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Research Article

PRIVATE INVESTMENT ABSORPTION FOR TRANSMISSION NETWORK EXPANSION CONSIDERING WIND POWER UNCERTAINTY

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ABSTRACT
Despite of attracting the large value of investment cost in the power system arising from power industry deregulation, and unlike the generation and distribution sub-systems, transmission sector is still suffering from a lack of attractive private investment. This is due to the pricing policies of transmission service, tariffs, and investment risks. Besides, power systems' uncertainties can significantly discourage investors to invest in the transmission parts, due to their impact on the risk of investment return. In line with the impacts of uncertainties on the investment risks, it is very important to study the impacts of uncertainties associated with the wind power generation. Wind generation has founded its place in many power industries and is expected to have a notable portion in future power production. However, changeability and uncontrollability of this generation type made it a main source of uncertainty in power systems. Accordingly, wind power penetration can play a key role in increasing the investment risk in transmission networks. In this paper, the impacts of wind generation on the investment risk and recovered investment cost in the transmission network expansion are investigated. Wherein, with different portions of wind power penetration, the recovered values of invested cost in the transmission network are calculated and compared. To this end, some of the conventional generation capacities are replaced by wind type. The presented Transmission Network Expansion Planning (TNEP) problem is considered in a multi-objective form with objectives of minimum investment cost, maximum recovered investment cost, and maximum network reliability. The NSGA II algorithm is performed to determine the trade-off regions between TNEP objectives, and the Fuzzy satisfying method is used to decide about the final optimal plan. The simulations are implemented on the IEEE 24-bus reliability test system (RTS).

***Keywords**: Investment Return, Wind Generation, NSGA II, Point Estimation Method, Private Investment, Transmission Network Expansion Planning*

INTRODUCTION
Transmission Network Expansion Planning (TNEP) is one of the most important aspects in the traditional power system planning, in which the generation provided capacity to meet the anticipated needs of the loads should be transferred in a reliable and cost optimized manner. During the recent decades, deregulation changed the objectives of this topic as providing non discriminatory and competitive market conditions for all participants with respect to the reliability criteria (Maghouli *et al.*, 2009; Wang *et al.*, 2008). Contradicting interests and handling non-commensurable objective functions of TNEP in the deregulated environment led to this problem be considered from different standpoints. One of these stand points is absorption more private investment by transmission section of a power system. To this end, private investors must be encouraged with the maximum return rate and minimum risk to recover their investments. This need applying cost allocation methodologies to determine the merchant/economic transmission lines for investment (Gil *et al.*, 2005; Gil *et al.*, 2006; Zolezzi & Rudnick, 2002).
Despite of attracting the large value of investment cost in the power system arising from power industry deregulation, and unlike the generation and distribution sub-systems, transmission sector is still suffering from a lack of attractive private investment. This is due to pricing policies of transmission service, tariffs and investment risks. Besides, power systems' uncertainties can significantly discourage investors to

invest in the transmission part (Arabali *et al.,* 2014; Salazar *et al.,* 2007; Wu *et al.,* 2006). On the other hand, deregulation and unbundling led to appearing much more uncertainties in power systems and escalate the existing ones (Buygi *et al.,* 2004), which can be prohibitive factors for more private investment absorption. Generally, there are two categories of random and nonrandom uncertainties in the deregulated power systems; the random one is mainly related to load, wind farms' generation, generators' bids and outputs, availability of power system facilities and etc.; and uncertainties such as generation expansion/closures, load expansion/closures and market rules are categorized in the nonrandom type (Buygi *et al.,* 2004; Moeini-Aghtaie *et al.,* 2012). More private investment absorption is not compatible with these uncertainties, and taking them into the transmission expansion account can significantly increase the investment risks. However, studying the impacts of these uncertainties on the investment risks and determining the merchant projects can open up new research topics in TNEP issue.

In line with the impacts of uncertainties on the investment risks, it is very important to study the impacts of uncertainties associated with the wind power generation. Wind generation has founded its place in many power industries and is expected to have a notable portion in future power production (World Wind Energy Association, 2015). However, changeability and uncontrollability of this generation type made it a main source of uncertainty in power systems (Hamidi *et al.,* 2011). Accordingly, wind power penetration can play a key role in increasing the investment risk in transmission networks. Previously, impact of wind power penetration on the TEP problem and the related objective functions is frequently considered (Moeini-Aghtaie *et al.,* 2012; Munoz *et al.,* 2012; Orfanos *et al.,* 2013; Ugranlı & Karatepe, 2015). In this paper, the impacts of wind generation on the investment risk and recovered investment cost in the transmission network expansion are investigated. Wherein, with different portions of wind power penetration, the merchant/economic transmission lines and the recovered values of invested cost are determined and compared. To this end, some of the conventional generation capacities are replaced by wind type. By doing so, it can be seen how wind power penetration can change investors' incentive to invest in the transmission section of a power system.

