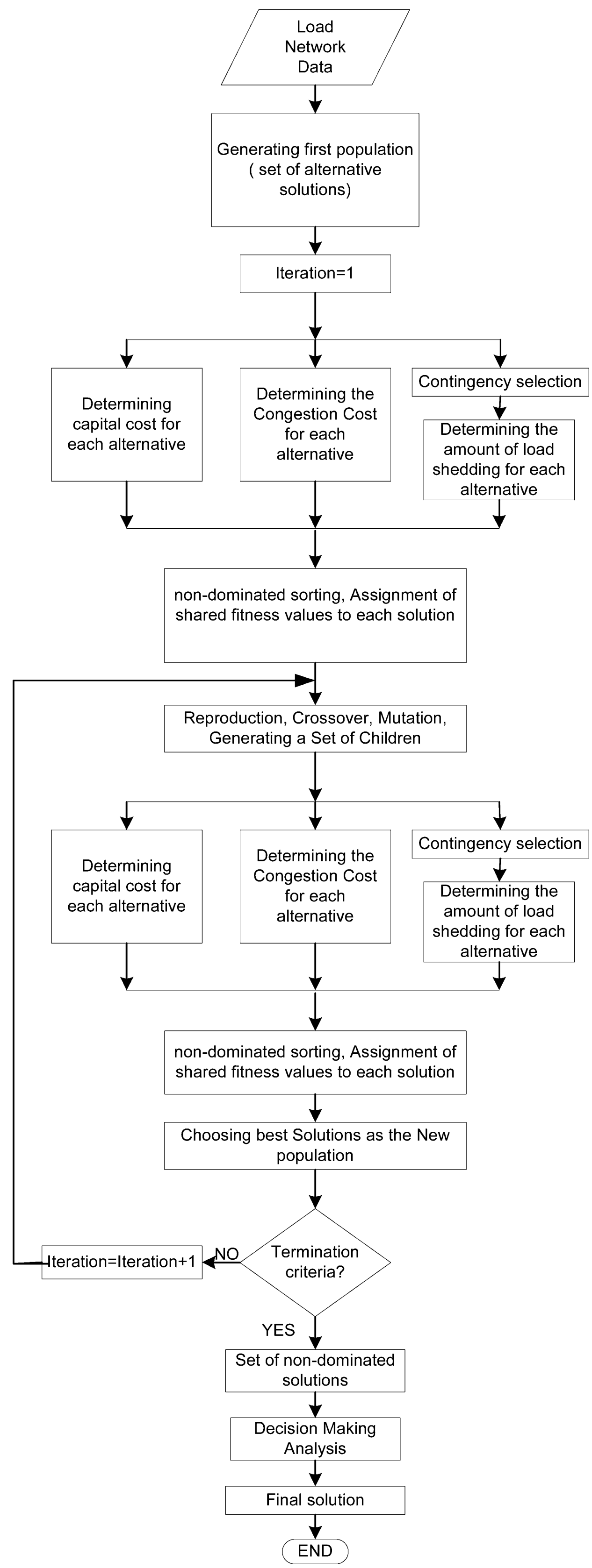

Fig. 4. Flowchart of the proposed algorithm.

conflicting relationship between investment cost and other two

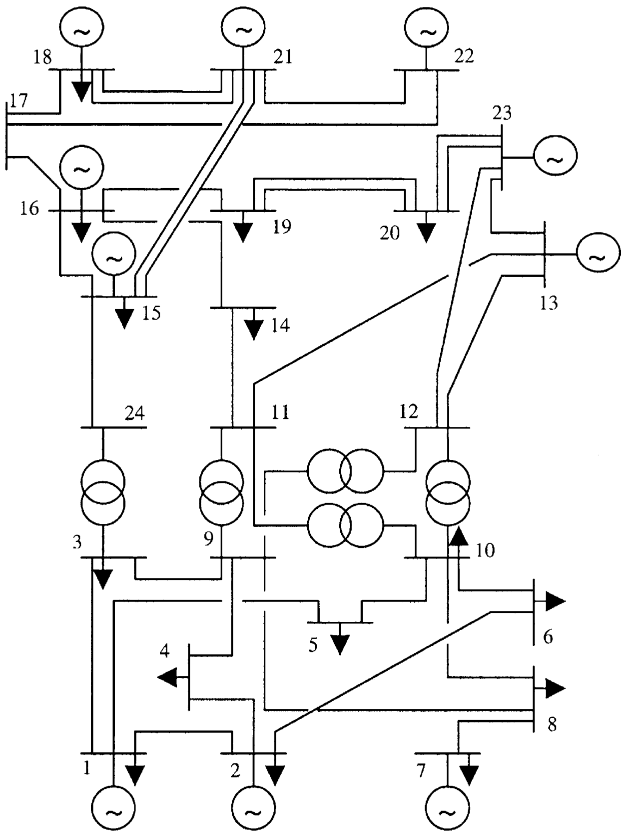

Fig. 5. IEEE 24-bus test system.

