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Robust Transmission Network Expansion Planning Considering the Effect of Uncertain Generation from Renewable Energy Source

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Abstract: This study proposes a novel method of Robust Transmission Network Expansion Planning (RTNEP) considering effect of renewable energy generation. The RTNEP problem will be formulated by using an AC Model instead of DC Model in order to obtain more accurate result. The investment cost of transmission lines and operating cost of conventional generators are considered as the objective function of the planning. In order to obtain the robust expansion plan for all possible scenarios of renewable energy generation and loads, the method to select the suitable scenarios as the considered criteria in the planning is proposed. To obtain the optimal expansion plan, a metaheuristic algorithm called Adaptive Tabu Search (ATS) is employed in the proposed RTNEP. With the proposed method, ATS iterates between the main problem which minimizes the investment cost and operating cost and the subproblem which is the process to avoid the violation of system operating constraints by using generation re-dispatch and curtailments of renewable energy generation and loads. The IEEE Reliability Test System 79 (RTS 79) is used to test the proposed method and to study the effect of renewable energy generation on RTNEP. The results show that the proposed RTNEP provides the solution more robust than the previous works and the effect of renewable energy generation on RTNEP is rather high which cannot be neglected in the planning.

Key words: Adaptive Tabu search, renewable energy generation, robust transmission network expansion planning, scenarios selection, model, function

INTRODUCTION

Because of the electrical demand growth, transmission expansion is needed to resolve the electricity inadequacy problem by the minimal investment and operating costs while system operating constraints are not violated and system reliability should be acceptable (Akbari *et al*., 2012; Cebeci *et al*., 2011; Sepasian *et al*., 2006). Moreover, from the energy sustainability viewpoint, the Ministry of Energy (Thailand) has proposed an implementation plan of renewable energy resources in electricity generation with the target of 19,684.40 MW in the year 2036 (Anonymouse, 2015). Although, this kind of power generation can reduce fossil fuel consumption and CO_2 emission, its intermittent characteristics, especially solar and wind power can increase the uncertainty of net power injection at the connecting bus which consequently affects the system operation and planning. Therefore, Transmission Network Expansion Planning (TNEP) for integrating these intermittent power generations has to be revised in order to ensure the security of system operation among intermittent renewable energy generations and loads.

Practically, Transmission Network Expansion Planning (TNEP) is generally planed based on the experiences of system planners. The method is based on the minimum cost solution techniques (Khatib, 2003; Stoll, 1989; Sullivan *et al*., 2003). A set of alternatives of expansion plans is selected from the set of all feasible plans. The computational tool is only power system analysis software based on the Newton-Raphson algorithm (Grainger and William, 1994) for solving a set of nonlinear power flow equations. After that, the suitable plan in a set of alternative plans is selected by the planners based on experiences and results from power flow solutions.

From the literature review of TNEP, TNEP methods can be classified into 3 methods consisting of mathematical method, heuristic method and meta-heuristic method (Latorre *et al*., 2003). For the mathematical method, optimization techniques such as bender

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decomposition (Asadamongkol and Eua-Arporn, 2010), linear programming (Chanda and Bhattacharjee, 1994), dynamic programming (Dusonchet and El-Abiad, 1973), nonlinear programming (Youssef and Hackam, 1989) and mixed integer programming (Bahiense *et al*., 2001) are mostly used. For the heuristic method, a sensitivity analysis is used to allocate the additional transmission lines (Ekwue and Cory, 1984). Some researches use the sensitivity index with respect to the load curtailment to identify transmission line investment (Monticelli *et al*., 1982). For the meta-heuristic method, a Simulated Annealing (SA) is proposed for long-term TNEP (Romero *et al*., 1995), a Tabu search is presented for single Stage TNEP (STNEP) (Silva *et al*., 2001). A Genetic Algorithm (GA) for multistage planning of TNEP is presented (Escobar *et al*., 2004).

For the TNEP considering the renewable energy generation, transmission planning with renewable energy source integration using Discrepancy Bounded Local Search (DBLS) is proposed (Bent *et al*., 2011). TNEP problem by using mixed-integer linear program considering the impact of wind power operation is modeled (Munoz *et al*., 2012). Ant colony optimization for TNEP considering wind power is presented (Fuchs *et al*., 2011). However, the solutions of the references (Fuchs *et al*., 2011) are not sufficient for all possibility of uncertain renewable energy generation and loads. Consequently, a heuristic method of TNEP by using chronological power flow in order to cope with the uncertain power of wind power is proposed (Silva *et al*., 2012). In addition, stochastic programming is applied to model the uncertainties. For example, research by Yu *et al*. (2009) applies a stochastic programming called chance-constrained programming to transform the probabilistic attribute of the problem into a deterministic situation in order to solve the load and wind farm uncertainties. However, there is the limitation because it needs an accurate probability distribution of the uncertain variables which is difficult to obtain in practice.

Another method to cope with the uncertain variables is robust optimization which is widely used for making decision under uncertainty not only for system planning but also system operation (Hajimiragha *et al*., 2011; Yu and Rosehart, 2012; Saric and Stankovic, 2009; Bertsimas *et al*., 2013). The transmission expansion planning using robust optimization is usually called Robust Transmission Network Expansion Planning (RTNEP). For the advantage of this optimization, the requirement is only the range of variation of uncertain variables which differ from the stochastic optimization. From the previous RTNEP works (Yu *et al*., 2011) uses Taguchi's Orthogonal Array Testing (TOAT) for selecting the optimal scenarios of uncertain renewable energy generation and loads for planning. However, TOAT does not fully cover the range of all uncertain variables and therefore results in the obtained solution may not be exactly robust. While, Jabr (2013) defines the uncertainties of renewable energy generation and load into the maximum and minimum values. Moreover, Alizadeh *et al*. (2013) considers the uncertainties of estimated investment costs of transmission lines and the forecasted electricity. The values of uncertain variables are defined as the maximum and minimum values as the same as Rider *et al*. (2007).