Owing to TNEP in deregulated power systems is a multi-objective optimization problem, a posteriori approach with the ability of generating trade-off between different objectives should be applied. These trades-offs enable the transmission expansion planner to decide about the final plan for a better subjective judgment (Maghouli *et al.,* 2009; Wang *et al.,* 2008). Heretofore, some mathematical and evolutionary algorithms are proposed to find trade-off between TNEP objectives. State-of-the art on TNEP shows the genetic based NSGA II algorithm (Deb *et al.,* 2002; Shukla & Deb, 2007) enjoys more attention due to its simple implementation and inherent capability in determining trade-off regions of TNEP optimization problem (Arabali *et al.,* 2014; Maghouli *et al.,* 2011; Moeini-Aghtaie *et al.,* 2012). Due to this, here we apply this algorithm to handle the considered form of multi-objective TNEP problem. Then, the final optimal solution is searched among the Pareto (non-dominated) solutions by the Fuzzy decision making method based on the decision maker preferences. Here, the pursued objectives in the optimization process are the minimum value of allocated investment cost, with its maximum recovery, and maximum reliability of transmission network. It is worthy to note that minimizing the investment cost of the transmission lines reduces the tariffs of transmission services and facilitates competition in a power market (Maghouli *et al.,* 2009). Also, a reliable transmission network plays an important role in a successful trade in competitive electricity market (Choi *et al.,* 2005; Lopez *et al.,* 2013; Maghouli *et al.,* 2011). The uncertainties associated with load are modelled using the well-known probability density function (pdf) of the Gaussian distribution (Zou *et al.,* 2012), and addressed in the optimization problem by the Point Estimation Method (PEM) (Rosenblueth, 1975); the PEM is a simple yet relatively-accurate technique to calculate probabilistic power flow in power systems (Verbič & Cañizares, 2006).

The remainder of this paper is organized as follows. Initially, the problem modeling and solution method are explained. So, the simulation results are presented. Finally, some concluded remarks are drawn.

Problem Modeling and Solution Method

In this section, modeling, mathematical formulation and solution method of the considered multi-objective TNEP problem are explained in detail.

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Objective Functions

Different objectives can be addressed in the TNEP problem in the deregulated environments. Here, the pursued objectives are minimization of allocated investment cost, maximization of investment cost recovery, and maximization of transmission network reliability.

Investment cost minimization: Conventionally, the objective of reducing the transmission network expansion cost is the first and main objective in TNEP problem. In the new environments, minimizing the investment cost of the transmission lines reduces the tariffs of transmission services and facilitates competition for power market participants (Maghouli *et al.*, 2009). The investment cost IC is minimized as:

$$Min\, IC = Min \sum_{ij \in \Omega_c} c_{ij} n_{ij} \tag{1}$$

Where, IC is the total investment cost, c_{ij} the cost of an added line and n_{ij} is the number of added lines to the right-of-way of *i-j*. Ω_c is the set of right-of-ways.

Maximization of recovered investment cost: Insufficient transmission capacity is a serious obstacle in providing non discriminatory and competitive market conditions to participants (Fang & Hill, 2003). Incentives policies can encourage private investors and attract their investments to build new lines and improve transmission system capacity. These policies must be so that encourages investors with high rate of investment return and low level of risk (Arabali *et al.*, 2014). Thus, to encourage investors, the merchant/economic transmission lines (attractive lines) should be determined using a cost allocation methodology (Gil *et al.*, 2005; Gil *et al.*, 2006; Zolezzi & Rudnick, 2002). Hereby, the recovered investment costs can be maximized as:

$$Max\, RIC = Max \sum_{l=1}^{L} RIC_l^{AL} \tag{2}$$

Where, RIC, RIC_l^{AL} and L are the recovered investment cost, the recovered investment cost by the attractive line *l* and the set of attractive lines, respectively.

To determine the set of attractive lines, a cost allocation method should be applied. Different cost allocation methods are presented and implemented by electric utilities. Postage-stamp rate, contract path, MW-mile, and unused transmission capacity methods enjoy more practical application, among others. The postage-stamp rate method does not require the power flow calculations and is independent of the transmission distance and network configuration.

The method is based on the assumption that the entire transmission system is used, regardless of the actual facilities that carry the transmission service. The contract path method is analogous to an embedded cost method that does not require power flow calculations. This method restricts the transaction to a specified and artificial path which may differ dramatically from contract paths. The MW-mile is a power flow based method that is also known as a line-by-line method, because it considers changes in MW transmission flows and transmission line lengths in miles. This method does not consider the percentage of use of transmission line capacity.

