A Multi-Objective Transmission Expansion Planning Framework in Deregulated Power Systems With Wind Generation

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***Abstract*—Integration of renewable energy resources into the power system has increased the financial and technical concerns for the market-based transmission expansion planning. This paper proposes a stochastic framework for transmission grid reinforcement studies in a power system with wind generation. A multi-stage multi-objective transmission network expansion planning (TNEP) methodology is developed which considers the investment cost, absorption of private investment and reliability of the system as the objective functions. A non-dominated sorting genetic algorithm (NSGA II) optimization approach is used in combination with a probabilistic optimal power flow (POPF) to determine the Pareto optimal solutions considering the power system uncertainties. Using a compromise-solution method, the best final plan is then realized based on the decision-maker preferences. The proposed methodology is applied to the IEEE 24-bus Reliability Tests System (RTS) to evaluate the feasibility and practicality of the developed planning strategy.**

***Index Terms*—Attractive lines, deregulated market, multi-objective optimization, NSGA II, private investment, transmission network expansion planning.**

I. Introduction

TRANSMISSION system plays a key role in the successful transition of a regulated power system to a deregulated structure by providing a non-discriminatory competitive environment for power market participants [1]. An appropriate strategy for transmission network expansion planning (TNEP) guarantees a fair competition within the market as the system load and generation grow. However, TNEP in a deregulated power system (DPS) should consider several objectives rather than the single objective of investment cost minimization which is taken into account in a traditional TNEP [2]–[4]. In a DPS, minimizing the investment cost of the transmission lines is more highlighted in the sense that the pricing mechanism of the transmission services is influenced by the investment cost. This objective is required to lower the tariffs of transmission services for the market participants [2]. Market-based criteria should also be considered for TNEP to motivate the private investors and increase their participation in transmission projects [3]. In addition, successful trade in a competitive power market requires a desirable level of reliability which should be effectively implemented in TNEP [4].

Unlike other parts of the power system, the transmission section has not been attractive enough to absorb private investments due to the transmission service pricing, tariffs and investment risk. The lack of economic incentives in recovering the investment cost is the main drawback for construction of the new transmission projects in the United States [5]. The situation is even more stringent when the power system uncertainties increase with increasing penetrations of variable renewable energy sources such as wind and solar. With a nameplate installed capacity of 60 007 MW as of December 31, 2012, wind energy has become a significant resource in many electric utility systems across the United States [6]. In addition, favorable wind profiles in remote areas from the load centers necessitate the construction of new transmission lines which are less utilized due to the intermittent nature of wind power [6]. Therefore, the TNEP strategy in a restructured power market with renewable energy generation should address the private investors' concerns and provide economic incentives to encourage their investment in the transmission network.

The transfer capability of a transmission system is limited by the reliability criteria which are established by the North American Electric Reliability Council (NERC), Regional Reliability Council, or local jurisdiction (state or ISO). These criteria are determined by the stability limits, thermal limits, voltage collapse, and resource deficiency of the transmission lines [8]. Inefficient utilization of transmission infrastructure to accommodate electricity trades between different entities in a restructured market causes the transmission system to be operated closer to its physical constraints [9], [10]. Therefore, the secure and efficient operation of the transmission network is of significant importance to provide a desirable level of reliability and avoid congestion in a DPS. Towards this end, the TNEP strategy should offer transparent transmission prices while maintaining system reliability to support a competitive and non-discriminatory environment for the participants and circumvent the market power in a deregulated structure.

Two types of projects are proposed to alleviate the bottlenecks regarding the transmission expansion: reliability projects

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and market economic projects [10]. The reliability projects are regulatory requirements to satisfy the reliability criteria where an approved transmission rate is assigned to the investment recovery. In contrast, the cost recovery rate of the economic projects is not regulatory approved. Wind power intermittency and uncertainty regarding customer behaviors complicate the investment decision for merchant transmission projects. Thus, TNEP in a restructured power system should provide a proper strategy to consider the uncertainties of the system and maximize private investments absorption.

TNEP has been the subject of investigation in several studies [2], [11]–[20]. Deterministic methods were developed in [2] and [11]–[14] for TNEP problem without taking the power system uncertainties into account. While some studies have used stochastic models [15], [16], none incorporated the reliability criteria into the modeling. Reference [17] proposed a probabilistic TNEP framework for the power systems with high wind penetration but did not consider the risk involved in transmission investments. A game-theory based TNEP was proposed in [18] to manage the risk without incorporating the financial factors. References [2], [16], [17], [19], and [20] proposed multi-objective optimization framework to consider different criteria including investment cost, congestion cost and reliability for TNEP in deregulated power systems. However, none of these references addressed the financial aspects of transmission lines, which are the determining factors for the private investment. This is particularly essential in restructured power systems where the lack of economic incentives and measures for the transmission sector discourage private investment. Therefore, an appropriate strategy is required to determine the market economic projects and mitigate the monopoly power over the transmission network.

