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An approach for evaluating the impact of an intermittent renewable energy source on transmission expansion planning*

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Abstract: We propose a new robust optimization approach to evaluate the impact of an intermittent renewable energy source on transmission expansion planning (TEP). The objective function of TEP is composed of the investment cost of the transmission line and the operating cost of conventional generators. A method to select suitable scenarios representing the intermittent renewable energy generation and loads is proposed to obtain robust expansion planning for all possible scenarios. A meta-heuristic algorithm called adaptive tabu search (ATS) is employed in the proposed TEP. ATS iterates between the main problem, which minimizes the investment and operating costs, and the subproblem, which minimizes the cost of power generation from conventional generators and curtailments of renewable energy generation and loads. The subproblem is solved by nonlinear programming (NLP) based on an interior point method. Moreover, the impact of an intermittent renewable energy source on TEP was evaluated by comparing expansion planning with and without consideration of a renewable energy source. The IEEE Reliability Test System 79 (RTS 79) was used for testing the proposed method and evaluating the impact of an intermittent renewable energy source on TEP. The results show that the proposed robust optimization approach provides a more robust solution than other methods and that the impact of an intermittent renewable energy source on TEP should be considered.

Key words: Adaptive tabu search, Renewable energy generation, Robust optimization, Transmission expansion planning
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1 Introduction

Due to electrical load growth, transmission line expansion is needed to resolve the problem of inadequate electricity supply. Expansion needs to be achieved with minimal additional investment and operating costs, and without violating system operating constraints or *n*-1 security constraints (Sepasian *et al.*, 2006; Cebeci *et al.*, 2011; Akbari *et al.*, 2012). Moreover, from the viewpoint of energy sustainability, the Ministry of Energy (Thailand) has proposed an implementation plan for renewable energy resources in electricity generation with a target of 10.1% of the total system electricity consumption in the coming decade (DEDE, 2012). Intermittent renewable energy generation attributes, especially those of solar and wind power, can increase the uncertainty of power injection at the connecting bus, which consequently affects the operation and planning of the system. Therefore, the plan to integrate intermittent power generation has to be revised to ensure that it is robust enough to cover all intermittent renewable energy generation and loads.

Transmission expansion planning (TEP) is a process for determining an optimal transmission expansion plan which ensures that the electricity demand can be met throughout a planning period. In general, system planners conduct TEP in association

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with generation expansion planning (GEP) to serve the increase in demand. The plan obtained from the TEP process is generally a minimum cost plan complying with the defined planning criteria. In practice, a TEP generally relies on the experience of system planners, and the method is based on minimum cost solution techniques (Stoll, 1989; Khatib, 2003; Sullivan *et al.*, 2003). A set of alternative expansion plans in the planning period is selected from the set of all feasible plans. The computational tool employed is power system analysis software, based on the Newton-Raphson algorithm (Grainger and William, 1994) for solving a set of nonlinear power flow equations. A suitable plan from a set of alternative plans is then selected by the planners based on experience and results from power flow solutions.

TEP methods can be classified into three types: mathematical, heuristic, and meta-heuristic methods (Latorre *et al.*, 2003). Among the mathematical methods, optimization techniques such as bender 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. Among the heuristic methods, a sensitivity analysis is used to allocate the additional transmission lines (Ekwue and Cory, 1984). In some studies, a sensitivity index with respect to load curtailment has been used to identify transmission line investment (Monticelli *et al.*, 1982). Among the meta-heuristic methods, which are the most suitable for solving TEP with an AC model that is nonconvex in nature (Asadamongkol and Eua-Arporn, 2010), a simulated annealing (SA) algorithm has been proposed for long-term TEP (Romero *et al.*, 1996), and a new variant of tabu search (TS) for single-stage TEP (STEP) (da Silva *et al.*, 2001). A genetic algorithm (GA) for multistage planning of transmission expansions has been presented by Escobar *et al.* (2004).