This drawback of MW-mile method is improved by unused transmission capacity method wherein all transmission users are responsible to pay for both the actual capacity use and the unused transmission capacity. So, the transmission users are charged based on the percentage utilization of the facility capacity, and the rule of transmission service cost in MW-mile method for transaction *t* is revised as (Shahidehpour *et al.*, 2002).

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$$TC_t = \sum_{k=1}^{K} C_k \frac{\left|f_{t,k}\right|}{\overline{f}_k} \tag{3}$$

Where, TC_t is the cost of transmission service for *t*th transaction, $\left|f_{t,k}\right|$ and is the flow of *k*th line for *t*th transaction. $\overline{f}_k$ and C_k are the maximum capacity and the cost of transmission service per MW for *k*th line, respectively. K is the set of all lines.
Here, we use this method to allocate the transmission service cost of a built prospective line and consequently determine its ability in recovering investment cost. Having the total cost of transmission service for line *l*, the annual revenue (A_l^n) from this line would be calculated as:

$$A_l^n = \alpha TC_l \tag{4}$$

The annual return α is the investor share in the earned revenue from transmission service. So, the present worth of total revenue from the installed line *l* can be calculated using (5). In fact, by doing so the recovered investment cost by the line *l* is determined.

$$RIC_l = \sum_{n=1}^{N} \frac{A_l^n}{(1+d)^n} + SC_l \tag{5}$$

Where, SC_l is the present worth of salvage cost of *l*th line, d and N are discount rate and the time horizon, respectively. However, to determine the merchant/economic transmission lines (attractive lines) an appropriate economic analysis is needed. To do this, a present worth method is used and this is assumed that a transmission project is merchant if satisfy two criteria of the minimum rate of investment recovery ($MRIR$) and the desirable level of investment risk ($Risk_d$), as follows:

$$\frac{mean(RIC_l)}{IC_l} \geq MRIR \tag{6}$$

$$\frac{std(RIC_l)}{mean(RIC_l)} \leq Risk_d \tag{7}$$

Where, $mean$ and std denote to the expected value and standard deviation from expected value, respectively. Accordingly, the probabilistic distribution of the recovered investment costs by built prospective lines must be determined. This is done by calculating probabilistic OPF that takes the random behavior of loads into the account. In the next sections, more discussion about the probabilistic OPF is presented.
Maximization of transmission network reliability: As the final objective function, the reliability of the transmission network is maximized. A reliable transmission network plays an important role in a successful trade in the competitive electricity market. The presented publications on TNEP show that different reliability and security criteria can be inserted in TNEP formulation. Here, an N-1 based

probabilistic reliability analysis is used (Billinton & Allan, 1994), in which 1) respect to operational constraints, the power system must be able to withstand loss of any transmission facility, 2) in post-contingency situations, the sum of the interrupted load and curtailed wind generation should be minimized. Hereby, the objective function pertained to the transmission network reliability is calculated as:

$$Min\, RI = Min \sum_{c \in \theta} P_c (IL^c + CWG^c) \tag{8}$$

Where, RI denotes the reliability index, IL^c and CWG^c are interrupted load and curtailed wind generation due to contingency c, respectively. P_c is the occurrence probability of contingency c, and θ is the set of contingencies.

To determine the interrupted load and curtailed wind generation with each contingency, a market-based optimal power flow is calculated. A one-sided bidding model is supposed for power market where participants offer incremental costs as hourly cost function in tandem with their maximum generation. The Independent System Operator (ISO) would minimize the Hourly Social Cost (HSC) as follows (Maghouli *et al.*, 2011):

$$Min\, HSC = Min \left\{ \sum_{i=1}^{n_g} P_{g_i}(t_h)(a_i P_{g_i}(t_h) + b_i) + \sum_{j=1}^{n_d} pf_j (\overline{P}_{d_j} - P_{d_j}) \right\} \tag{9}$$

Where, pf_j is the penalty factor of interrupted load at bus *j*. The objective function (9) is subject to hourly DC load flow constraints as the physical constraints of power network:

$$\boldsymbol{S^T f} + \boldsymbol{P_g} + \boldsymbol{IL} = \boldsymbol{P_d} \tag{10a}$$

$$f_{ij} - B_{ij}(n_{ij}^0 + n_{ij})(\theta_i - \theta_j) = 0 \tag{10b}$$

$$\left| f_{ij} \right| \le (n_{ij}^0 + n_{ij}) \overline{f}_{ij} \tag{10c}$$

$$\underline{\boldsymbol{P}}_{\boldsymbol{g}} \le \boldsymbol{P_g} \le \overline{\boldsymbol{P}}_{\boldsymbol{g}} \tag{10d}$$

$$\underline{\boldsymbol{P}}_{\boldsymbol{d}} \le \boldsymbol{P_d} \le \overline{\boldsymbol{P}}_{\boldsymbol{d}} \tag{10e}$$