This paper develops a multi-stage multi-objective TNEP framework to provide the investors with economic incentives and maximize the absorption of private investment. An NSGA II optimization is used to obtain a set of Pareto optimal solutions that are non-dominant with respect to all objective functions. The best final plan is then selected using a decision-making method.

Section II explains the modeling methods including the wind, load and transmission financial modeling. Section III proposes a NSGA II optimization to solve the multi-objective problem of TNEP. It also presents a market-based OPF in combination with $2m+1$ estimation that characterizes power system uncertainties in TNEP. An efficient decision-making method is explained in Section III to select the best optimal solution based on the planner's preferences. Case studies and their simulation results are given in Section IV. Section V presents conclusions.

II. Modeling

A. Wind and Load Modeling

Probability density functions (PDFs) are used to model the uncertainties associated with wind speed and load demand [21]. The behavior of wind speed is stochastically characterized using the Weibull distribution:

$$f_{wd}(v) = \left(\frac{\alpha}{\beta}\right)\left(\frac{v}{\beta}\right)^{\alpha-1} e^{-\left(\frac{v}{\beta}\right)^{\alpha}}, \quad 0 \leq v \leq \infty \tag{1}$$

where α, β, v and f_{wd} are the shaping, scaling coefficients, wind speed and PDF of wind speed, respectively. The power-speed curve is used to calculate the wind power as [22]

$$P_W = \begin{cases} 0 & v \leq v_i, v \geq v_o \\ \dfrac{v - v_i}{v_r - v_i} P_{W_r} & v_i \leq v \leq v_r \\ P_{W_r} & v_r \leq v \leq v_o \end{cases} \tag{2}$$

where v_i, v_r, v_o, P_{W_r}, and P_W are the cut-in, rated, cut-out wind speeds, rated, and output wind powers, respectively. The variation of load demand is modeled by the Gaussian distribution as

$$f_{ld}(l) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[-\frac{(l-\mu)^2}{2\sigma^2}\right] \tag{3}$$

where l, μ, σ, f_{ld} are the load, mean value, standard deviation, and PDF of the load, respectively. Maximum likelihood estimation (MLE) is used to obtain the parameters of PDFs for historical wind speed and load data.

B. Transmission Financial Modeling

a) Transmission Pricing: An appropriate transmission pricing mechanism is required to calculate the cost of transmission services based on the extent of use of transmission resources. A well-organized and fair pricing method creates economic signals and incentives for the essential reinforcement and expansion of the transmission network. Postage-stamp rate and contract path are traditional methods for the recovery of transmission costs. The postage-stamp rate method charges transmission users based on an average embedded cost where the real extent of use of transmission facilities by each user is not considered. The contract path method restricts the transaction to a specified path which may differ from the actual path taken in reality. The MW-mile method recovers the transmission costs based on the actual use of the transmission network calculated by DC power flow. This strategy cannot provide a fair pricing mechanism because it recovers all the costs regardless of the extent of use of transmission line capacity [23]. The unused transmission capacity method is an enhanced version of MW-mile method to charge the users based on the percentage utilization of the transmission facility. The cost equation for this method is given by

$$\mathrm{TC}_t = \sum_{k=1}^{K} \frac{C_k \cdot L_k \cdot |f_{k,t}|}{|\bar{f}_k|} \tag{4}$$

where TC_t is the cost of transmission service and $f_{k,t}$ is the flow of line k for transaction t. C_k, L_k and $\bar{f}_k$ are the cost per MW per unit length, length, and maximum capacity for line k, respectively.

b) Rate of Return and Investment Risk Evaluation: Rate of return and risk are the most important determining factors for the investment in transmission projects. Power system uncertainties increase the risk level and make transmission investment less attractive to the private investors. Modern portfolio theory (MPT) provides a mathematical model to select an economic portfolio based on risk-return trade-offs and efficient diversification [24]. Here, the return rate of an investment is a

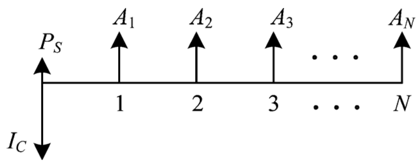

Fig. 1. Cash flow diagram for an investment.

random variable whose mean value indicates the expected profitability. The variance of the return is an indication of the risk involved which shows the deviation from the expected return. The mean-variance criterion is the basis of MPT for investment choice under uncertainties [25]. An economic portfolio or project gives the highest rate of return with a desirable level of risk. The return rate of an investment is calculated by solving the following equation for i:

$$\sum_{n=1}^{N} \frac{A_n}{(1+i)^n} = I_C - P_S \tag{5}$$

where I_C is the investment cost, P_S is the present worth of the salvage value, A_n is the annual revenue, and i is the return rate of the investment.

Fig. 1 shows the cash flow diagram for an investment.

III. Methodology

A multi-stage posterior method is used in this paper for transmission expansion planning in a deregulated environment. A set of Pareto optimal solutions is obtained which provides more flexibility when compared to one optimal solution for the single objective formulation. A compromise-solution method is used to find the best solution based on the planner's preferences.