For the development of meta-heuristic methods, enhanced leader particle swarm optimization (ELPSO) has been proposed to avoid easily becoming trapped in the local optima of the original particle swarm optimization (PSO), by increasing the explorative and exploitative capabilities (Rezaee Jordehi, 2015d). Moreover, the application of chaotic based methods to the big bang big crunch (BBBC) algorithm and bat swarm optimization (BSO) has been proposed to avoid easily becoming trapped in the local optima of the original BBBC and BSO, respectively (Rezaee Jordehi, 2014a; 2015b). In addition, meta-heuristic methods have been used in many applications outside of TEP. For example, the optimal locating and setting of FACTS devices in electric power systems are solved by the brainstorm optimization algorithm (BSOA), which is an algorithm inspired by the brainstorming process in human beings (Rezaee Jordehi, 2015a). ELPSO is used to solve the optimal allocation of distributed thyristor controlled series compensators (D-TCSCs) (Rezaee Jordehi, 2015c). Teaching learning based optimization (TLBO) is used to find the optimal setting of thyristor controlled series compensators (TCSCs) in electric power systems (Rezaee Jordehi, 2014b). Returning to the TEP problem, Mori and Sone (2001) have compared the GA, SA, and TS methods usually used to solve the problem of TEP with an AC model. Their results show that TS is the most efficient method for solving TEP. Therefore, TS was used in this study.

For TEP, considering the uncertainties as associated with renewable energy generation and loads, generation and transmission planning with renewable energy source integration using discrepancy bounded local search (DBLS) has been proposed (Bent *et al.*, 2011). Muñoz *et al.* (2012) modeled the TEP problem using mixed-integer linear programming and considered the impact of wind power operations on system security and the reserve market. Fuchs *et al.* (2011) used ant colony optimization for TEP considering wind power. However, these solutions are not sufficient for all possibilities of uncertain renewable energy generation and loads. Consequently, Leite da Silva *et al.* (2012) proposed a heuristic method for TEP using chronological power flow to cope with the uncertain power of a wind power resource. In addition, stochastic programming has been applied to model the uncertainties using random variables. For example, Yu *et al.* (2009) applied a stochastic programming called chance-constrained programming to solve the load and wind farm uncertainties. However, its application is limited because it needs an accurate probability distribution of the uncertain parameters, which is difficult to obtain in practice. Moreover, chance-constrained programming is quite complicated, requiring the convolution of probability distribution functions (PDFs) which are approximated using discrete methods. The accurate computation of the convolution requires the use of a small step size, which itself requires a large number of Monte Carlo simulations and thus high computation time.

Another method for coping with the uncertain parameters in TEP is robust optimization, which is a field of optimization theory that deals with uncertain parameters not only for system planning (Hajimiragha *et al.*, 2011) but also for system operation (Sarić and Stanković, 2009; Yu and Rosehart, 2012; Bertsimas *et al.*, 2013). The advantage of this optimization is that, unlike stochastic optimization, it requires only the range of variation of uncertain parameters. In studies of TEP using robust optimization, known as robust transmission expansion planning (RTEP), Yu *et al.* (2011) used Taguchi's orthogonal array testing (TOAT) to select the optimal scenarios of uncertain renewable energy generation and loads, and a genetic algorithm to find the optimal solution. However, TOAT does not fully cover the range of all uncertain parameters and therefore results in a solution which may not be very robust. Jabr (2013) defined the uncertainties of renewable energy generation and load as maximum and minimum values and used mixed integer linear programming to find the optimal solution. Alizadeh *et al.* (2013) considered the uncertainties of the estimated investment cost of transmission lines and forecasted electricity demands, and used mixed integer linear programming to solve the problem. The values of uncertain parameters are defined as the maximum, and the minimum values are defined as in Jabr (2013). However, the maximum and minimum values do not cover all the uncertainties found in actual situations.

In this paper, we present a new robust optimization approach to solve TEP. We propose scenarios suitable for making a robust expansion plan for all possible scenarios based on intermittent renewable energy generation and loads in one year. ATS is employed in the proposed RTEP. ATS iterates between the main problem, which minimizes the investment and operating costs, and the subproblem, which minimizes the total power generation of conventional generators and curtailments of renewable energy generation and loads. The impact of an intermittent renewable energy source on TEP is evaluated by comparison of expansion plans which either do or do not consider intermittent renewable energy generation.

The main contributions of this work are as follows:

1. The calculation of operating cost, which is rarely considered in previous RTEP studies, is presented and included with the investment cost in the objective function.