$$0 \le n_{ij} \le \overline{n}_{ij}, \ \forall (i,j) \in \Omega_c \tag{10f}$$

Hereby, the interrupted load at but *j* due to contingency *c*, would be calculated as:

$$IL_j^c = \overline{P}_{d_j} - P_{d_j} \tag{10g}$$

Where, $\boldsymbol{S}$ is the node-branch incidence matrix, and $\boldsymbol{f}$, $\boldsymbol{P_g}$, $\boldsymbol{IL}$ and $\boldsymbol{P_d}$ are the vectors of power flows, generated powers, interrupted loads, and supplied loads, respectively. f_{ij}, B_{ij} and $\overline{f}_{ij}$ are the power flow, susceptance, and power flow limit of a line in the right-of-way *i-j*. θ_i and θ_j are the voltage angles at buses *i* and *j*. n_{ij}^0, n_{ij} and $\overline{n}_{ij}$ are the number of existing lines, number of new lines and maximum number of added lines in the right-of-way *i-j*. $\boldsymbol{P_g}$, $\underline{\boldsymbol{P}}_{\boldsymbol{g}}$ and $\overline{\boldsymbol{P}}_{\boldsymbol{g}}$ are the vectors of power output, lower and upper generation limits. $\underline{\boldsymbol{P}}_{\boldsymbol{d}}$ and $\overline{\boldsymbol{P}}_{\boldsymbol{d}}$ are the vectors of lower load limits and load demands. $\overline{P}_{d_j}$ and P_{d_j} are load demand and supplied load at bus *j*. All variables in (10) are hourly parameters except for the number of added lines that for the sake of simplicity the time index of t_h is removed.

Note that, according to current operating practice in many countries, wind power must be priority dispatched. There upon, in the above formulation the production of a wind generator can be curtailed, only if the OPF problem is infeasible.

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Let us use a contingency selection strategy to achieve better CPU time in this reliability analysis. That, all contingencies are ranked based on the product of their occurrence probability and total value of interrupted load and curtailed wind generation; later on, the contingencies in which the mentioned value is very small, are neglected.

Probabilistic OPF

The random behavior of wind generation necessitates performing probabilistic OPF (POPF) to obtain the probabilistic distribution of output variables. The needed output variables are recovered investment costs by transmission lines and reliability index. The probabilistic distributions of recovered investment costs can be determined by calculating POPF and (3)-(5). Here, the expected value of reliability index is needed that can be calculated as (8); wherein IL^c and CWG^c are expected values of interrupted load and curtailed wind generation determined by calculating POPF. In the literature, several techniques such as simulation, analytical and approximation methods are proposed to calculate POPF. Computational burden is the major weakness for the simulation methods, and analytical methods need complex mathematical calculations. The approximation methods are simple and relatively-accurate that can make a compromise between the previous mentioned methods. The point estimation method (PEM) is proposed by Rosenblueth (1975) and is first used in Verbič & Cañizares, (2006) to calculate POPF, and frequently used in TNEP literature (Arabali *et al.*, 2014; Moeini-Aghtaie *et al.*, 2012). Accordingly, we use the two point estimation method (2-PEM) to determine the probabilistic distributions of output variables. The input variables are wind speed at the location of wind generators.

Wind Modeling

The stochastic behavior of wind speed is modeled by probabilistic distribution function, as the commonly used Weibull distribution. The output of each wind generator is calculated from the power-speed curve (Manwell *et al.*, 2010):

$$P_W = \begin{cases} 0 & v \le v_{ci}, v \ge v_{co} \\ P_R\,(v - v_{ci})/(v_r - v_{ci}) & v_{ci} \le v \le v_r \\ P_R & v_r \le v \le v_{co} \end{cases} \tag{11}$$

where, P_R, P_W, v_{ci}, v_r and v_{co} are rated, output wind generations, cut-in, rated and cut-out wind speeds, respectively.

Optimization Method

Making trade-off between different objectives of TNEP problem in deregulated environment needs a posteriori approach.

The approach should handle different objectives and enables decision makers to decide about the best plan based on a cost-benefit analysis. This necessitates using the concept of Pareto optimality; a solution is Pareto-optimal (non-dominated) that improves at least one objective function, without degrading the other objective functions.

Heretofore, some mathematical and evolutionary algorithms are proposed to find the non-dominated solutions of a multi-objective optimization problem. Among them, NSGA has shown its capability and robustness in handling non-convex and non-linear problems, and mixed integer programming (Deb *et al.*, 2002; Shukla & Deb, 2007).

In this paper, we use the NSGA II algorithm to determine trade-off between objectives of the considered TNEP problem. The algorithm starts with a random initial population that is sorted into sets of Pareto solutions called Pareto fronts.