Consequently, this study presents a new method for RTNEP considering intermittent renewable energy generation and loads. The suitable scenarios selection based on intermittent renewable energy generation and loads in a target year is proposed. ATS is employed in the proposed RTNEP for solving optimization problem. It iterates between the main problem which minimizes the investment cost and operation cost and the subproblem which is the process to avoid the operating violation by generation re-dispatch and the curtailments of renewable energy generation and loads. The main contribution of this works can be summarized as.

The calculation of operating cost which is rarely considered in previous RTNEP works is presented and is included with the investment cost in the objective function.

According to Yu *et al*. (2011), Jabr (2013) and Alizadeh *et al*. (2013), the selected scenario for planning cannot guarantee the robustness percentage of the system at 100 based on the forecasted renewable energy generation and loads profiles in a target year. Consequently, the algorithm based on the maximum renewable energy generation and loads curtailments for selecting the suitable scenarios of the planning is proposed to achieve the greater robustness.

Most of the subproblems of TNEP and RTNEP are modelled as linear programming. However, this study uses the nonlinear programming based on interior point method in order to obtain more accurate solution.

The effect of renewable energy generation on RTNEP, especially the cost of planning has never been studied in the previous works. Therefore, this aspect is taken into account.

Formulation of transmission network expansion planning: Generally, the forecasted amounts of renewable energy generation and loads in the target year are uncertain. However, in this studied, these uncertainties are neglected. In this study, the formulations of TNEP both without and with the intermittent renewable energy generation and loads based on AC Model are described.

TNEP without intermittent renewable energy generation and loads: The objective of TNEP is to install the transmission lines to reliably support the loads with the minimum investment and operating costs. The transmission line candidates are predefined based on the right of ways. Generally, the peak load scenario is selected for solving TNEP. However, for TNEP considering renewable energy generation, suitable selection of renewable energy generation values is difficult and has not been well discussed in the previous researches. Therefore, three renewable energy generation values consisting of zero, half capacity and full capacity (Yu *et al*., 2011) are selected for testing. Consequently, the test of this TNEP can be classified into three cases which denoted by TNEP 1-3 based on the zero, half and full capacities of renewable energy generation, respectively. The formulation of TNEP is presented as follows. Objective function:

$$\text{Minimize}\left(\sum_{k=1}^{nc} c_{ij}^k x_{ij}^k + \sum_{g=1}^{ng} c_g P_g\right) \tag{1}$$

Subject to:

$$\begin{aligned} &P_{Gi} + (P_{Ri} - P_{RCi}) - (P_{Di} - P_{DCi}) = \\ &\sum_{j\in N(i)} P_{ij}\left(1 + x_{ij}^k\right), i \in \Omega^b, i = 1,\dots,nb \end{aligned} \tag{2}$$

$$\begin{aligned} &Q_{Gi} + Q_{Ci} - Q_{Ni} - (Q_{Di} - Q_{DCi}) = \\ &\sum_{j\in N(i)} Q_{ij}\left(1 + x_{ij}^k\right), i \in \Omega^b, i = 1,\dots,nb \end{aligned} \tag{3}$$

$$V_i^{min} \le V_i \le V_i^{max}, i \in \Omega^b, i = 1, \dots, nb \tag{4}$$

$$\sqrt{\left(P_{ij}^m\right)^2 + \left(Q_{ij}^m\right)^2} \le \left(S_{ij\_lim}^m\right), ij \in \Omega^{tl}, m = 1,\dots,nl \tag{5}$$

$$P_g^{min} \le P_g \le P_g^{max}, g \in \Omega^g, g = 1, \dots, ng \tag{6}$$

$$Q_g^{min} \le Q_g \le Q_g^{max}, g \in \Omega^g, g = 1,\dots,ng \tag{7}$$

$$Q_{Ci}^{min} \le Q_{Ci} \le Q_{Ci}^{max}, i \in \Omega^b, i = 1,\dots,nb \tag{8}$$

$$Q_{INi}^{min} \le Q_{INi} \le Q_{INi}^{max}, i \in \Omega^b, i = 1,\dots,nb \tag{9}$$

$$0 \le P_{RCi} \le P_{Ri}, i \in \Omega^b, i = 1,\dots,nb \tag{10}$$

$$0 \le P_{DCi} \le P_{Di}, i \in \Omega^b, i = 1,\dots,nb \tag{11}$$

$$0 \le Q_{DCi} \le Q_{Di}, i \in \Omega^b, i = 1,\dots,nb \tag{12}$$

$$\begin{aligned} &P_{ij}^m + iQ_{ij}^m = |V_i|^2\left(g_{ij} - i\left(b_{ij} + \frac{1}{2}b_{sh\_ij}\right)\right) - \\ &V_i V_j^*\left(g_{ij} - ib_{ij}\right), ij \in \Omega^{TL}, i \in \Omega^{nb}, m = 1,\dots,nl \end{aligned} \tag{13}$$

$$\sum_{k=1}^{nc} x_{ij}^k \le nc, x_{ij} \in \Omega^{tc} \tag{14}$$

$$x_{ij} = \begin{cases} 0; & x_{ij} \notin \Omega^{tc} \\ \text{1 or 0 depend on the} & \\ \text{randomness in the process;} & x_{ij} \in \Omega^{tc} \end{cases} \tag{15}$$

TNEP with intermittent renewable energy generation and loads: In other words, this TNEP can be called "Robust TNEP (RTNEP)". The uncertainties of renewable energy generation and loads are considered in the optimization formulation. For easy to understand, the model of research (Jabr, 2013) is used for explanation. The minimum and maximum values of the uncertain variable are used as the considered scenarios in the planning (Jabr, 2013). Therefore, the vector u which is defined as the uncertain vector consisting of the renewable energy generation and loads can be written as shown in Eq. 16 and 17:

$$u = [P_{Ri},\dots, P_{Rnb}, P_{Di},\dots,P_{Dnb}, Q_{Di},\dots,Q_{Dnb}], i = 1,\dots,nb \tag{16}$$

$$u \in U = \left[u^{min}, u^{max}\right] \tag{17}$$

From Eq. 16 and 17, the variable P_{Ri}, P_{Di} and Q_{Di} can be expressed as follows:

$$P_{Ri} \in \{P_{Ri}^{min}, P_{Ri}^{max}\}, i \in \Omega^b, i = 1,\dots,nb \tag{18}$$

$$P_{Di} \in \{P_{Di}^{min}, P_{Di}^{max}\}, i \in \Omega^b, i = 1,\dots,nb \tag{19}$$

$$Q_{Di} \in \{Q_{Di}^{min}, Q_{Di}^{max}\}, i \in \Omega^b, i = 1,\dots,nb \tag{20}$$