2. According to Yu *et al.* (2011), Alizadeh *et al.* (2013), and Jabr (2013), the defined values of uncertain parameters cannot guarantee 100% robustness of the system based on the renewable energy generation and loads profile in a year, which is an actual situation. Consequently, we propose an algorithm based on the maximum renewable energy generation and load curtailments for selecting suitable scenarios for renewable energy generation and loads.

3. Most of the subproblems of TEP or RTEP are modeled using linear programming. However, in this study, we use nonlinear programming based on the interior point method to obtain a more accurate solution in the RTEP process.

4. The impact of an intermittent renewable energy source on TEP, especially in terms of a cost comparison, is taken into account.

The notations used in this paper are listed in Table 1.

2 Transmission network expansion planning formulation

In this section, the mathematical formulations of TEP with and without intermittent renewable energy generation and loads are presented. These two formulations are modeled by an AC model which is solved using the Newton-Raphson method.

2.1 TEP without intermittent renewable energy generation and loads

The objective of the TEP problem is to select transmission lines to support the loads reliably and with minimum investment and operating costs. The transmission line candidates are predefined based on the corridors or right of ways. In general, the peak load scenario is selected for solving TEP. However, for renewable energy generation, suitable selection of renewable energy generation values is very difficult

Table 1 Notations used in this paper

Parameter	Description
Indices	
k	Index of transmission line candidate
b	Index of bus
i	Index of 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
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 the renewable energy source at bus i (US$/MW)
oc_i	Outage cost of load at bus i (US$/MW)
$V_i^{\min}$, $V_i^{\max}$	Minimum and maximum limits of voltage magnitude at bus i (p.u.)
S_{ij_lim}	Apparent power limit of transmission line ij (MV·A)
$P_g^{\min}$, $P_g^{\max}$	Minimum and maximum limits of power generation of generator g (MW)
$Q_g^{\min}$, $Q_g^{\max}$	Minimum and maximum limits of reactive power generation of generator g (Mvar)
$Q_{\mathrm{C}i}^{\min}$, $Q_{\mathrm{C}i}^{\max}$	Minimum and maximum limits of reactive power generation of the capacitor at bus i (Mvar)
$Q_{\mathrm{IN}i}^{\min}$, $Q_{\mathrm{IN}i}^{\max}$	Minimum and maximum limits of reactive power consumption of the inductor at bus i (Mvar)
g_{ij}	Series conductance in the π-model of the transmission line
b_{ij}	Series susceptance in the π-model of the transmission line
b_{sh_ij}	Shunt susceptance in the π-model of the transmission line
n_{c}	Number of transmission line candidates
n_{g}	Number of generators
n_{b}	Number of buses
n_{l}	Number of all transmission lines in the system
n_{s}	Number of stages
n_{y}	Number of years for each stage
t_{el}	Expected life time of the transmission line (year)
$\boldsymbol{u}$	Intermittent vector which represents the intermittent renewable energy generation and loads
r	Interest rate (percent per year)
r_{d}	Demand growth rate (percent per year)
sv	Salvage value of the transmission line (US$)
c_{inv}	Investment cost (US$)
c_{opr}	Operating cost (US$)
$\mathrm{pv}_{\mathrm{inv}}$	Present value of investment cost subtracted by its salvage value (US$)
$\mathrm{pv}_{\mathrm{opr}}$	Present value of operating cost (US$)
H	Number of hours without renewable energy generation and load curtailments
n_{hy}	Number of hours in a year
Variables	
x_{ij}	Investment variable in $\{0, 1\}^{n_{\mathrm{c}}}$ (binary variable) representing a decision on the selection of transmission line candidates for the investment plan. That is, x_{ij}=1 if the transmission line candidate ij is selected; otherwise, it is not selected
P_g, Q_g	Power and reactive power generation of generator g (MW)
$P_{\mathrm{G}i}$, $P_{\mathrm{R}i}$, $P_{\mathrm{D}i}$	Power of conventional generation, renewable energy generation, and loads at bus i (MW)
$Q_{\mathrm{G}i}$, $Q_{\mathrm{D}i}$	Reactive power of generation and loads at bus i (Mvar)
$Q_{\mathrm{C}i}$, $Q_{\mathrm{IN}i}$	Reactive power generation and consumption of the capacitor and the inductor at bus i
$P_{\mathrm{RC}i}$, $P_{\mathrm{DC}i}$	Curtailments of renewable energy generation and 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.)