The Pareto fronts are ranked with the aid of the non-dominancy concept that the first front includes the individuals with the highest fitness value, and so on. The crowding distance is computed for each individual and the population diversity is measured by the average value of crowding distances. The parents are selected based on their non-dominancy ranks and crowding distances to generate offsprings, using crossover, mutation and selection operators, for the next iteration. This procedure continues till the termination criterion is not satisfied (Deb *et al.*, 2002).

Final Decision Making

Having trade-off between TNEP objectives provides decision maker with a bird's eye view to select the best solution. To take decision maker judgment into account to select the final solution an appropriate method with the ability of human thought modeling is needed. The Fuzzy satisfying method is a proper tool to achieve this aim owing to its similarity to human subjective reasoning. A strictly monotonically declining and continuous membership function is assigned to each objective (Sakawa & Yano, 1989). Respect to each objective, a solution takes a value from 0 to 1 from membership function. This value indicates to what extent a solution satisfies the decision maker about an objective. The linear membership function used in this paper is as follows:

$$\mu_{f_i}(x) = \begin{cases} 0 & f_i(x) > f_i^{\max} \\ (f_i^{\max} - f_i(x)) / (f_i^{\max} - f_i^{\min}) & f_i^{\min} \le f_i(x) \le f_i^{\max} \\ 1 & f_i(x) < f_i^{\min} \end{cases} \tag{12}$$

Where, μ_{f_i} is the membership function value for the *i*th objective function, $f_i^{\max}$ and $f_i^{\min}$ are the maximum and minimum values for the *i*th objective function, and $f_i(x)$ is the value of this objective function for solution *x*. Based on the decision maker judgment, the satisfaction (desired) level of each objective is determined.

Solving optimization problem of (13), the final solution will be found. This formulation would minimize the total deviations from desired levels.

$$\min_{x \in \varphi} \quad \sum_{i=1}^{3} | \mu_{d_i} - \mu_{f_i} |^p \tag{13}$$

Where, $0 \le p < \infty$. μ_{d_i} is the satisfaction level of *i*th objective, and φ is the set of solutions. This formulation would minimize the *p*-norm deviations from satisfaction levels. The trade-off between objectives derived by NSGA II could help the decision maker to select reasonable satisfaction levels.

Implemented Algorithm

Flowchart of the implemented algorithm to solve the multi-objective TNEP problem is presented in Figure 1. The first population is initialized and objective functions are determined for each individual of the population.

The investment cost for each individual (each transmission plan) is calculated using (1). Adding each plan to the transmission network, the values of RI and RIC are determined. The reliability index RI is calculated using (8)-(10). The RIC value is determined by calculating POPF and (2)-(7). The POPF is performed in no-contingency status (normal condition) to obtain probabilistic distribution of lines flow. For each new line, the transmission service cost, the annual revenue and the present worth of total revenue (i.e. recovered investment cost) are calculated from (3)-(5).

Having probabilistic distribution of RIC for each line, the satisfaction of minimum rate of investment recovery and desirable level of investment risk criteria are checked using (6) and (7), respectively. This is to determine whether a built prospective line is attractive (merchant) for private investors or not. Having the set of attractive lines, the RIC value for each individual of the population is calculated using (3). After determining objective functions for all individuals, the population is sorted with respect to the objective functions based on non-dominancy concept and crowding distance is calculated for each individual.

The parents are selected based on their non-dominancy ranks and crowding distances. The offsprings are generated using crossover, mutation and selection operators, for the next iteration. This process continues for next generations until the termination criterion (number of iterations) is satisfied. If the termination criterion is satisfied, the non-dominated individuals would be provided as trade-off between TNEP objectives. In the end, decision maker decides about the final optimal plan based on his/her preferences using Fuzzy satisfying method.