A. Objective Functions

a) Investment Cost Minimization: Minimizing the transmission investment cost in a deregulated environment decreases the cost of transmission services for market participants. The transmission investment cost *IC* is minimized using

$$\text{Min } IC = \text{Min} \sum_{(i,j)\in\Omega} c_{ij} \cdot n_{ij} \tag{6}$$

where *IC* is the total investment cost of a candidate plan, c_{ij} is the cost of an added line and n_{ij} is the number of added lines to the corridor i-j, and Ω is the set of all corridors.

b) Private Investment Maximization: Power system uncertainties and the obstacles facing merchant transmission projects in a restructured electricity market discourage private investment in TNEP [26]. Insufficient transmission capacity mitigates the non-discriminatory competitive environment for market participants resulting in a monopoly power over the transmission network. An appropriate transmission expansion strategy is required to maximize private investment and eliminate monopolies in a deregulated environment.

Based on the revised unused transmission capacity method, the periodic revenue for transmission line l is calculated by

$$A_n^l = \alpha \cdot \text{TC}_l \tag{7}$$

where A_n^l is the periodic revenue, α is the annual return, and TC_l is the total cost of transmission service for the transmission line l. A_n^l and (5) are then utilized to calculate the rate of return (i) for each new transmission investment.

The rate of return for each transmission line is a probabilistic variable since it is determined using the power flow with random inputs. The mean value and standard deviation of the rate of return, defined as the expected rate of return (ROR_l) and investment risk (Risk_l), are used as two viable criteria to evaluate the investment in transmission projects [3]. These two parameters are then compared with the minimum attractive rate of return (*MARR*) and desirable risk level (Risk_d) to determine whether the transmission projects are attractive for private investors [3]. A transmission project is attractive if the following inequality constraints are satisfied:

$$\text{ROR}_l \geq \text{MARR} \tag{8a}$$

$$\text{Risk}_l \leq \text{Risk}_d \tag{8b}$$

where ROR_l is the rate of return and Risk_l is the and risk of investment for the transmission line l. Attractive transmission projects which satisfy (8) can absorb private investment. We maximize private investment PI^{AL} for the determined attractive lines:

$$\text{Max PI}^{\text{AL}} = \text{Max} \sum_{l=1}^{L} \text{PI}_l^{\text{AL}} \tag{9}$$

where PI^{AL} and PI_l^{AL} are the absorbed private investment for the attractive lines and lth attractive line, respectively. L is the set of attractive lines determined by constraint (8).

c) Reliability Maximization: Traditional transmission planning for conventional generation with firm capacities typically uses the deterministic $n-1$ security criterion for reliability analysis. This type of analysis is not appropriate for non-firm wind generation which is unlikely to exceed the $n-1$ firm transfer capacity. This results in an under-utilized transmission system as the high voltage transmission lines are usually available with high probability while the chance of wind generation curtailment when the $n-1$ contingency occurs is small. Therefore, a probabilistic reliability analysis is required to include both adequacy and security criteria for the expansion planning of transmission systems with wind generation. The probabilistic analytical state enumeration method is used here to calculate the reliability index [27]. This method uses the interrupted load and probability for every contingency to calculate the reliability index of a transmission network. Expected energy not supplied (EENS) is utilized as an energy index to represent the reliability level of transmission network. The reliability index of a transmission network can be calculated using

$$\text{EENS}_T = \sum_{i\in\phi} \sum_{j\in\Theta} \text{IL}_i^j \cdot P_j \tag{10}$$

where EENS_T is the expected energy not supplied for the transmission network, IL_i^j is the interrupted load at bus i due to the contingency j, P_j is the occurrence probability of contingency j, Θ represents the load buses, and ϕ is the set of contingencies. The occurrence probability (P_j) for each contingency j is obtained by multiplying the probability of component j not being available by the probability of other components being available. The following linear programming subproblem which minimizes the total interrupted load is solved to calculate the interrupted load (IL_i^j) for each contingency:

$$\text{Obj. Fun} = \min_{j\in\theta} \sum_{i\in\phi} \mathrm{IL}_i^j. \tag{11}$$

This objective function is subject to the following physical constraints of the network:

$$\sum_{i=1}^{n_b} P_{g_i} = \sum_{i=1}^{n_b} P_{d_i} \tag{12a}$$
$$f_{jk} = B_{jk}\left(n_{jk} + n_{jk}^{ex.}\right)(\theta_j - \theta_k) \tag{12b}$$
$$|f_{jk}| \le \left(n_{jk} + n_{jk}^{ex.}\right)\overline{f}_{jk} \tag{12c}$$
$$\underline{P}_{g_i} \le P_{g_i} \le \overline{P}_{g_i} \tag{12d}$$
$$\underline{P}_{d_i} \le P_{d_i} \le \overline{P}_{d_i} \tag{12e}$$
$$0 \le n_{jk} \le \overline{n}_{jk} \quad \forall(j,k)\in\Omega \tag{12f}$$
$$\mathrm{IL}_i^j = \overline{P}_{d_i} - P_{d_i} \tag{12g}$$