and has not been well discussed in previous studies. Based on Yu *et al.* (2011), three renewable energy generation values, including zero, half capacity, and full capacity values, are selected. Consequently, the test can be classified into three cases, denoted by TEP_ZERO, TEP_HALF, and TEP_FULL. The formulation of TEP is shown below:

Objective function

$$\min\left(\sum_{k=1}^{n_c} c_{ij}^k x_{ij}^k + \sum_{g=1}^{n_g} c_g P_g\right) \tag{1}$$

subject to the following:

1. Power balance constraint:

$$P_{Gi} + (P_{Ri} - P_{RCi}) - (P_{Di} - P_{DCi}) = \sum_{j\in N(i)} P_{ij}(1+x_{ij}),\ i\in\Omega^{b},\ i=1,2,...,n_b, \tag{2}$$

$$Q_{Gi} - (Q_{Di} - Q_{DCi}) = \sum_{j\in N(i)} Q_{ij}(1+x_{ij}),\ i\in\Omega^{b},\ i=1,2,...,n_b. \tag{3}$$

2. Bus voltage constraint:

$$V_i^{\min} \le V_i \le V_i^{\max},\quad i\in\Omega^{b},\ i=1,2,...,n_b. \tag{4}$$

3. Apparent power flow constraint:

$$\sqrt{(P_{ij}^m)^2 + (Q_{ij}^m)^2} \le S_{ij\_\lim}^m,\quad ij\in\Omega^{tl},\ m=1,2,...,n_l. \tag{5}$$

4. Real and reactive power of generator constraint:

$$P_g^{\min} \le P_g \le P_g^{\max},\ g\in\Omega^{g},\ g=1,2,...,n_g, \tag{6}$$

$$Q_g^{\min} \le Q_g \le Q_g^{\max},\ g\in\Omega^{g},\ g=1,2,...,n_g. \tag{7}$$

5. Capacitor and inductor installation constraint:

$$Q_{Ci}^{\min} \le Q_{Ci} \le Q_{Ci}^{\max},\ i\in\Omega^{b},\ i=1,2,...,n_b, \tag{8}$$

$$Q_{INi}^{\min} \le Q_{INi} \le Q_{INi}^{\max},\ i\in\Omega^{b},\ i=1,2,...,n_b. \tag{9}$$

6. Curtailment of renewable energy generation and loads:

$$0 \le P_{RCi} \le P_{Ri},\ i\in\Omega^{b},\ i=1,2,...,n_b, \tag{10}$$

$$0 \le P_{DCi} \le P_{Di},\ i\in\Omega^{b},\ i=1,2,...,n_b. \tag{11}$$

7. Real and reactive power flow in relation to bus voltage:

$$P_{ij}^m + \mathrm{i}Q_{ij}^m = |V_i|^2\left(g_{ij} - \mathrm{i}\left(b_{ij} + \frac{1}{2}b_{\mathrm{sh}\_ij}\right)\right) - V_iV_j^*(g_{ij} - \mathrm{i}b_{ij}),\ ij\in\Omega^{tl},\ i\in\Omega^{n_b},\ m=1,2,...,n_l. \tag{12}$$

8. Number of installed transmission lines:

$$\sum_{k=1}^{n_c} x_{ij}^k \le n_c,\ ij\in\Omega^{tc}. \tag{13}$$

9. Binary variable constraint:

$$x_{ij} = \begin{cases} 0, & ij\notin\Omega^{tc}, \\ \text{1 or 0 (depending on the randomness} & \\ \text{in the process)}, & ij\in\Omega^{tc}. \end{cases} \tag{14}$$

2.2 TEP with intermittent renewable energy generation and loads

In general, for TEP with uncertain parameters, two values (minimum and maximum) of renewable energy generation and loads are selected as the considered scenarios (Jabr, 2013):

$$P_{Ri} \in \{P_{Ri}^{\min},\ P_{Ri}^{\max}\},\ i\in\Omega^{b},\ i=1,2,...,n_b, \tag{15}$$

$$P_{Di} \in \{P_{Di}^{\min},\ P_{Di}^{\max}\},\ i\in\Omega^{b},\ i=1,2,...,n_b. \tag{16}$$