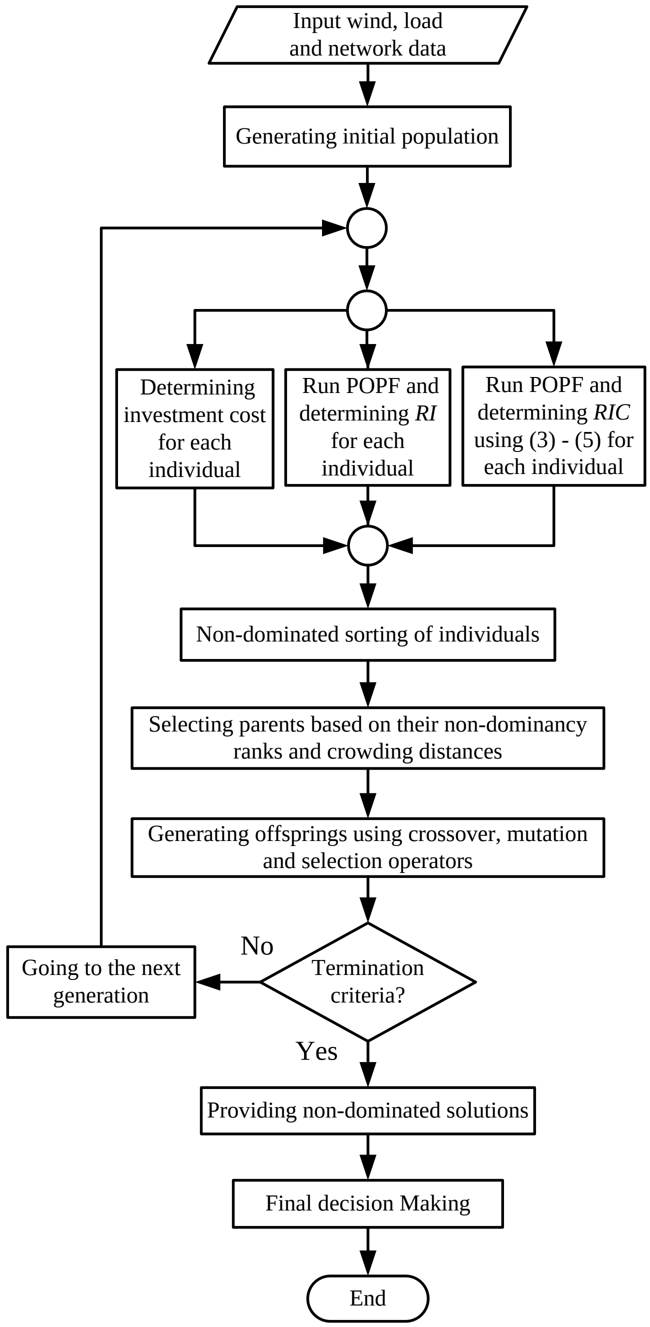


Figure 1: Flowchart of the Implemented Algorithm

RESULTS AND DISCUSSION

Simulattion Results

These simulations are carried out in MATLAB environment with Matpower operation functions (Zimmerman *et al.*, 2011). The IEEE 24-bus reliability test system is used as the case study. The needed data of system have been taken from (Fang & Hill, 2003; Subcommittee, 1979). Let us assume, this network must be expanded for the next fifteen years and load and generation are increased with annual incremental rates of 8% and 7%, respectively. The existing 34 paths as well as 7 new right-of-ways are the candidate paths for transmission line installation. The values of minimum rate of investment recovery

($MRIR$), desirable level of investment risk ($Risk_d$), annual return (α) and discount rate (d) are 90%, 10%, 30%, and 10%, respectively.

The generation buses 2, 7 and 22 are selected to install wind power capacity. The conventional generation capacities at these buses are 192, 300 and 300 MW at the first year, respectively. In order to study impact of wind generation uncertainty, some of conventional capacities at these buses are replaced by wind generation type.

For each percentage of conventional capacity replacement, the algorithm of Figure 1 is implemented to solve the considered TNEP problem.

Initially, the algorithm is implemented with no wind capacity installation. In this condition, we're dealing with a deterministic TNEP problem. The determined trade-offs between objectives of the considered TNEP problem is presented in Figure 2. Figure 2(a) is a trade-off between the investment and recovered investment costs.

This Figure shows there is an incremental and supportive relation between investment cost and recovered investment cost. In lower values of investment cost, the transmission network has more potential to recover the invested cost; the number of new installed lines is fewer and transmission network is more congested and utilized, and consequently more revenue from the new lines is earned to return the investment cost.

However, for investment cost of M$16 and above, the supportive relation between investment cost and recovered investment cost comes to a saturation mode. Owing to, the excess installation of new lines with low utilization of them reduces the value of recovered investment cost.

The trade-off between investment cost and the reliability index is as Figure 2(b). This Figure illustrates that the reliability of transmission network increases as much as increase in the investment cost. Because, an investment cost increment improves transmission capacity and consequently improves the network reliability. This Figure shows, with about M$7 of investment cost, the reliability index becomes negligible.

Now, two other simulations are separately performed; one with 40% and another with 80% of conventional capacity replacement at buses 2, 7 and 22 by wind type. For the sake of comparison, the obtained results along with the previous one are shown in Figure 3 in a collective manner. Hereby, we can better analyze the impact of wind generation uncertainty on the TNEP objective, especially on the recovered investment cost.