where f_{jk}, B_{jk}, and $\overline{f}_{jk}$ are the power flow, susceptance, and power flow limit of the line in corridor $j-k$. θ_j and θ_k are the voltage phases at bus j and k. $n_{jk}^{ex.}, n_{jk}$ and $\overline{n}_{jk}$ are the number of existing lines, number of new transmission lines and maximum number of added lines in corridor $j-k$. $P_{g_i}, \underline{P}_{g_i}$, and $\overline{P}_{g_i}$ are the power output, lower and upper generation limits for the ith generating unit. $P_{d_i}, \underline{P}_{d_i}$ and $\overline{P}_{d_i}$ are the supplied load, lower load limit and load demand for the ith bus. IL_i^j, the interrupted load at bus i due to the contingency j, is calculated by the taking the difference of the demand and the supplied load at each bus [8]. To reduce the simulation time of the reliability analysis, we use a contingency selection strategy that 1) ranks contingencies based on the product of their probability and interrupted load and 2) neglects contingencies for which this value is very small.

B. NSGA II Optimization

Generally, there are multiple optimum solutions for the multi-objective optimization of TNEP. A set of Pareto optimal solutions that are non-dominant with respect to all the objective functions is used. Several evolutionary algorithms have been proposed to solve a multi-objective optimization problem using the non-dominancy concept [28]. Elitist non-dominated sorting genetic algorithm (NSGA II) is an efficient evolutionary algorithm to handle the non-linearity, non-convexity and discontinuity of TNEP [28]. NSGA II is initialized using a set of randomly selected initial solutions. The initialized population is sorted into sets of Pareto solutions called Pareto fronts. The Pareto fronts are ranked based on their non-dominancy levels where the individuals of the first front are assigned the highest fitness value and so on. Crowding distance is calculated for each individual as a measure of proximity to its neighbors. The average crowding distance represents population diversity. A binary tournament algorithm is used to select parent populations based on their non-dominancy rank and crowding distance. Crossover, mutation and selection operators are then utilized to generate offsprings from the selected population for the next iteration. This process halts upon the satisfaction of a termination criterion [29].

C. Market-Based Optimal Power Flow

A one-sided auction market is incorporated into the OPF where the market participants submit their hourly price bids in the form of marginal generation costs. The hourly social cost (HSC) is minimized in an electricity market-based OPF using [16]

$$\text{Obj. Fun} = \text{Min}\left\{\sum_{i=1}^{n_g} P_{g_i}(t_h)\left(a_i P_{g_i}(t_h) + b_i\right) + \sum_{i=1}^{n_b} \alpha_i(\overline{P}_{d_i} - P_{d_i})\right\} = \text{Min (HSC)} \tag{13}$$

where α_i is a large penalty cost assigned to the interrupted load at each bus i. This objective function is subject to the constraints (12a)–(12f) for normal operating conditions.

D. Market-Based Probabilistic OPF

Due to the stochastic nature of wind power and load in TNEP, it is necessary to use probabilistic OPF analysis. Simulation, analytical and approximate methods are commonly used to perform probabilistic OPF (POPF) [30]. To avoid the computational burden of Monte Carlo simulation and mathematical calculations associated with analytical methods, we use Hong's approximate but efficient point estimation $(2m+1)$-scheme [31]. Note that although the mapping function from inputs to outputs is not known explicitly for our problem, the successive operators corresponding to this mapping, (5), (7) and (12a)–(12f) and (13), are all continuous with continuous derivatives which satisfy the conditions required for Hong's $(2m+1)$ method to converge.

In a $K \times m$ scheme, statistical information of the random input variables is represented by K points called concentrations. A location $x_{i,k}$ and a weight $w_{i,k}$ are used to form the kth concentration of the ith random variable. The location is determined by

$$x_{i,k} = \mu_{x_i} + \xi_{i,k}\cdot\sigma_{x_i} \tag{16}$$

where μ_{x_i}, σ_{x_i}, and $\xi_{i,k}$ are the mean, standard deviation, and standard location of the kth concentration for the random input variables x_i.

The weight and standard location are calculated by solving the following nonlinear system of equations:

$$\sum_{k=1}^{K} w_{i,k} = 1/m \tag{17a}$$
$$\sum_{k=1}^{K} w_{i,k}\cdot(\xi_{i,k})^j = \lambda_{i,j}, \quad j=1,\ldots,2K-1. \tag{17b}$$

The jth standard central moment of the ith random variable, $\lambda_{i,j}$, is

$$\lambda_{i,j} = \frac{M_j(x_i)}{(\sigma_{x_i})^j}. \tag{18}$$

The jth central moment of the ith random variable, $M_j(x_i)$, is given by

$$M_j(x_i) = \int_{-\infty}^{\infty} (x_i - \mu_{x_i})^j \cdot f_{x_i}\, dx_i \tag{19}$$

where f_{x_i} is the probability density function of the random variable x_i.