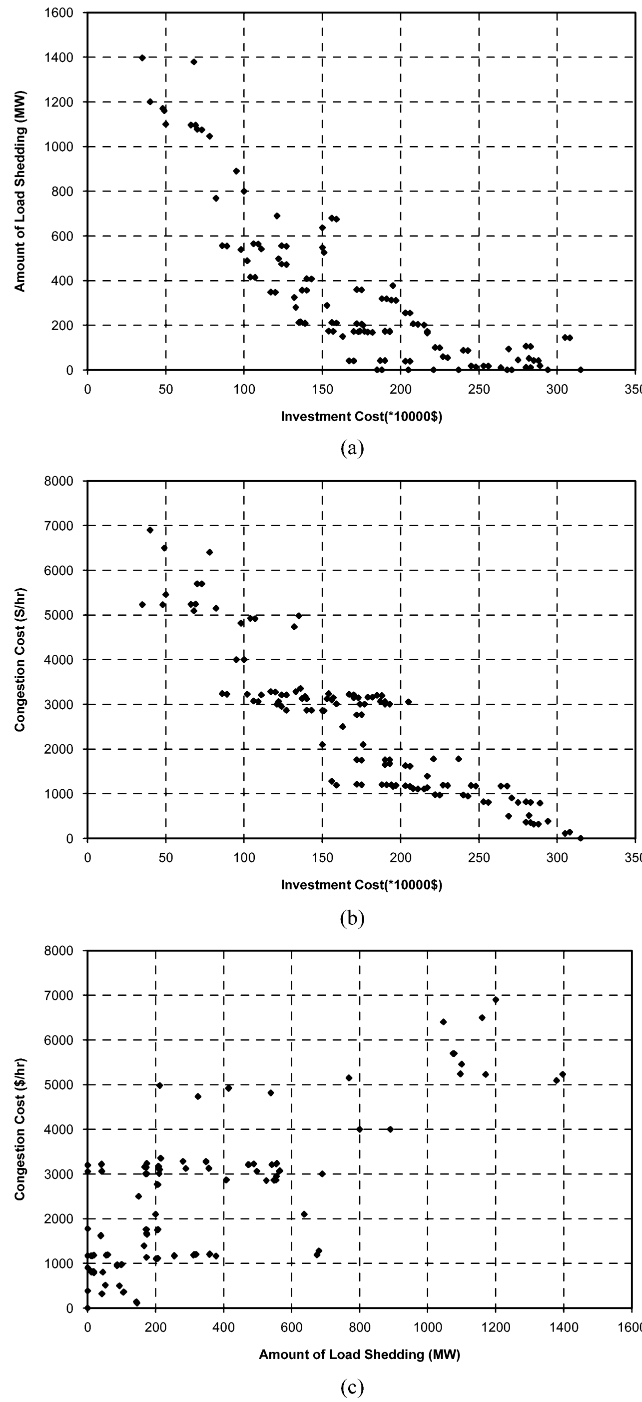

Fig. 6. Nondominated solutions (IEEE 24-bus test system). (a) Trade-off between amount of load shedding and investment cost. (b) Trade-off between congestion cost and investment cost. (c) Trade-off between congestion cost and amount of load shedding.

objectives, while Fig. 6(c) shows a fairly supportive relation between minimizing congestion cost and the amount of load shedding (reliability criteria). A more general and detail study on relation between congestion cost and system reliability improvement with respect to different network configurations can be found in [29] and [30].

It can be observed that the amount of load shedding is not reduced any more (is not sensitive) when investing more than about 2 million $ while the congestion cost looses its sensitivity when investing more than 3 million $.

Another observation is that the improvement rate of the second objective (minimizing congestion cost) with respect to the amount of investment is near zero in some regions such as between 1 to 1.5 million $, and for the third objective (minimizing amount of load shedding), the improvement rate is continuously decreasing. Note that these observations may be not valid for other systems.