The objective function of RTNEP is the same as Eq. 1. Moreover, the constraints (Eq. 2-15) has to satisfy all values of P_{Ri}, P_{Di} and Q_{Di} as shown in Eq. 18-20, respectively. Consequently, the constraints have to be adapted by adding vector u in order to design the robust planning. The formulation is shown below. Objective function:

$$\text{Minimize}\left(\sum_{k=1}^{nc} c_{ij}^{k} x_{ij}^{k} + \sum_{g=1}^{ng} c_g P_g\right) \tag{21}$$

Subject to:

$$\begin{aligned}&P_{Gi} + \left(u_i - P_{RCi}(u)\right) - \left(u_{nb+i} - P_{DCi}(u)\right) = \\ &\sum_{j\in N(i)} P_{ij}(u)\left(1 + x_{ij}^{k}\right), i \in \Omega^b, i = 1,\ldots,nb, \forall u \in U\end{aligned} \tag{22}$$

$$\begin{aligned}&Q_{Gi} + Q_{Ci} - Q_{INi} - \left(u_{2nb+i} - Q_{DCi}(u)\right) = \\ &\sum_{j\in N(i)} Q_{ij}(u)\left(1 + x_{ij}^{k}\right), i \in \Omega^b, i = 1,\ldots,nb, \forall u \in U\end{aligned} \tag{23}$$

$$V_i^{\min} \le V_i(u) \le V_i^{\max}, i \in \Omega^i, i = 1,\ldots,nb, \forall u \in U \tag{24}$$

$$\begin{aligned}&\sqrt{\left(P_{ij}^{m}(u)\right)^2 + \left(Q_{ij}^{m}(u)\right)^2} \le \left(S_{ij\_lim}^{m}\right), \\ &ij \in \Omega^{tl}, m = 1,\ldots,nl, \forall u \in U\end{aligned} \tag{25}$$

$$P_g^{\min} \le P_g \le P_g^{\max}, g \in \Omega^g, g = 1,\ldots,ng \tag{26}$$

$$Q_g^{\min} \le Q_g \le Q_g^{\max}, g \in \Omega^g, g = 1,\ldots,ng \tag{27}$$

$$Q_{Ci}^{\min} \le Q_{Ci} \le Q_{Ci}^{\max}, i \in \Omega^b, i = 1,\ldots,nb \tag{28}$$

$$Q_{INi}^{\min} \le Q_{INi} \le Q_{INi}^{\max}, i \in \Omega^b, i = 1,\ldots,nb \tag{29}$$

$$0 \le P_{RCi}(u) \le u_i, i \in \Omega^b, i = 1,\ldots,nb, \forall u \in U \tag{30}$$

$$0 \le P_{DCi}(u) \le u_{nb+i}, i \in \Omega^b\ i = 1,\ldots,nb, \forall u \in U \tag{31}$$

$$0 \le Q_{DCi}(u) \le u_{2nb+i}, i \in \Omega^b\ i = 1,\ldots,nb, \forall u \in U \tag{32}$$

$$\begin{aligned}&P_{ij}^{m}(u) + iQ_{ij}^{m}(u) = \left|V_i(u)\right|^2\left(g_{ij} - i\left(b_{ij} + \frac{1}{2}b_{sh\_ij}\right)\right) - \\ &V_i(u)V_j^{*}(u)\left(g_{ij} - ib_{ij}\right), \\ &ij \in \Omega^{TL}, i \in \Omega^{nb}, m = 1,\ldots,nl, \forall u \in U\end{aligned} \tag{33}$$

$$\sum_{k=1}^{nc} x_{ij}^{k} \le nc, ij \in \Omega^{tc} \tag{34}$$

$$x_{ij} = \begin{cases} 0; & x_{ij} \notin O^{tc} \\ \text{1 or 0 depend on the} & \\ \text{randomness in the process;} & x_{ij} \in O^{tc} \end{cases} \tag{35}$$

This formulation cannot be solved directly because the constraints have to be satisfied for all uncertain variables in vector u. Therefore, Sullivan *et al.* (2003), Subcommittee (1979), Youssef and Hackam (1989) propose the solving method to deal with vector u. To solve this formulation in this study, study proposes an exact approach by using ATS algorithm.

In addition, selecting the minimum and maximum values of the uncertain variables as shown in Eq. 17 is only one of the methods to select the scenario for planning. There is another method as presented by Yu *et al.* (2011) which uses the TOAT to select the values of the uncertain variables. This means that the uncertain values in the set of uncertainty U can be the other values. In this study, the new method for selecting the uncertain values is proposed in this study.

MATERIALS AND METHODS

Proposed robust transmission network expansion planning: The proposed RTNEP is solved by meta-heuristic method. Even if, the calculation time of this meta-heuristic method is rather high, it can give the solution more accuracy than the solutions of other methods (Latorre *et al.*, 2003). A meta-heuristic method called "Adaptive Tabu Search" (Katdee, 2010) is utilized in this study. The detail of the proposed RTNEP is explained in the following study.