The most suitable optimization to deal with uncertain parameters in TEP is robust optimization. Therefore, we name this TEP robust transmission expansion planning (RTEP). To formulate this planning, the objective function and constraints of RTEP are the same as in (1) and (2)–(14), respectively. Moreover, the constraints (2)–(14) have to satisfy all values of P_{Ri} and P_{Di} as shown in Eqs. (15) and (16), respectively. To write the formulation easily, the intermittent vector $\boldsymbol{u}$ is defined to represent the intermittent renewable energy generation and loads:

$$\boldsymbol{u} = \left[P_{Ri},...,P_{Rn_b},P_{Di},...,P_{Dn_b}\right],\ i=1,2,...,n_b, \tag{17}$$

$$\boldsymbol{u} \in \left[\boldsymbol{u}^{\min},\boldsymbol{u}^{\max}\right]. \tag{18}$$

For RTEP formulation, some of the constraints of TEP described in Section 2.1 are used. However, some constraints have to be applied by adding vector $\boldsymbol{u}$ to design the robust planning:

Power balance constraint:

$$P_{\mathrm{G}i}+\left(P_{\mathrm{R}i}(\boldsymbol{u})-P_{\mathrm{RC}i}(\boldsymbol{u})\right)-\left(P_{\mathrm{D}i}(\boldsymbol{u})-P_{\mathrm{DC}i}(\boldsymbol{u})\right) = \sum_{j\in N(i)} P_{ij}(1+x_{ij}),\ i\in\Omega^{\mathrm{b}},\ i=1,2,\ldots,n_{\mathrm{b}}, \tag{19}$$

$$Q_{\mathrm{G}i}-\left(Q_{\mathrm{D}i}(\boldsymbol{u})-Q_{\mathrm{DC}i}(\boldsymbol{u})\right) = \sum_{j\in N(i)} Q_{ij}(1+x_{ij}),\ i\in\Omega^{\mathrm{b}},\ i=1,2,\ldots,n_{\mathrm{b}}. \tag{20}$$

Curtailments of renewable energy generation and loads are

$$0\le P_{\mathrm{RC}i}(\boldsymbol{u})\le P_{\mathrm{R}i}(\boldsymbol{u}),\ i\in\Omega^{\mathrm{b}},\ i=1,2,\ldots,n_{\mathrm{b}}, \tag{21}$$

$$0\le P_{\mathrm{DC}i}(\boldsymbol{u})\le P_{\mathrm{D}i}(\boldsymbol{u}),\ i\in\Omega^{\mathrm{b}},\ i=1,2,\ldots,n_{\mathrm{b}}. \tag{22}$$

In conclusion, the formulation of RTEP consists of objective function (1) and constraints (4)–(9), (12)–(14), and (19)–(22). This formulation cannot be solved directly because the constraints have to be satisfied for all values of intermittent vector $\boldsymbol{u}$. Therefore, in this study we propose a method to solve this formulation.

3 Proposed robust optimization approach for solving RTEP

The proposed RTEP is solved using a meta-heuristic method. Although the calculation time of this method is rather high, the solution can be more accurate than those of other methods (Latorre *et al.*, 2003). Adaptive tabu search (ATS) (Katdee, 2010) is used in this study. The details of the proposed RTEP are explained in the following subsections.

3.1 Main problem

The operating cost has rarely been considered in previous RTEP studies. Therefore, this study includes the operating cost in the objective function. In the case of investment cost, since the expected lifetime of the transmission line installed in each stage is usually longer than the considered planning period, salvage values of these transmission lines should be taken into account at the end of the planning period to reflect the use of the transmission line.

The salvage value at the end of the planning period can be estimated using a straight line method (Sullivan *et al.*, 2003). The salvage value of the equipment can be calculated using

$$\mathrm{sv}=c_{\mathrm{inv}}\frac{t_{\mathrm{el}}-n_{\mathrm{y}}(n_{\mathrm{s}})}{t_{\mathrm{el}}}. \tag{23}$$

The present value of the investment cost subtracted by its salvage value can be calculated from

$$\mathrm{pv}_{\mathrm{inv}}=c_{\mathrm{inv}}\left(1-\frac{t_{\mathrm{el}}-n_{\mathrm{y}}n_{\mathrm{s}}}{t_{\mathrm{el}}(1+r)^{n_{\mathrm{y}}n_{\mathrm{s}}}}\right). \tag{24}$$