For applying the fuzzy satisfying method, the decision maker should determine the minimum and the maximum values for each objective. The amount of load shedding and congestion cost in the base case (without any new lines) have been chosen as the maximum values of f_2 and f_3 (5427.2 $/h and 1963.1 MW, respectively) and their minimums have been set to 0.

For determining the minimum value of the first objective (investment cost), a classical single objective optimization model for transmission expansion planning has been solved resulting in 0.35 million $ investment cost for an adequate network corresponding to the addition of one new line in 1–2, 6–10, and 7–8 right-of-ways.

The objective function for this problem is defined as

$$\mathrm{Min} f = \sum_{(i,j)\in\Omega} c_{ij} n_{ij} + pf \sum_{k\in\Gamma} r_k. \tag{14}$$

The maximum value of this objective can be selected as the maximum expected available budget or the investment cost of the most expensive nondominated solution. Here, the second option has been chosen thus, the maximum value of this objective will be 3.15 million $.

TABLE I
NUMBER OF OPTIMAL NEW BRANCHES IN EACH CASE

Right-of-way	Number of branches added			
	Case 1	Case 2	Case 3	Case 4
1-2	0	0	1	0
3-9	1	1	1	1
6-10	1	1	1	1
7-8	1	1	1	1
10-12*	1	1	1	1
14-16	1	1	1	1
6-8**	1	1	1	1
20-22**	0	1	0	1

*: Indicates transformer
**: Indicates new right-of-way

Now, the decision maker should be asked to specify the reference membership values for each objective. The trade-offs depicted in Fig. 6 can help the decision maker to choose reasonable reference membership values. For example, Fig. 6(a) shows that the least cost secure solution (with zero load shedding) needs 1.85 million \$ investment so, to have a secure network, the amount of investment should be more than 1.85 million \$ or the reference membership value for the first objective (minimizing investment cost) should be less than $(3.15-1.85)/(3.15-0.35)=0.46$. In other words, selecting a reference value greater than 0.46 for the first objective will not guarantee to reach a secure solution. Table I shows the resulting solutions for the following cases:

Case 1: reference values are set to 0.45, 0.35, and 1 for three objectives, respectively, and using the minimax method
Case 2: reference values are set to 0.4, 0.6, and 1 for three objectives, respectively, aiming to find a solution with lower congestion cost and using the minimax method
Case 3: same as case 1 but using the metric distance method
Case 4: same as case 2 but using the metric distance method

The third and fourth cases were defined to determine the influence of the decision making method on the final solution. Note the p parameter in (11) is set to be 2, implying a 2-norm.

It can be observed that the two decision making methods have a minor effect on the final results. Also, the results show that some of the projects such as reinforcement of right-of-ways 3–9 and 6–10 are suggested in all cases. Therefore it can be concluded that these projects are "must do" ones regarding the security criteria.

Table II shows the objective values for different cases. It can be observed that by decreasing the reference value of the investment cost criteria together with increasing the desired satisfaction level for congestion cost objective, leads to a solution with much lower congestion cost while maintaining the security criteria. Comparing the best solutions of cases 1 and 3 shows that, using the metric distance method results in 1.62% increase of investment cost and only 0.2% decrease of congestion cost while, the best solutions for cases 2 and 4 are the same. In practical cases, the decision maker should run a detail decision making analysis with different methods of decision making to find the final compromise solution among the nondominated ones. Note

TABLE II
OBJECTIVE VALUES OF THE OPTIMAL SOLUTION IN EACH CASE

Case	Investment cost (million \$)	Amount of load shedding (MW)	Congestion cost (\$/hr)
1	1.85	0	3203
2	2.21	0	1788.4
3	1.88	0	3196.6
4	2.21	0	1788.4

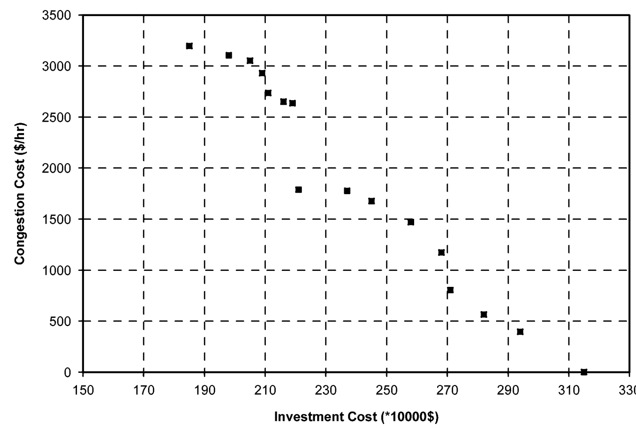

Fig. 7. Nondominated solutions in double objective model (IEEE 24-bus test system).

that the resulting solution should be checked to comply with dynamic stability and short circuit criteria in the second phase of planning process.