Main problem: From literature review, the operating cost is rarely considered in the previous research. Therefore, this paper includes the operating cost into the objective function. Moreover, in the case of the investment cost, since expected life time of the transmission line installed is usually longer than the considered planning period, salvage values of these transmission lines should be considered at the end of the planning period to reflect the utilization of the transmission line. The salvage value can be estimated by a straight line method (Eq. 7) which can be calculated by Eq. 36:

$$sv = c_{inv}\left(\frac{el - ny(ns)}{el}\right) \tag{36}$$

The present value of the investment cost subtracted by its salvage value can be calculated by Eq. 37:

$$pv_{inv} = c_{inv}\left(1 - \frac{el - ny(ns)}{el(1+r)^{ny\cdot ns}}\right) \tag{37}$$

Table 1: Calculation time of various algorithms

Algorithm	Primal/dual interior point	Trust region reflective	Active set	Interior point
Calculation time (sec)	0.140	0.789	63.962	0.431

For the operating cost, it is assumed that the cost for each year increases by the same rate as the demand growth. Therefore, the present value of the operating cost can be calculated by Eq. 38:

$$pv_{opr} = \frac{c_{opr}}{\left(1+dr\right)^{(ny-1)}}\left(1+\left(\frac{1+dr}{1+r}\right)+\ldots+\left(\frac{1+dr}{1+r}\right)^{ny-1}\right) \tag{38}$$

Consequently, the objective function can be formulated as shown in Eq. 39 with the constraints in Eq. 22-35. Objective function:

$$\text{Minimize}\left(\sum_{k=1}^{nc} pv_{inv}^{k} x_{ij}^{k} + \sum_{g=1}^{ng} pv_{opr}^{g} P_g\right) \tag{39}$$

Subproblem: During the ATS iteration which is one of the step in this study, the subproblem is solved in order to avoid the operating limit of the given system configuration which is obtained from the random process of ATS. This study uses Nonlinear Programming (NLP) based on primal/dual interior point. The objective function can be modelled as follows. Objective function:

$$\text{Minimize}\left(\sum_{g=1}^{ng} c_g P_g + \sum_{i=1}^{nb} rc_i P_{RCi} + \sum_{i=1}^{nb} oc_i P_{DCi}\right) \tag{40}$$

The constraints (Eq. 22-35) are used in the subproblem formulation. For the algorithm used to solve this problem formulation, various nonlinear programming for optimal power flow in MATLAB are tested in order to find the minimum calculation time among the all algorithms. The test is running on an Intel Core i5 3.0 GHz processor based computer. The results are presented as shown in Table 1. From Table 1, the lowest calculation time is primal/dual interior point algorithm. Therefore, this algorithm is selected.

Proposed method for scenario selection: In order to plan the system with higher robustness, the proposed method considers every hourly value of forecasted renewable energy generation and loads in a target year. Scenario Selection Indicator (SSI) based on the maximum renewable energy generation and load curtailments will be calculated every hour. These curtailments are obtained by solving the formulation in Eq. 40 and 2-15. If the curtailments of renewable energy generation/load in the hour are high, it means that the renewable energy generation and loads of this hour should be considered as the scenario of the planning. Otherwise, the renewable energy generation and loads of this hour may not be significant to be considered. The SSI can be separated into 2 indicators, i.e., SSI of Renewable energy Generation (SSIRG) and SSI of Loads (SSIL) as presented:

$$SSIRG_h = \frac{\sum_{i}^{nb} P_{RCi,h}}{\sum_{i}^{nb} P_{Ri,h}} \tag{41}$$

$$SSIL_h = \frac{\sum_{i}^{nb} P_{DCi,h}}{\sum_{i}^{nb} P_{Di,h}} \tag{42}$$

The procedure of the proposed method can be explained as the following steps:

- Set the “considered indicator value” of SSIRG and SSIL and set the index of hour (h) to 1
- Calculate $SSIRG_h$ and $SSIL_h$
- Compare the $SSIRG_h$ and $SSIL_h$ with the considered indicator value. If the $SSIRG_h$ or $SSIL_h$ is equal or higher than the “considered indicator value”, select this hour has one of the considered scenario for planning, if else, do not select this hour
- Set h = h+1. If h is higher than the number of hour in a year, end the process and accumulate all of considered scenarios, if else, go to 2)

Evaluation of the expansion plan robustness: In the actual situation, there are various combinations of intermittent renewable energy generation and loads. Although, the result from the proposed RTNEP can guarantee the feasibility of all scenarios from the proposed scenario selection method, it does not mean that the result can guarantee the feasibility of all combinations of uncertain variables. Therefore, the robustness of the expansion plan should be evaluated.

This study uses the renewable energy generation and loads data of each hour in a year for evaluating the robustness of the expansion plan. To evaluate the robustness, every hour in a year of renewable energy generation and loads are executed by the formulation (Eq. 40 and 2-15). The expansion plan robustness can be evaluated by Eq. 43:

$$\text{Robustness}\left(\%\right) = \frac{H}{nhy}\times 100 \tag{43}$$

Summary of the proposed RTNEP procedure: Procedure of the proposed RTNEP can be summarized as shown in the following steps.

Select the scenarios by the proposed method. Solve RTNEP by using ATS. The process can be explained as. ATS randomizes the investment variable x_{ij} into the system. After that, this network configuration is solved by subproblem formulation.

Evaluate the quality of the solution obtained from Eq. 1. If the solution can operate without any violation and the curtailments for all of the considered scenarios, this solution will be given the quality score according to the investment and operating costs. On the other hand, if the solution cannot operate without any violation and the curtailments for all of the considered scenarios, this solution will be given zero quality score. After that, collect the quality score of this solution.

Do the iteration as shown in study until the iteration reaches the iteration limit. Compare the solution based on the quality score. After that, select the best solution as the optimal solution. Evaluate the robustness of the optimal solution by Eq. 43.