In the case of operating cost, it is assumed that the cost for each year increases by the same rate as the growth in demand. Therefore, the present value of the operating cost can be calculated from

$$\mathrm{pv}_{\mathrm{opr}}=\frac{c_{\mathrm{opr}}}{(1+r_{\mathrm{d}})^{n_{\mathrm{y}}-1}}\left(1+\left(\frac{1+r_{\mathrm{d}}}{1+r}\right)+\ldots+\left(\frac{1+r_{\mathrm{d}}}{1+r}\right)^{n_{\mathrm{y}}-1}\right). \tag{25}$$

Consequently, the objective function of the proposed RTEP can be formulated as

$$\min\left(\sum_{k=1}^{n_{\mathrm{c}}}\mathrm{pv}_{\mathrm{inv}}^{k}x_{ij}^{k}+\sum_{g=1}^{n_{\mathrm{g}}}\mathrm{pv}_{\mathrm{opr}}^{\mathrm{g}}P_{g}\right) \tag{26}$$

with constraints (4)–(9), (12)–(14), and (19)–(22).

3.2 Subproblem

During the ATS iteration, the subproblem is solved to avoid approaching the operating limit of the given system configuration which is obtained from the random process of the ATS algorithm. To ensure the high accuracy of the solution, in this work we formulate the subproblem by an AC model, which is solved by nonlinear programming (NLP) based on the primal dual interior point method. The objective function can be written as

$$\min\left(\sum_{g=1}^{n_{\mathrm{g}}}c_{g}P_{g}+\sum_{i=1}^{n_{\mathrm{b}}}\mathrm{rc}_{i}P_{\mathrm{RC}i}+\sum_{i=1}^{n_{\mathrm{b}}}\mathrm{oc}_{i}P_{\mathrm{DC}i}\right). \tag{27}$$

The constraints (2)–(14) are used in the subproblem formulation. For the algorithm to solve this problem formulation, each algorithm of nonlinear programming for optimal power flow in MATLAB was tested to select the one that gives the minimum calculation time. The test was run on a computer with an Intel Core i5 3.0 GHz processor. The primal dual interior point algorithm gave the minimum calculation time (Table 2). Therefore, this algorithm was selected to solve the subproblem.

Table 2 Calculation time of various algorithms

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

3.3 Proposed method for scenario selection

To plan a system with high robustness, the scenarios considered for planning should cover as many uncertainties as possible. Consequently, the proposed method considers every hourly value of the actual renewable energy generation and load in a target year. A scenario selection indicator (SSI) based on the maximum renewable energy generation and load curtailments is calculated every hour. These curtailments are obtained by solving the formulations (27) and (2)–(14). If the renewable energy generation and load in a given hour are curtailed, then the renewable energy generation and load of that hour should be taken as the scenario considered for planning. Otherwise, the renewable energy generation and load of that hour may not be sufficiently significant to be considered. The SSI can be separated into two indicators, a scenario selection indicator of renewable energy generation (SSIRG) and a scenario selection indicator of loads (SSIL):

$$\mathrm{SSIRG}_h=\sum_{i=1}^{n_\mathrm{b}}P_{\mathrm{RC}i,h}\Big/\sum_{i=1}^{n_\mathrm{b}}P_{\mathrm{R}i,h}, \tag{28}$$

$$\mathrm{SSIL}_h=\sum_{i=1}^{n_\mathrm{b}}P_{\mathrm{DC}i,h}\Big/\sum_{i=1}^{n_\mathrm{b}}P_{\mathrm{D}i,h}. \tag{29}$$

The procedure of the proposed method can be described in the following steps:

1. Set the 'considered indicator value' of SSIRG and SSIL and set the index of hour (h) to 1.

2. Calculate SSIRG_h and SSIL_h.

3. Compare SSIRG_h and SSIL_h with the considered indicator value. If SSIRG_h or SSIL_h is equal to or higher than the 'considered indicator value', select this hour h as the scenario considered for planning; otherwise, do not select this hour.

4. Set h=h+1. If h is higher than the number of hours in a year, end the process and accumulate all the scenarios considered; otherwise, go to step 2.

3.4 Evaluation of expansion plan robustness

In an actual situation, there are various combinations of intermittent renewable energy generation and loads. Although the solution from RTEP can operate without system violation for all considered scenarios obtained by the scenario selection method, the solution obtained will probably not operate without system violation for all actual combinations of renewable energy generation and loads. Therefore, a method for evaluating the efficiency of the solution using a robustness indicator is presented.