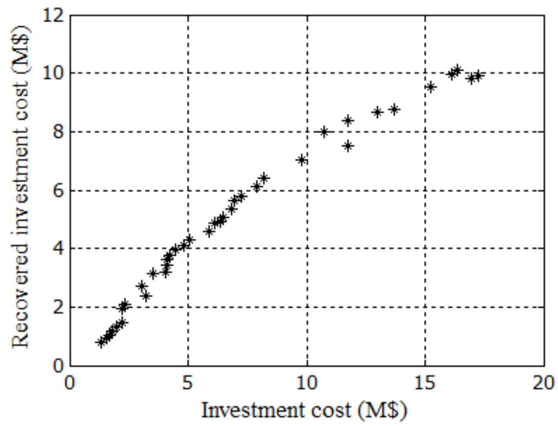
Figure 3(a) shows, in deterministic condition (no conventional capacity replacement), the recovered investment cost is more than other cases. In this condition, the maximum recovered investment cost is M$10. While, this value is M$8 and M$6.2 for 40% and 80% of conventional capacity replacement by wind capacity, respectively.

As an illustrative instance, suppose the investment cost is M$10.75; in deterministic condition, M$7.98 (74%) of it is recovered.

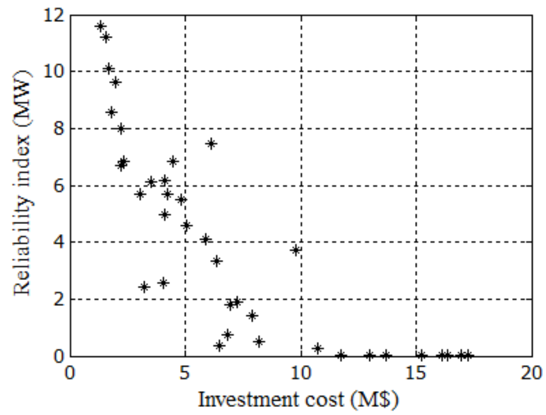
While, M$6.47 (60%) / M$5.67 (53%) of this investment cost value will be recovered, if 40% / 80% of the conventional capacity be replaced. Also, in deterministic condition, the relation between investment cost and recovered investment cost reaches to the saturation mode at the investment cost of M$16 and above.

But, this saturation mode appears at about M$13 and M$11.5 of investment cost for 40% and 80% of conventional capacity replacement, respectively. This is because, the stochastic behavior of wind generation increases the uncertainty level and investment risk, and consequently the remainder new transmission projects becomes non-attractive; the remainder new transmission lines cannot satisfy one or both of the criteria of the minimum rate of investment recovery ($MRIR$) and the desirable level of investment risk ($Risk_d$), i.e. the criteria (6)-(7).

Figure 3(b) provides trade-offs between investment cost and reliability index. This Figure shows, replacing the conventional capacity by the wind type increases the reliability index. Consequently, more investment cost is needed to reduce reliability index and improve network reliability.

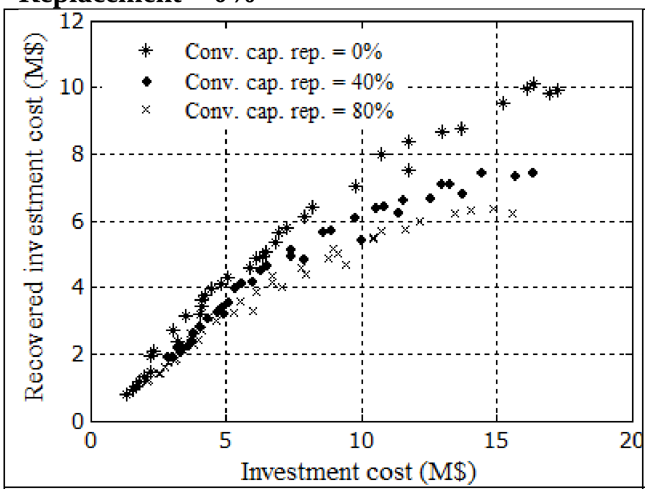


(a) Trade-off between Investment Cost and Recovered Investment Cost

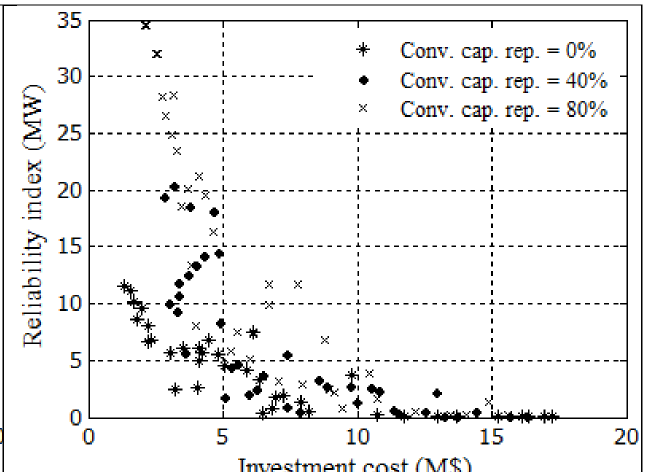


(b) Trade-off between Investment Cost and Reliability Index

Figure 2: The Determined Trade-offs between TNEP Objectives, when Conventional Capacity Replacement = 0%