As indicated earlier, running a single objective optimization with classic objective function (aimed to find an adequate solution), results in a solution with investment cost of 0.35 million \$. Surprisingly, this solution has also been detected by the proposed multi-objective optimization model as a nondominated solution with 1397.1 MW of load shedding and congestion cost of 5232 \$/h. Comparing this solution with the least cost secure solution (solution found in case 1) shows that, investment cost of the optimal secure solution in this case study is 5.3 times the investment cost of the adequate one. Due to this large difference between the cost of a secure solution and the adequate one, it can be concluded that leaving the security analysis to the second phase of planning process may severely jeopardize the purpose of "optimal planning."

Note that if the planner is not interested only in secure solutions (those with zero load shedding), the probability of load shedding can be calculated easily and incorporated in the decision making process.

B. Double Objective Model (IEEE 24-Bus Test System)

Considering the security criterion as a constraint, the optimization model will have two objectives of minimizing investment cost and congestion cost.

The nondominated solutions in this case are shown in Fig. 7. These solutions were founded after 63 iterations.

While the decision making methods used in triple objective model are also applicable in this case, here a simple ranking method could be used based on the incremental cost-benefit

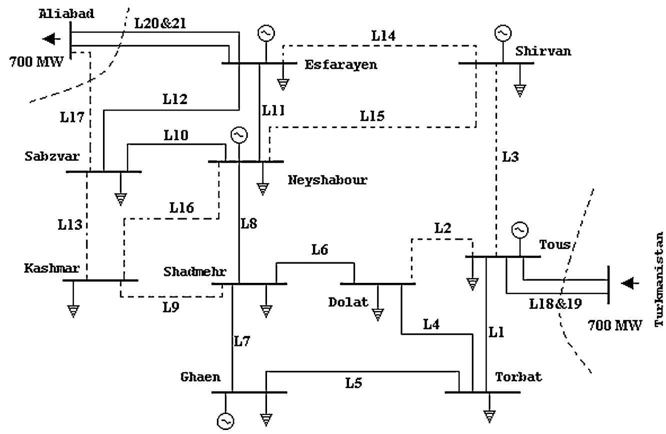

Fig. 8. Northeastern part of Iranian national 400-kv transmission grid.

(ICB) ratio concept. Comparing nondominated solutions with the base case, the ICB of each solution can be defined as

$$\mathrm{ICB}_i = \frac{\Delta CC_i}{\Delta \mathrm{Inv}_i} \tag{15}$$

where ΔCC_i is the difference between congestion cost of the base case and solution i (reduction in congestion cost) and $\Delta \mathrm{Inv}_i$ is the difference between investment cost of the base case and solution i (as the base case condition means zero investment so, $\Delta \mathrm{Inv}_i = \mathrm{Inv}_i$).

Among the nondominated solutions depicted in Fig. 7, the solution with 2.71 million \$ investment cost has the largest ICB which is 16.47. Congestion cost of this solution is 805 \$/h and its implementation requires installing new lines or transformers in 3–9, 3–24, 6–10, 7–8, 10–11, 14–16, 6–8, and 20–22 right-of-ways.

C. Iranian Power System

The proposed approach was also applied to a part of Iranian power system in order to compare the historical expansion plan and the expansion plan developed by the proposed methodology. Fig. 8 shows the simplified northeast part of Iranian national 400-kV transmission grid considered in this case study. This part of Iranian power system network is connected at one point to the main interconnected grid and at another point is connected to the neighboring country, Turkmenistan.