In this study, we use renewable energy generation and load data for each hour in a target year to evaluate the robustness of the expansion plan. To evaluate the robustness, every hour in a target year of renewable energy generation and loads is executed by the formulation of (27) and (2)–(14). The expansion plan robustness can be evaluated using:

$$\text{Robustness}=\frac{H}{n_\mathrm{hy}}\times 100\%. \tag{30}$$

3.5 Summary of the proposed RTEP procedure

From Sections 3.1–3.4, the procedure of the proposed RTEP can be summarized in the following steps:

1. Select the scenarios using the method proposed in Section 3.3.

2. Solve RTEP using ATS. The process is described below:

2.1. ATS will randomize the investment variable x_{ij} into the system. After that, this network configuration is solved by the subproblem formulation (Section 3.2).

2.2. Evaluate the quality of the solution obtained from step 2.1. If the solution can operate without violation or curtailments for all the scenarios considered in vector $\boldsymbol{u}$, the solution will be given a quality score according to the investment and operating costs. On the other hand, if the solution cannot operate without violation or the curtailments for all of the scenarios considered, it will be given a zero quality score. Collect the quality score of the solution.

2.3. Carry out the iteration as shown in steps 2.1 and 2.2 until it reaches the iteration limit.

2.4. Compare the solutions based on their quality scores and select the best solution as the optimal solution.

3. Evaluate the robustness of the optimal solution by Eq. (30).

4 Numerical results and discussion

The proposed algorithm was applied to the IEEE Reliability Test System 79 (RTS79) (Rider *et al.*, 2007). The renewable energy sources (wind farms) were assumed to be connected at bus 7 and bus 22. The capacity of each wind farm was assumed to be 990 MW and the parameters of each wind generator were defined as follows: cut-in speed 4 m/s, rated speed 13.62 m/s, and cut-out speed 25 m/s (Yu *et al.*, 2011). The active power output of the wind farm was calculated using the model of Zahedi (2012) based on wind speed data from northeast Thailand. For ATS optimization, the parameters of ATS were set as follows: the maximum number of iterations was 1000, the number of neighbor solutions was 20, and the maximum repetition of the solutions was 3. For economic calculation, the parameters were set as follows: r and r_d were 0.1, n_y was 9 years, t_{el} was 25 years, and n_s was 1 stage (single stage planning).

The proposed method was run on a computer with an Intel Core i5 3.0 GHz processor. All programs were written using MATLAB R2011A. The tests were divided into three parts. Firstly, we tested TEP without intermittent renewable energy generation and loads (Section 4.1). Secondly, we tested TEP with intermittent renewable energy generation and loads (Section 4.2). Thirdly, we evaluated the impact of the intermittent renewable energy source on TEP (Section 4.3). The results are discussed in Section 4.4.

4.1 Results of TEP without intermittent renewable energy generation and loads

To compare the planning results from different scenarios, the tests were divided into three cases: TEP_ZERO, in which the scenario of a zero value of renewable energy generation is considered, TEP_HALF, in which the scenario of a half capacity value is considered, and TEP_FULL, in which the scenario of a full capacity value is considered. For loads, the peak load value was considered in all three cases. The planning results are shown in Table 3.

Table 3 shows that the cost of the TEP result varied in the same direction as the robustness of the system. The average calculation time of the TEP method was 38.86 min.

4.2 Results of TEP with intermittent renewable energy generation and loads

Robust optimization was used in this TEP. Therefore, the name of this TEP was changed to robust transmission expansion planning (RTEP). The results of RTEP from three methods for selecting the scenarios of renewable energy generation and loads were compared. For the first method, two values (minimum and maximum) of renewable energy generation and loads were selected (Jabr, 2013). This method was defined as RTEP_MIN_MAX. For the second method, TOAT (Yu *et al.*, 2011) was used. The total number of uncertain variables in this system was 19, consisting of 2 renewable energy sources (wind farms) and 17 loads. Each level of each uncertain variable was assigned two values (zero and maximum capacity value for renewable energy generation and minimum and maximum values for loads). Therefore, orthogonal array $L_{32}(2^{19})$ (University of York, 2004) was chosen to generate the scenarios. This method was defined as RTEP_TOAT. Lastly, the method proposed in Section 3.5 for selecting scenarios was used. The first 10 highest values of SSIRG and SSIL are shown in Table 4.