(a) Trade-off between Investment Cost and Recovered Investment Cost



(b) Trade-off between Investment Cost and Reliability Index

Figure 3: The Determined Trade-offs between TNEP Objectives, with Different Percentages of Conventional Capacity Replacement

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The decision making results from the Fuzzy satisfying method are presented in Tables 1 and 2. Table 1 gives the results for each level of uncertainty, with different satisfaction levels. For the satisfaction levels $\mu_{d1} = 0.5$, $\mu_{d2} = 1$ and $\mu_{d3} = 1$ of Table 1, the final plans are as Table 2.

This Table shows, in deterministic condition more attractive lines for investing exists. These lines are selected as the final plan to expand transmission network. Hereby, the number of selected attractive lines is 9, 7 and 5 for 0%, 40%, and 80% of conventional capacity replacement, respectively. This is due to that some of lines cannot satisfy one or both of $MRIR$ and $Risk_d$ criteria. For instance, the new line 8-9 satisfies these criteria and is selected as an attractive line for 0% and 40% of conventional capacity replacement.

However, this line cannot satisfy the $Risk_d$ criterion when conventional capacity replacement is 80%, so is not an attractive line for private investing. Also, the line 15-21 is selected as attractive in deterministic condition, but due to inability in satisfying the $MRIR$ criterion is not selected for the two other conditions.

Table 1: Fuzzy Decision Making

Satisfaction Levels			Conv. cap. rep. = 0%			Conv. cap. rep. = 40%			Conv. cap. rep. = 80%		
μ_{d1}	μ_{d2}	μ_{d3}	IC[a]	RIC[b]	RI[c]	IC	RIC	RI	IC	RIC	RI
0.5	1	1	11.76	8.38	0	11.53	6.67	0.29	10.75	5.67	1.68
1	0.5	1	6.45	5.04	0.3	6.24	4.55	2.42	7.06	3.99	3.08
1	1	0.5	4.24	3.78	5.70	7.34	5.14	5.59	4.32	3.08	19.55

[a]: Investment cost (M$)
[b]: Recovered investment cost (M$)
[c]: Reliability index (MW)

Table 2: Final Plans, $\mu_{d1} = 0.5$, $\mu_{d2} = 1$ and $\mu_{d3} = 1$

Path		Conv. cap. rep. = 0%				Conv. cap. rep. = 40%				Conv. cap. rep. = 80%			
From	To	X[a]	Risk[b](%)	RIC[c](%)	AL[d]	X	Risk(%)	RIC(%)	AL	X	Risk(%)	RIC(%)	AL
1	5	1	0	54	No	1	9	54	No	0	-	-	-
2	6	1	0	46	No	1	9	40	No	1	27	30	No
3	24	1	0	97	Yes	1	3	97	Yes	1	6	90	Yes
6	10	1	0	91	Yes	1	6	98	Yes	1	9	97	Yes
8	9	1	0	93	Yes	1	9	91	Yes	1	17	93	No
8	10	0	-	-	-	1	15	40	No	0	-	-	-
10	11	1	0	72	No	0	-	-	-	1	8	55	No
10	12	1	0	106	Yes	1	2	86	No	1	6	90	Yes
12	23	1	0	96	Yes	1	3	90	Yes	1	4	67	No

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13	23	1	0	63	No	0	-	-	-	0	-	-	-
14	16	1	0	114	Yes	1	6	94	Yes	1	9	103	Yes
15	21	1	0	90	Yes	1	3	82	No	1	7	51	No
15	24	1	0	98	Yes	1	1	98	Yes	1	6	88	No
16	17	1	0	120	Yes	1	5	107	Yes	1	9	92	Yes
17	18	1	0	58	No	1	3	74	No	1	6	30	No
14	23	0	-	-	-	1	6	40	No	0	-	-	-

[a]: Installation status
[b]: Risk of investment
[c]: Recovered investment cost
[d]: Attractive line

Conclusion

The impact of wind generation on the recovered investment cost in transmission network expansion was investigated in this paper. As it was described, the NSGA II algorithm was performed to determine the trade-off regions between TNEP objectives, and the Fuzzy satisfying method was applied to decide about the final optimal plan.

Simulation results show that wind generation penetration can reduce the number of attractive lines and consequently reduces the recovered value of investment cost. This can significantly discourage private investors from investing in the transmission section of power systems. This is because, the wind generation is changeable and uncontrollable and a new transmission line may ineffectively be utilized, so the line returns the private investment with a disappointing rate.

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