Upon obtaining all concentrations $(x_{i,k}, w_{i,k})$, the vector of random output variables $Z(ik)$ is calculated for each point $(\mu_{x_1}, \mu_{x_2}, \ldots, x_{i,k}, \ldots, \mu_{x_m})$ using the nonlinear input-output function F as follows:

$$Z(i,k) = F(\mu_{x_1}, \mu_{x_2}, \ldots, x_{i,k}, \ldots, \mu_{x_m}). \tag{20}$$

The jth moments of the random output variables are then estimated by

$$E[Z^j] \cong \sum_{i=1}^{m}\sum_{k=1}^{K} w_{i,k} \cdot (Z(i,k))^j. \tag{21}$$

Setting $K = 3$ and $\xi_{i,3} = 0$ yields $x_{i,3} = \mu_{x_i}$ in (17) and results in the same point of $(\mu_{x_1}, \mu_{x_2}, \ldots, \mu_{x_i}, \ldots, \mu_{x_m})$ for m of the $3m$ locations:

$$\xi_{i,k} = \frac{\lambda_{i,3}}{2} + (-1)^{3-k}\sqrt{\lambda_{i,4} - \frac{3}{4}\lambda_{i,3}^2} \quad k = 1, 2, \xi_{i,3} = 0 \tag{22}$$

$$w_{i,k} = \frac{(-1)^{3-k}}{\xi_{i,k}(\xi_{i,1} - \xi_{i,2})} \quad k = 1, 2$$
$$w_{i,3} = \frac{1}{m} - \frac{1}{\lambda_{i,4} - \lambda_{i,3}^2}. \tag{23}$$

Instead of using $w_{i,3}$ for each location, the weight w_0 is used and updated for the m locations in the $(2m+1)$-scheme as $\xi_{i,3} = 0$ and $x_{i,k} = \mu_{x_i}$ are the same for m of the $3m$ points:

$$w_0 = \sum_{i=1}^{m} w_{i,3} = 1 - \sum_{i=1}^{m} \frac{1}{\lambda_{i,4} - \lambda_{i,3}^2}. \tag{24}$$

To perform a POPF, the non-linear input-output function F in (20) is replaced with the OPF equations (13) and (12a)–(12f).

E. Decision Making

A set of Pareto optimal solutions is obtained as the result of solving the multi-stage posterior TNEP problem. Once the non-dominated set is determined, a rational decision needs to be made by the planner to find the final optimal plan. The decision making represents a compromise between different objectives based on the planner's preferences. We use a compromise solution as an efficient decision-making method to realize the best solution among the set of Pareto optimal solutions. This method minimizes the normalized Euclidian distance between the potential optimal and utopia points. The utopia point is defined as

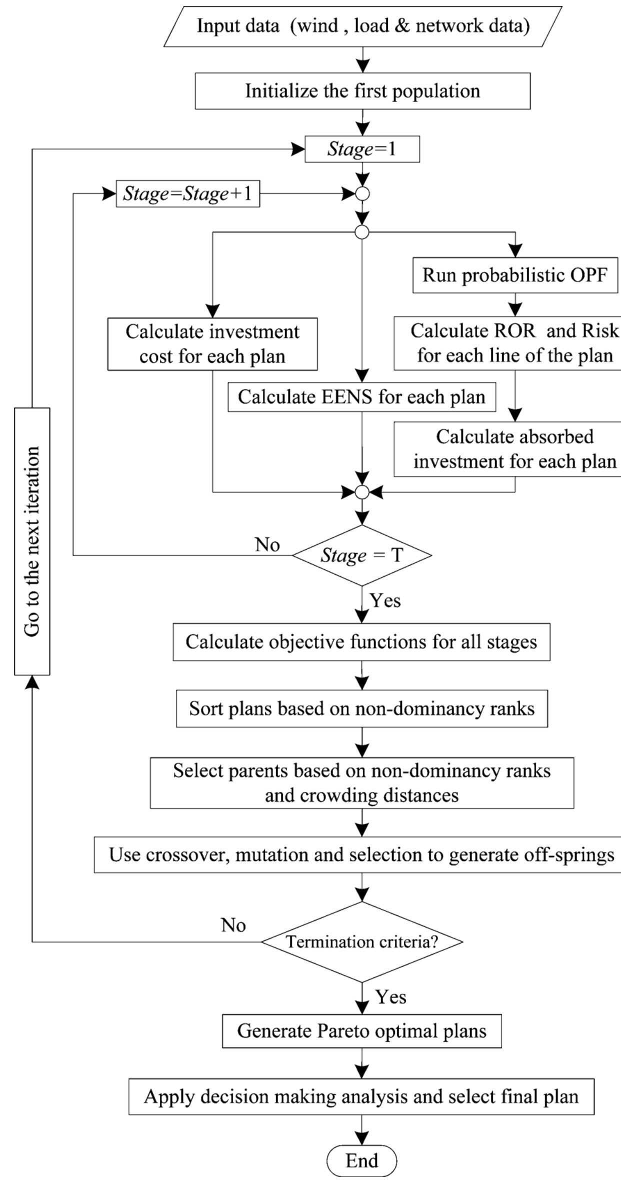

Fig. 2. Flowchart for the proposed TNEP framework.