RESULTS AND DISCUSSION

The proposed algorithm is applied to the IEEE Reliability Test System 79 (RTS79) (Rider *et al*., 2007). Moreover, renewable energy sources which are wind farms are assumed to be connected at buses 7 and 22. The capacity of each wind farm is assumed to be 990 MW and the parameters of each wind generator are as follows: cut-in speed is 4 m/sec, rated speed is 13.62 m/sec and cut-out speed is 25 m/sec (Yu *et al*., 2011). The active power output of wind farm is calculated by the model by Zahedi (2012) with the wind speed data in the northeast of Thailand. For the ATS optimization, the parameters of ATS are set as follows: maximum number of iteration is 1,000, number of neighbor solutions is 20 and maximum repetition of the solutions is 3. For the economic calculation, the rest of parameters are set as follows: r and dr are 0.1, ny is 9, el is 25 and ns is 1.

The proposed method runs on an Intel Core i5 3.0-GHz processor based computer. All programs are written on MALAB R2011A.

The results of TNEP without intermittent renewable energy generation and loads: As previously mentioned in the study, the tests can be classified into three cases which denoted by TNEP 1-3 based on the zero, half and full capacities of renewable energy generation, respectively (Table 2).

From Table 2, it can be observed that the costs of TNEP results are varied in the same way of the system robustness. The average calculation time of TNEP method is 38.86 min.

The results of TNEP with intermittent renewable energy generation and loads: This subsection presents the results of TNEP with intermittent renewable energy generation and loads or RTNEP. The results of RTNEP with the three methods for selecting the scenarios of renewable energy generation and loads are compared. For the first method, the two values (minimum and maximum) of renewable energy generation and loads are selected. The result of this method is defined as RTNEP-1. For the second method, TOAT as proposed by Yu *et al.* (2011) is used. The total number of uncertain variables in this system is 19 which results from 2 renewable energy generation (wind farms) and 17 loads. Each uncertain value is defined to have two levels (zero and maximum capacity values for renewable energy generation and minimum and maximum values for loads). Therefore,

Table 2: Results of TNEP without intermittent renewable energy generation and loads

	TNEP-1	TNEP-2	TNEP-3
Case (solution)	$n_{6\text{-}10} = 2$, $n_{7\text{-}8} = 1$, $n_{2\text{-}8} = 2$, $n_{1\text{-}8} = 1$, $n_{8\text{-}9} = 1$, $n_{17\text{-}18} = 1$, $n_{10\text{-}11} = 1$, $n_{12\text{-}13} = 2$, $n_{14\text{-}16} = 1$	$n_{6\text{-}10} = 1$, $n_{1\text{-}2} = 2$, $n_{10\text{-}11} = 1$, $n_{16\text{-}17} = 1$, $n_{12\text{-}13} = 1$, $n_{17\text{-}18} = 1$, $n_{9\text{-}11} = 1$, $n_{17\text{-}18} = 1$, $n_{5\text{-}10} = 1$, $n_{15\text{-}24} = 1$, $n_{14\text{-}16} = 1$, $n_{15\text{-}21} = 2$	$n_{7\text{-}8} = 1$, $n_{1\text{-}2} = 1$, $n_{6\text{-}7} = 1$, $n_{16\text{-}17} = 1$, $n_{3\text{-}24} = 1$, $n_{11\text{-}13} = 1$, $n_{9\text{-}12} = 1$, $n_{2\text{-}8} = 1$, $n_{14\text{-}16} = 1$, $n_{15\text{-}21} = 1$, $n_{12\text{-}23} = 1$, $n_{16\text{-}23} = 1$
Pv_{inv} ($\times 10^6$ US\$)	326.40	399.99	491.06
PV_{opr} ($\times 10^6$ US\$)	8,447.44	6,758.89	5,079.14
Total cost ($\times 10^6$ US\$)	8,773.84	7,158.88	5,570.20
Robustness (%)	70.48	30.56	41.86

orthogonal array $L_{32}(2^{19})$ (Anonymous, 2004) is chosen to generate the testing scenarios. The result of this method is defined as RTNEP-2. Lastly, the proposed method for selecting scenarios is used. The first 10 highest values of SSIRG and SSIL are shown in Table 3.

Certainly, the more hours are considered in the planning, the more robustness of the planned system will be. However, the calculation time will be increased as well. Therefore, the considered indicator value has to be set in order to select only the significant hours for the planning. At first, the considered indicator values are assumed to be 0.3773 and 0.0744 for SSIRG and SSIL, respectively in order to consider only the most significant hour of SSIRG and SSIL. Consequently, the renewable energy generation and loads at hours "209" and "8.274" from Table 3 are selected as the considered scenarios for the planning, respectively. The result of this method is defined as RTNEP-3.

The three results of RTNEP are shown in Table 4. It can be observed that only the robustness percentage of RTNEP-3 result is 100.00. This means that the proposed method of RTNEP with the assumption of considered indicator values is the most efficient comparing with other methods. However, the total cost of RTNEP-3 result is the highest comparing with the total cost of RTNEP-1 and -2 results. It can be implied that increasing the robustness will cause the higher cost.

Table 3: The first 10 highest values of SSIRG and SSIL

Hour	SSIRG	Hour	SSIL
209	0.3773	8.274	0.0744
7.787	0.3772	8.610	0.0692
4.095	0.3771	8.436	0.0687
233	0.3770	8.434	0.0678
203	0.3768	8.442	0.0652
3.737	0.3768	8.266	0.0640
3.783	0.3768	8.276	0.0640
4.935	0.3768	8.322	0.0640
4.119	0.3767	8.462	0.0635
3.779	0.3767	8.268	0.0624

Effect of renewable energy generation on RTNEP: For studying the effect of renewable energy generation on RTNEP, the original RTS 79(36) is used. The wind farms are assumed to be installed at buses 3, 4, 5, 14, 17, 19 and 20. The capacity of each wind farm is varied from 0-25 MW to study the effect of renewable energy generation on RTNEP. In addition, the proposed RTNEP method which is most efficient based on the robustness percentage as proved in Table 4 is used.

Only the most significant hours which have the highest SSIRG and SSIL are selected as the considered scenarios in the planning. The test result is shown in Fig. 1.