In Fig. 8 solid lines correspond to the existing 400-kV lines and dashed lines represent candidate new right-of-ways. A new power plant and a new load bus will be in service at the Shirvan and Kashmar regions, respectively (at the end of planning horizon) and the network should be able to transit a 700-MW wheeling transaction from Turkmenistan to the main Iranian interconnected grid. At the end of planning horizon (ten years in this paper), the total load will be 5766 MW and the total installed capacity will be 6150 MW (excluding the 700-MW wheeling transaction). The network data and investment costs can be found in the Appendix. Up to four lines in existing and new right-of-ways are considered as candidates. A generator at the Turkmenistan bus with 700-MW generation at a fix price (30 \$/MWh) and a 700-MW load at the Aliabad bus have been considered for modeling the wheeling transaction. For forcing the wheeling transaction to 700 MW, minimum and maximum capacity of the generator at Turkmenistan bus are equally defined to 700 MW.

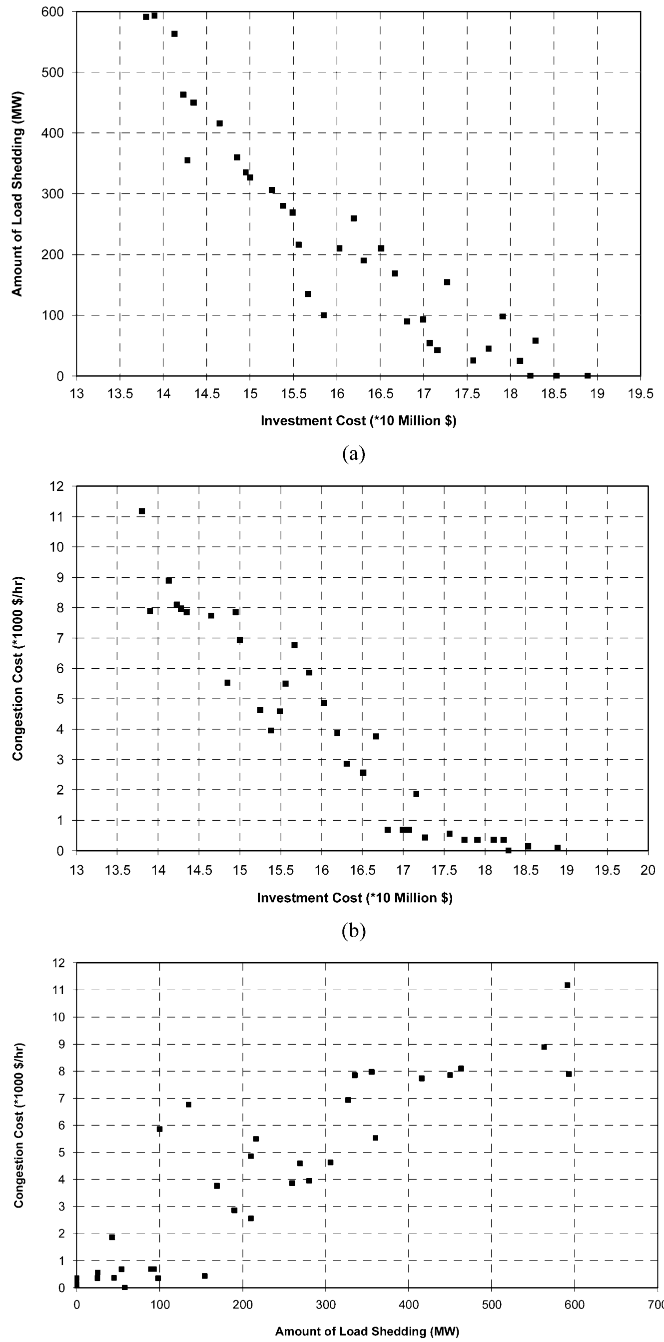

Fig. 9. Nondominated solutions (northeastern part of Iranian national 400-kV transmission grid). (a) Trade-off between the amount of load shedding and investment cost. (b) Trade-off between congestion cost and investment cost. (c) Trade-off between congestion cost and amount of load shedding.

Considering the triple objective formulation (5) with population size of 200, 34 nondominated solutions were found by the proposed algorithm after 123 iterations. Fig. 9 shows these nondominated solutions.