a point which is sufficiently close to the minimum point. The Euclidian distance for our multi objective TNEP is minimized as follows [32]:

$$\min_{U\in\Phi}\left\{\sum_{i=1}^{n_o}\left|F_i(U) - F_i^0\right|^2\right\}^{\frac{1}{2}}. \tag{25}$$

$F_i(U)$ is the ith normalized objective function given by

$$F_i(U) = \frac{f_i^{\max} - f_i(U)}{f_i^{\max} - f_i^{\min}} \tag{26}$$

where $f_i^{\max}$ and $f_i^{\min}$ are the maximum and minimum values for the ith objective function. $f_i(U)$ and F_i^0 are the ith objective function value and normalized utopia point. Φ is the set of Pareto optimal solutions. Setting $F_i^0 = 1$ in (25) makes each objective function as close as possible to its minimum point. Normalization is required for a multi objective problem where the objective functions have different units.

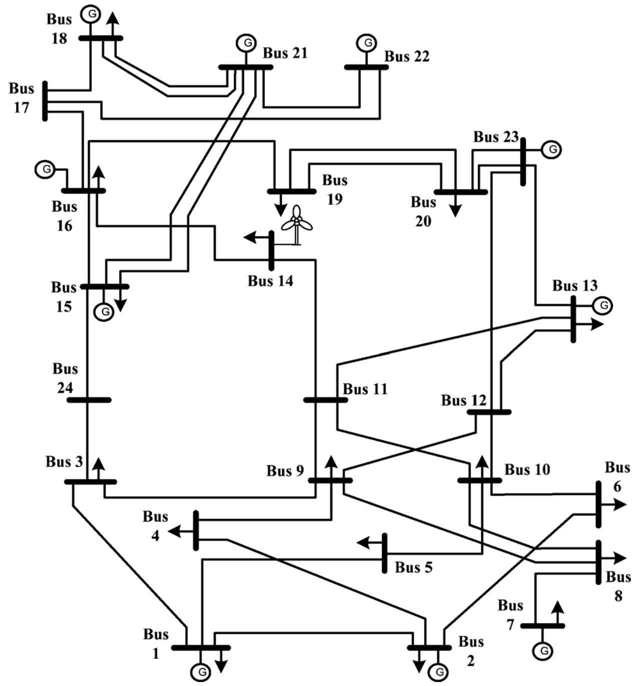

Fig. 3. IEEE 24-bus test system with wind installed at bus 14.

F. Proposed Algorithm

Fig. 2 shows the flowchart of the proposed algorithm for the multi-objective multi-stage TNEP problem. The algorithm begins with initializing the first population as the candidate transmission lines. The investment cost is determined for each plan using (6). Probabilistic OPF is used to calculate the line flows under normal operating conditions. The revenues for the transmission lines are obtained based on the line flow results and (7). Solving (5) for i gives the rate of return for the investment for each line in a plan. The $(2m+1)$ point estimate scheme is utilized to perform the POPF and calculate the rate of return for each transmission line. The input-output function F in (20) is the composition of the OPF equations (12a)–(12f) and (13), periodic revenue (7), and rate of return equation (5). The mean-variance criterion is used to calculate ROR_l and Risk_l from the investment for each line obtained in the previous step (the mean value and standard deviation of the return rate give the expected ROR_l and investment risk Risk_l). These two parameters are evaluated using (8a) and (8b) to determine whether the transmission line is attractive for private owners. The absorbed private investment is then evaluated for each plan based on (8). If these constraints are satisfied for a transmission line, the line is attractive and the associated investment is considered as the absorbed private investment. The absorbed private investment is calculated for all attractive transmission lines using (9). The reliability index (EENS) for each plan is calculated using (10)–(12).

Once all the plans are obtained for the planning horizon, the solutions are ranked and the parent population is selected using a binary tournament algorithm. Crossover, mutation and selection generate the off-spring population for the next iteration. This process is iterated until the termination criterion is satisfied. Upon obtaining the Pareto optimal plans from NSGA II, the decision maker uses an algorithm to select the final optimal solution based on the planner's preference.