From Fig. 1, when the capacity of each wind farm increases from 0-15 MW, it is unnecessary to expand the new transmission line because the existing system can operate without any violations and curtailments of all hours in a year (100% of robustness). However, when the capacity increases from 16-19 MW, it will cause the system robustness to be lower than 100%. Therefore, transmission lines have to be expanded in order to keep the system robustness at 100%. It can be concluded from Fig. 1 that, more installation of wind farms causes more investment cost of the expansion plan. Moreover, when the capacity increases from 20-25 MW, there is no solution from all transmission line candidates that can keep the system robustness at 100%.

In addition, for the comparison between conventional generators and renewable energy generation, the conventional generators are assumed to be installed at buses 3, 4, 5, 14, 17, 19 and 20 instead of wind farms. The capacity of each conventional generator is varied from 0-25 MW. The result shows that there is no transmission lines expansion because the system can keep the robustness at 100% for all the test cases.

Table 4: Results of RTNEP

	RTNEP-1	RTNEP-2	RTNEP-3
Case (solution)	$n_{6\text{-}10} = 2$, $n_{7\text{-}8} = 2$, $n_{2\text{-}8} = 2$, $n_{1\text{-}8} = 1$, $n_{8\text{-}9} = 1$, $n_{17\text{-}18} = 2$, $n_{10\text{-}11} = 1$, $n_{4\text{-}9} = 1$, $n_{1\text{-}5} = 2$, $n_{5\text{-}10} = 1$, $n_{15\text{-}16} = 1$, $n_{14\text{-}16} = 1$, $n_{6\text{-}7} = 2$, $n_{14\text{-}23} = 1$	$n_{6\text{-}10} = 2$, $n_{7\text{-}8} = 3$, $n_{2\text{-}8} = 1$, $n_{1\text{-}8} = 1$, $n_{8\text{-}9} = 1$, $n_{3\text{-}24} = 1$, $n_{8\text{-}10} = 1$, $n_{16\text{-}17} = 2$, $n_{9\text{-}11} = 1$, $n_{14\text{-}16} = 1$, $n_{6\text{-}7} = 1$, $n_{12\text{-}23} = 1$, $n_{19\text{-}20} = 1$	$n_{6\text{-}10} = 2$, $n_{7\text{-}8} = 2$, $n_{2\text{-}8} = 1$, $n_{1\text{-}8} = 1$, $n_{8\text{-}9} = 1$, $n_{10\text{-}12} = 1$, $n_{20\text{-}23} = 1$, $n_{1\text{-}2} = 2$, $n_{4\text{-}9} = 1$, $n_{17\text{-}18} = 1$, $n_{3\text{-}24} = 1$, $n_{14\text{-}16} = 2$, $n_{6\text{-}7} = 2$, $n_{16\text{-}19} = 1$, $n_{19\text{-}23} = 1$, $n_{1\text{-}3} = 1$
No. of considered scenarios	4	32	2
pv_{inv} (×10^6 US$)	477.95	509.28	536.96
pv_{opr} (×10^6 US$)	4,985.23	5,224.79	6,696.52
Total cost (×10^6 US$)	5,463.18	5,734.06	7,233.48
Robustness (%)	74.50	87.48	100.00
Calculation time (minutes)	155.79	1,068.79	67.04

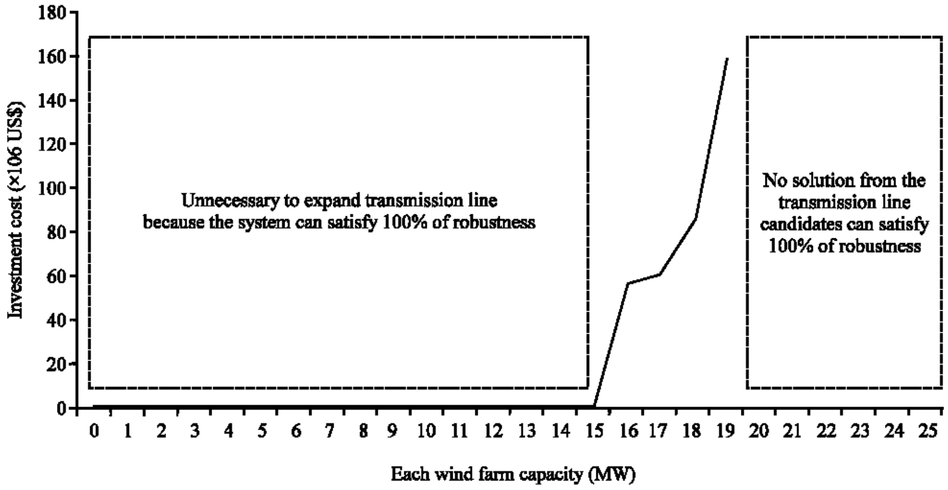

Fig. 1: Effect of wind farms on investment cost of expansion plan

From the results of TNEP and RTNEP, it can be concluded that the robustness of RTNEP results are higher than the robustness of TNEP results. This indicates that RTNEP is more suitable than TNEP when considering the intermittent renewable energy generation and loads.

In the RTNEP results, the different methods for selecting the scenarios of renewable energy generation and loads lead to different results. The robustness of the result from the proposed method is highest compared with the robustness of the results from other methods. It can be concluded that the significant scenarios obtaining from the proposed method should be more considered in the planning than the scenarios obtained from the methods by Yu *et al.* (2011) and Jabr (2013).

For the calculation time comparison, the calculation time of TNEP method is certainly lower than the RTNEP because the TNEP method considers only a single value of renewable energy generation and loads in the planning while RTNEP method considers more than a single value depending on the method for selecting the scenarios. In RTNEP calculation, the calculation time based on TOAT method is highest compared with the calculation time of other methods because the number of considered scenarios in the planning is highest.

Finally, the effect of renewable energy generation on RTNEP is studied. The results show that more installation of renewable energy generation causes more investment cost of an expansion plan. On the other hand, if the conventional generators are installed instead of renewable energy generation, there is no investment cost. Therefore, this issue should be carefully considered before deciding to accept renewable energy generation into the system.