Starting with the base case configuration, a single objective optimization has been performed with minimizing investment cost as the objective to find the minimum and maximum of each objective similar to what has been done in Section IV-A

TABLE III
COMPARISON OF THE PROPOSED ALGORITHM PLAN AND IGMC'S PRACTICE

	L1	L2	L3	L9	L13	L14	L17
IGMC Plan	0	1	1	1	1	1	1
Proposed Algorithm Plan	1	2	1	1	1	2	0

TABLE IV
INVESTMENT COSTS OF BRANCHES IN NEW RIGHT-OF-WAYS (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	14	23	86
6	8	18	16	23	114
6	7	50	19	23	84
7	2	25	20	22	36

TABLE V
PARAMETERS OF BID FUNCTIONS (IEEE 24-BUS TEST SYSTEM)

Bus	a	b	Bus	a	b
1	0.01131	12.145	16	0.0667	9.2706
2	0.01131	12.145	18	0.0028	5.345
7	0.0122	17.924	21	0.0028	5.345
13	0.003	20.023	22	0.001	0.5
15	0.0667	9.2706	23	0.00392	8.919

TABLE VI
INVESTMENT COSTS OF BRANCHES (NORTHEASTERN PART OF IRANIAN NATIONAL 400-KV TRANSMISSION GRID)

Line	Length (km)	Capacity (MW)	Investment cost (\$/MW-km)
L1	183	800	200
L2	180	800	
L3	175	800	
L4	110	1100	200
L5	240	800	
L6	44	1100	
L7	181	800	
L8	132	1100	
L9	80	1100	
L10	110	1100	
L11	170	800	
L12	90	1100	
L13	120	1100	
L14	60	1100	
L15	198	800	
L16	105	1100	
L17	230	800	
L18 & L19	350	800	
L20 & L21	265	800	

resulting in 21663 \$/h, 3658 MW, and 138 million \$ for maximum congestion cost, maximum load shedding, and minimum cost for the adequate solution, respectively.

Note that for calculating the maximum congestion cost and maximum load shedding of the base case network, both isolated nodes (Shirvan and Kashmar) were excluded from the grid but, the load of Shirvan was included in the total load shedding.

Fig. 9(a) shows that the planner should at least invest 182.3 million \$ to have a secure solution. This means that the reference membership value for the first objective (minimizing investment cost) should be less than $(188.9-182.3)/(188.9-138) = 0.13$. Applying the fuzzy satisfying method with $\mu_1 = 0.11, \mu_2 = 0.9$, and $\mu_3 = 1$ results in a solution with investment cost of 185.3 million \$, zero load shedding (N-1 secure), and congestion cost of 140 \$/h at the peak load. This solution in companion with the expansion plan proposed by the Iranian Grid Management Company (IGMC) is presented in Table III. Note that the IGMC proposed plan is based on a five-year planning horizon while here in the simulation a ten-year planning horizon has been considered. This assumption is made to cause a more congested base case network because, with five-year planning horizon only line L1 will be congested.

The investment cost of the IGMC proposed plan is 150.8 m\$ and this solution is not among the nondominated solutions find by the proposed algorithm; may be because of different planning horizons and consequently different load level. Table III shows that both methods reached to almost the same expansion pattern which is construction and reinforcement of lines L2, L3, L9, L13, and L14.

As it can be seen, the proposed method generate a set of pareto-optimal solutions instead of one derived by the IGMC planning methodology. This set of alternatives gives the planner more flexibility for handing stakeholders' desires and will ease the recursive process of phase II analysis. For example, if the final solution could not satisfy the dynamic security constraints or short circuit limitations, the planner can simply switch to other solutions in the vicinity of the first one having similar performances with respect to objectives.

VII. 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.

There are several ways to improve the proposed algorithm such as incorporating risk analysis or probabilistic reliability assessment which are under development by the authors.

APPENDIX

Investment costs for existing right-of-ways for IEEE 24-bus test system can be found in [3] while for the new right-of-ways these costs are presented in Table IV. The bid function for each GENCO is defined in the form of $a_i p_i + b_i$ and the bid parameters are presented in Table V. For the northeastern part of

TABLE VII
PARAMETERS OF BID FUNCTIONS OF GENCOS AND LOAD LEVES
(NORTHEASTERN PART OF IRANIAN NATIONAL 400-kV TRANSMISSION GRID)

Bus	Maximum capacity (MW)	GENCOs' bid parameters		Load (MW)
		a	b	
Tous	1650	0.01131	12.145	506
Torbat	0	-	-	810
Dolat	0	-	-	823
Ghaen	800	0.01131	15.145	434
Shadmehr	0	-	-	1250
Neyshabour	1000	0.0222	17.924	531
Sabzvar	0	-	-	530
Esfarayen	1200	0.03	20.023	362
Shirvan	1500	0.01	12.445	0
Kashmar	0	-	-	520

Iranian national 400-kV transmission grid, investment costs of branches are given in Table VI and bid functions parameters and load levels are given in Table VII.

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