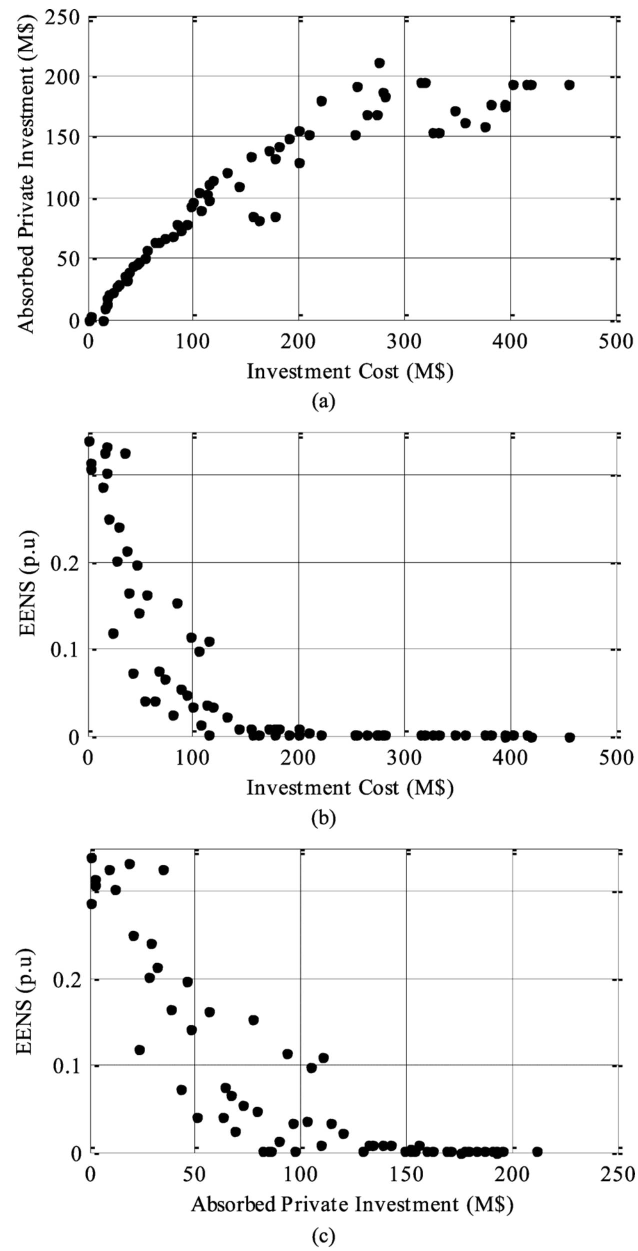

Fig. 4. Pareto optimal solutions for IEEE RTS and trade-offs between (a) absorbed private investment and investment cost. (b) EENS and investment cost. (c) EENS and absorbed private investment.

TABLE I
DECISION MAKING FOR TNEP

	Utopia Values			Objective Function Value		
Case	F_1^0	F_2^0	F_3^0	IC [a]	PI [b]	EENS [c]
I	0.75	0.4	0.98	107.55	89.8	0.0126
II	0.7	0.45	0.98	115.075	97.325	0.002

[a]: Investment cost (M$)
[b]: Absorbed private investment (M$)
[c]: Expected Energy Not Supplied (p.u)

IV. Case Studies

The proposed framework is used to determine the new transmission lines, their locations and the stages when the transmis-

TABLE II
TNEP RESULTS FOR THE FINAL PLANS

Corridor		Case I					Case II				
From	To	I[a]	RoR_l[b](%)	$Risk_l$[c] (%)	Stage	Merchant Transmission	I[a]	RoR_l[b](%)	$Risk_l$[c] (%)	Stage	Merchant Transmission
3	24	✓	23.03	0.99	2	✓	✓	22.71	0.99	2	✓
6	10	✓	24.28	1.79	2	✓	✓	24.53	1.68	2	✓
8	10	-	-	-	-	-	✓	17.84	1.35	3	✓
10	11	✓	15.68	0.8	3	✓	✓	15.42	0.79	3	✓
10	12	✓	1.45	0.17	3	-	✓	1.42	0.17	2	-
15	24	✓	18.06	1.57	2	✓	✓	19.47	1.37	2	✓
16	17	✓	16.97	1.36	3	✓	✓	18.93	1.61	3	✓
18	21	✓	23.85	0.89	2	✓	✓	24.9	0.89	2	✓
6	7	✓	7.93	2.07	3	-	✓	1.67	1.79	3	-

[a]: Installation status for transmission line l
[b]: Rate of return of investment for transmission line l
[c]: Risk of investment for transmission line l

sion reinforcement takes place within the IEEE 24-bus reliability test system (RTS) shown in Fig. 3 [33]. The OPF problem is solved using MATLAB [34]. Four stages, five years each, are considered for the 20-year planning horizon. Ten new right-of-ways as well as the existing 34 corridors are the candidate solutions for transmission installation. Transmission installation cost is $1000/MW-mile. Investment costs for the new transmission lines are given in the Appendix (Table IV) [2].

Table V shows the generation companies' (GenCos') bid coefficients. Load and generation growth rates of 7% and 6% per year are considered for the 20-year planning horizon. A wind farm is installed at bus 14 with an initial capacity of 500 MW. This capacity is increased to 750, 1000, 1250 and 1500 MW at the end of stages 1, 2, 3 and 4. The values of the discount rate, MARR, desirable risk level, and annual return are $d = 10\%$, $\mathrm{MARR} = 15\%$ $\mathrm{Risk}_d = 5\%$ and $\alpha = 25\%$.