CONCLUSION

A novel Robust Transmission Network Expansion Planning (RTNEP) with the intermittent renewable energy generation and loads is proposed. For the objective function of the planning, the operating cost calculation which is rarely considered in the previous researches is presented and is considered with the investment cost. Non-linear programming based on interior point method is used for solving subproblem in order to obtain more accurate result. From the test results, the proposed robust optimization approach can provide highest system robustness of the expansion planning among the intermittent renewable energy generation and loads compared with the methods of the previous researches. In addition, the effect of intermittent renewable energy generation on RTNEP is studied. The results show that more installation of intermittent renewable energy generation such as wind farms causes more investment cost of transmission line in the expansion plan.

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NOMENCLATURE

Indices:
- k: Index of transmission line candidate
- b: Index of bus
- I: Index of bus/sending bus
- j: Index of receiving bus
- g: Index of generator
- m:Index of all transmission lines in the system
- h: Index of hour in a year

Sets:
- Ω^{b}: Set of all buses
- Ω^{tl}: Set of all transmission lines in the system
- Ω^{g}: Set of all generators
- Ω^{tc}: Set of all transmission line candidates
- N(i): Set of buses connected to bus i by a transmission line
- U: Set of uncertainty

Constant parameters:
- c_{ij}: Investment cost of transmission line candidate ij (US$)
- c_{g}: Power generation cost of generator g (US$/MW)
- rc_{i}: Renewable energy generation cost of renewable energy source at bus i
- (US$/MW) oc_{i} (US$/MW): Outage cost of load at bus i
- V_{i}^{min}, V_{i}^{max}: Minimum and maximum limit of voltage magnitude at bus i (p.u.)
- S_{ij_lim}: Apparent power limit of transmission line ij (MVA)
- P_{g}^{min}, P_{g}^{max}: Minimum and maximum limit of power generation of generator g (MW)
- Q_{g}^{min}, Q_{g}^{max}: Minimum and maximum limit of reactive power generation of generator g (MVAr)
- Q_{Ci}^{min}, Q_{ci}^{max}: Minimum and maximum limit of reactive power generation of capacitor at bus i (MVAr)
- Q_{INi}^{min}, Q_{INi}^{max}: Minimum and maximum limit of reactive power consumption of inductor at bus i (MVAr)
- g_{ij}: Series conductance in the π-model of transmission line
- b_{ij}: Series susceptance in the π-model of transmission line
- b_{sh_ij}: Shunt susceptance in the π-model of transmission line
- nc: Number of transmission line candidates
- ng: Number of generators
- nb: Number of buses
- nl: Number of all transmission lines in the system
- ns: Number of stages
- ny: Number of years for each stage
- el: Expected life time of transmission line (year)
- u: Uncertain vector which represents the intermittent renewable energy generation and loads
- r: Interest rate (% per year)
- dr: Demand growth rate (% per year)
- sv: Salvage value of the transmission line (US$)
- c_{inv}: Investment cost (US$)
- c_{opr}: Operating cost (US$)
- pv_{inv}: Present value of investment cost subtracted by its salvage value (US$)
- pv_{opr}: Present value of operating cost (US$)
- H: Number of hours without renewable energy generation and load curtailments
- nhy: Number of hours in a year

Variables:
- x_{ij}: Investment variable in $\{0, 1\}^{nc}$ (binary variable) representing a decision on the selection of transmission line candidates into the investment plan, i.e., $x_{ij} = 1$ if the transmission line candidate ij is selected, otherwise it is not be selected
- P_{g}, Q_{g}: Power and reactive power generation of generator g (MW)
- P_{Gi}, P_{Ri}, P_{di}: Power of conventional generation, renewable energy generation and loads at bus i (MW)
- Q_{Gi}, Q_{Di}: Reactive power of generation and loads at bus i (MVAr)
- Q_{Ci}, Q_{INi}: Reactive power generation and consumption of capacitor and inductor at bus i, respectively
- P_{RCi}, P_{DCi}: Power curtailments of renewable energy generation and loads at bus i
- Q_{DCi}: Reactive power curtailments of loads at bus i
- P_{ij}, Q_{ij}: Power and reactive power flow from bus i to bus j (MW)
- V_{i}, V_{j}: Voltage magnitude at bus i and bus j (p.u.)

REFERENCES

Akbari, T., M. Heidarizadeh, M.A. Siab and M. Abroshan, 2012. Towards integrated planning: Simultaneous transmission and substation expansion planning. Electr. Power Syst. Res., 86: 131-139.

Alizadeh, B., S. Dehghan, N. Amjady, S. Jadid and A. Kazemi, 2013. Robust transmission system expansion considering planning uncertainties. IET. Generation Transm. Distrib., 7: 1318-1331.

Anonymous, 2004. Orthogonal arrays (Taguchi designs). University of York, York, England, UK.

Anonymous, 2015. Alternative energy development plan: AEDP 2015-2036. Ministry of Energy, THAILAND, Bangkok, Thailand.

Asadamongkol, S. and B. Eua-Arporn, 2010. Benders decomposition based method for multistage transmission expansion planning with security constraints. Ph.D Thesis, Department of Electrical Engineering, Chulalongkorn University, Bangkok, Thailand.

Bahiense, L., G.C. Oliveira, M. Pereira and S. Granville, 2001. A mixed integer disjunctive model for transmission network expansion. IEEE. Trans. Power Syst., 16: 560-565.

Bent, R.W., A. Berscheid and G.L. Toole, 2011. Generation and transmission expansion planning for renewable energy integration. Proceedings of the 17th Conference on Power Systems Computation, August 22-26, 2011, Los Alamos National Laboratory, Stockholm, Sweden, ISBN:978-1-61839-227-5, pp: 1-11.

Bertsimas, D., E. Litvinov, X.A. Sun, J. Zhao and T. Zheng, 2013. Adaptive robust optimization for the security constrained unit commitment problem. IEEE. Trans. Power Syst., 28: 52-63.