Fig. 4(a)–(c) shows the Pareto optimal solutions for TNEP. Each subfigure represents the trade-off region between the two objective functions. Fig. 4(a) shows a supportive relation between the investment cost and absorbed private investment. Increasing the capital investment for transmission installation increases the capacity of the corridors that transfers the generated power to the load centers. This decreases the reliability index (EENS) of the system. As a result, more load is supplied which requires an increment in power flow through the transmission lines. Increased utilization of transmission capacity raises the revenue and rate of return for the transmission lines and makes the investment more attractive for the private sector. However, the symbiotic relation between these two criteria comes to a saturation state for investment costs of M$220 and above. This is due to the fact that there is no significant reliability enhancement as the investment cost increases above M$220, which results in constant or even reduced absorption of private investment.

Fig. 4(b) shows the trade-off region between the EENS as the reliability index and investment cost of the system. The optimal plans have a reliability index in the range of 0–0.35 p.u. which corresponds to an investment cost of 0–455 M$. As shown, the reliability of the system is significantly enhanced by increasing the investment cost up to M$ 220 but is almost constant for larger investment costs.

Fig. 4(c) gives a quantitative representation of the trade-off between the reliability criterion and absorbed private investment for the IEEE RTS. An increase in the absorbed private investment implies an investment cost increment, which provides more transmission capacity and decreases the interrupted load and EENS of the system.

TABLE III
RELIABILITY RESULTS FOR THE FINAL PLANS

Stage		1	2	3	4
EENS (p.u)	Case I	0.0026	0.0016	0.0007	0.0126
	Case II	0.0026	0.0001	0.0002	0.0020

The optimal solutions given by Fig. 4(a)–(c) are non-dominant with respect to each other. Based on the planner preferences, the most appropriate solution is adopted as the final plan using the compromise-solution method. Table I shows the final optimal plan for two sets of utopia points represented by Cases I and II (F_1^0 for investment cost, F_2^0 for absorbed private investment, and F_3^0 for reliability index). The values of utopia points can be selected based on different factors such as available budget and desired security level of the system.

TNEP results for the final plans of Table I are given in Table II. This table shows the new added transmission lines, rate of returns and risks of investment for each new line and the stages when the expansion takes place within the IEEE 24-bus RTS. The results include two types of transmission lines: reliability and merchant transmission lines. Transmission lines with $\mathrm{ROR}_l \geq 15\%$ and $\mathrm{Risk}_l \leq 5\%$ are the merchant transmission lines that provide private investors with economic incentives. The remainder includes the reliability transmission lines required to meet regulatory reliability criteria. The EENS of the transmission system for the final plan is calculated for different stages and given in Table III. The system is simulated for the last year of stage 4. Based on the simulation, there is a low probability (0.031) that wind power exceeds the transmission limit during the year.

V. CONCLUSION

A stochastic framework for transmission network expansion planning in deregulated power systems with wind generation has been presented. The proposed method describes a multistage multi-objective model to satisfy reliability requirements and provide economic incentives for private investors. This is

TABLE IV
INVESTMENT COST OF NEW LINES

From	To	Investment Cost (M$)	From	To	Investment Cost (M$)
1	8	3.15	13	14	15.5
2	8	2.89	14	23	21.5
6	7	4.36	16	23	28.5
6	8	1.58	19	23	21
7	2	2.19	20	22	9

TABLE V
GENERATION COMPANIES' BID COEFFICIENT

Generators	a_i	b_i	Generators	a_i	b_i
G1	0.01131	12.145	G7	0.00667	9.2706
G2	0.01131	12.145	G8	0.00028	5.345
G3	0.0122	17.924	G9	0.00028	5.345
G4	0.003	20.023	G10	0.001	0.5
G5	0.001	4	G11	0.00392	8.919
G6	0.00667	9.2706	-	-	-

critical in a restructured power market with renewable energy generation where the stochastic nature of renewable resources and deregulation policies increase the investment risk and decrease the rate of return involved in transmission projects. A NSGA II-based POPF was used to determine trade-offs between reliability measures, absorption of private investments and installation costs for different solutions.

The decision-making process was performed for different values of the utopia point to determine the final optimal plan based on the planner's preferences. The final plans clearly show two groups of merchant and reliability transmission lines. The proposed strategy provides valuable insights for both private investors and transmission network operators. It also mitigates the monopoly power over transmission networks. Simulation results for the IEEE 24-bus RTS demonstrate the feasibility and practicality of the developed planning algorithm. Note that the simulation time for real large-scale networks with many uncertain variables can be reduced by: 1) parallel processing, 2) reduced number of contingencies, 3) smart initialization of GA, and 4) use of MATLAB's MEX-files instead of M-files.

APPENDIX

Table IV lists the investment cost of new lines, and Table V lists the generation companies' bid coefficient.

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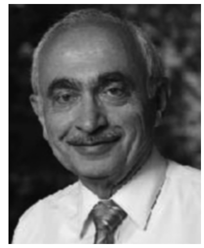

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