Cebeci, M.E., S. Eren, O.B. Tor and N. Giiven, 2011. Transmission and substation expansion planning using mixed integer programming. Proceedings of the Symposium on North American Power (NAPS'11), August 4-6, 2011, IEEE, Boston, Massachusetts, ISBN:978-1-4577-0417-8, pp: 1-5.

Chanda, R.S. and P.K. Bhattacharjee, 1994. Application of computer software in transmission expansion planning using variable load structure. Electr. Power Syst. Res., 31: 13-20.

Dusonchet, Y.P. and A. El-Abiad, 1973. Transmission planning using discrete dynamic optimizing. IEEE. Trans. Power Apparatus Syst., 4: 1358-1371.

Ekwue, A.O. and B.J. Cory, 1984. Transmission system expansion planning by interactive methods. IEEE. Trans. Power Apparatus Syst., 7: 1583-1591.

Escobar, A.H., R.A. Gallego and R. Romero, 2004. Multistage and coordinated planning of the expansion of transmission systems. IEEE. Trans. Power Syst., 19: 735-744.

Fuchs, I., S. Voller and T. Gjengedal, 2011. Improved method for integrating renewable energy sources into the power system of Northern Europe: Transmission expansion planning for wind power integration. Proceedings of the 10th International Conference on Environment and Electrical Engineering (EEEIC’11), May 8-11, 2011, IEEE, Rome, Italy, ISBN:978-1-4244-8779-0, pp: 1-4.

Grainger, J. and S.J. William, 1994. Power System Analysis. McGraw-Hill Education, New York, USA., ISBN:9780071133388, Pages: 787.

Hajimiragha, A.H., C.A. Canizares, M.W. Fowler, S. Moazeni and A. Elkamel, 2011. A robust optimization approach for planning the transition to plug-in hybrid electric vehicles. IEEE. Trans. Power Syst., 26: 2264-2274.

Jabr, R.A., 2013. Robust transmission network expansion planning with uncertain renewable generation and loads. IEEE. Trans. Power Syst., 28: 4558-4567.

Katdee, A., 2010. Tabu Searching. Rangsit University, Lak Hok, Thailand,.

Khatib, H., 2003. Economic Evaluation of Projects in the Electricity Supply Industry. Institution of Engineering and Technology, Stevenage, England, UK., ISBN-13:978-0-86341-304-9, Pages: 209.

Latorre, G., R.D. Cruz, J.M. Areiza and A. Villegas, 2003. Classification of publications and models on transmission expansion planning. IEEE. Trans. Power Syst., 18: 938-946.

Monticelli, A., A. Santos, M.V.F. Pereira, S.H. Cunha and B.J. Parker *et al*., 1982. Interactive transmission network planning using a least-effort criterion. IEEE. Trans. Power Apparatus Syst., 10: 3919-3925.

Munoz, C., E. Sauma, J. Contreras, J. Aguado and S.D.L. Torre, 2012. Impact of high wind power penetration on transmission network expansion planning. IET. Gener. Transm. Distrib., 6: 1281-1291.

Rider, M.J., A.V. Garcia and R. Romero, 2007. Power system transmission network expansion planning using AC model. IET. Gener. Transm. Distrib., 1: 731-742.

Romero, R., R.A. Gallego and A. Monticelli, 1995. Transmission system expansion planning by simulated annealing. Proceedings of the IEEE Conference on Power Industry Computer Application, May 7-12, 1995, IEEE, Salt Lake City, Utah, USA., pp: 278-283.

Saric, A.T. and A.M. Stankovic, 2009. A robust algorithm for Volt-Var control. Proceedings of the IEEE-PES Conference and Exposition on Power Systems (PSCE'09), March 15-18, 2009, IEEE, Seattle, Washington, USA., ISBN:978-1-4244-3810-5, pp: 1-8.

Sepasian, M.S., H. Seifi, A.A. Foroud, S.H. Hosseini and E.M. Kabir, 2006. A new approach for substation expansion planning. IEEE Trans. Power Syst., 21: 997-1004.

Silva, A.M.L.D., L.A.D.F. Manso, W.D.S. Sales, S.A. Flavio and G.J. Anders *et al*., 2012. Chronological power flow for planning transmission systems considering intermittent sources. IEEE. Trans. Power Syst., 27: 2314-2322.

Silva, E.L.D., J.A. Ortiz, G.C.D. Oliveira and S. Binato, 2001. Transmission network expansion planning under a tabu search approach. IEEE. Trans. Power Syst., 16: 62-68.

Stoll, H.G., 1989. Least-Cost Electric Utility Planning. JohnWiley & Sons, New York, USA., ISBN:9780471636144, Pages: 782.

Subcommittee, P., 1979. IEEE reliability test system power apparatus and systems. IEEE. Trans. Power Syst., 98: 2047-2054.

Sullivan, W.G., E.M. Wicks and J.T. Luxhoj, 2003. Engineering Economy. 12th Edn., Prentice Hall, Upper Saddle River, New Jersey, USA.,.

Youssef, H.K. and R. Hackam, 1989. New transmission planning model. IEEE. Trans. Power Syst., 4: 9-18.

Yu, H. and W.D. Rosehart, 2012. An optimal power flow algorithm to achieve robust operation considering load and renewable generation uncertainties. IEEE. Trans. Power Syst., 27: 1808-1817.

Yu, H., C.Y. Chung and K.P. Wong, 2011. Robust transmission network expansion planning method with Taguchi's orthogonal array testing. IEEE. Trans. Power Syst., 26: 1573-1580.

Yu, H., C.Y. Chung, K.P. Wong and J.H. Zhang, 2009. A chance constrained transmission network expansion planning method with consideration of load and wind farm uncertainties. IEEE. Trans. Power Syst., 24: 1568-1576.

Zahedi, A., 2012. Performance evaluation of wind turbine using Monte Carlo method and turbine power curve. Proceedings of the IEEE Conference on Power and Energy (IPEC’12), December 12-14, 2012, IEEE, Ho Chi Minh City, Vietnam, ISBN:978-1-4673-4584-2, pp: 161-165.