Certainly, the more scenarios that are considered for planning, the more robust the planned system will be. However, the calculation time will also increase. Therefore, the indicator value considered has to be set to select only significant scenarios for planning. At first, the indicator values considered were assumed to be 0.3906 and 0.0744 for SSIRG and SSIL, respectively, to select only the highest values of SSIRG and

Table 3 Results of TEP without intermittent renewable energy generation and loads

Case	Solution	PV_{inv} (×10^6 US$)	PV_{opr} (×10^6 US$)	Total cost (×10^6 US$)	Robustness (%)
TEP_ZERO	$n_{6\text{-}10}$=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	326.40	8447.44	8773.84	70.48
TEP_HALF	$n_{6\text{-}10}$=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	399.99	6758.89	7158.88	30.56
TEP_FULL	$n_{7\text{-}8}$=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	491.06	5079.14	5570.20	41.86

SSIL as the scenarios considered. Consequently, the renewable energy generation and loads at hours 7787 and 8736 from Table 4 were selected as the scenarios considered for planning. This method is defined as RTEP_PROPOSED.

The three results of the RTEP are shown in Table 5. Only RTEP_PROPOSED resulted in 100% robustness. This means that the proposed method of RTEP is the most efficient among the methods tested. However, the total cost of the RTEP_PROPOSED was higher than that of RTEP_MIN_MAX or RTEP_TOAT. Thus, increasing the robustness increases the cost.

Table 4 The first 10 highest values of SSIRG and SSIL

Hour	SSIRG	Hour	SSIL
7787	0.3906	8736	0.0744
4095	0.3905	8610	0.0692
203	0.3902	8436	0.0687
3783	0.3902	8434	0.0678
4935	0.3902	8442	0.0652
4119	0.3902	8266	0.0640
3779	0.3901	8276	0.0640
4931	0.3900	8322	0.0640
4115	0.3900	8462	0.0635
227	0.3899	8268	0.0624

4.3 Impact of intermittent renewable energy source on TEP

To evaluate the impact of an intermittent renewable energy source on TEP, the tests were divided into three cases as follows:

1. The system without a renewable energy source (wind farms at bus 7 and bus 22 removed).

2. The system with a renewable energy source (wind farms installed at bus 7 and bus 22).

3. The system with a conventional generator installed instead of a renewable energy source (two conventional generators installed with capacities being the same as those of wind farms at buses 7 and 22).

The above three cases were defined as RTEP_PROPOSED-1, RTEP_PROPOSED-2, and RTEP_PROPOSED-3, respectively. The proposed robust optimization approach was used to solve these three cases. As in Section 4.2, only the hours which had the highest SSIRG and SSIL were selected as the scenarios considered for planning.

The results (Table 6) show that the proposed method can guarantee 100% robustness for all uncertainties. For the cost comparison, the pv_{inv} of each case was firstly compared. The pv_{inv} of the RTEP_PROPOSED-1 case was the lowest because this case had fewer generators. This resulted in the lowest investment cost of the transmission lines for transmitting the power to loads. For RTEP_PROPOSED-2 and RTEP_PROPOSED-3, the pv_{inv} was similar due to the same number of generators.

Secondly, the pv_{opr} was compared. The pv_{opr} of RTEP_PROPOSED-1 was the highest because power from the conventional generators of this case had to be transmitted the longest distance. A longer distance for transmitting power results in a higher power loss. Therefore, the generators in this case had to generate the highest power compared with the power sources of the other cases to supply sufficient loads. For comparison of pv_{opr} between RTEP_PROPOSED-2 and RTEP_PROPOSED-3, because of the intermittent generation of wind farms in RTEP_PROPOSED-2, the conventional generators had to generate more power to supply the loads to compensate for the reduction in power from the wind farms when the wind speed was low. With RTEP_PROPOSED-3, in which two conventional generators were installed instead of two wind farms, the two new conventional generators can completely supply their loads. This resulted in a decrease in power generation

Table 5 Results of RTEP

Method	Solution	Number of considered scenarios	pv_{inv} ($\times10^6$ US$)	pv_{opr} ($\times10^6$ US$)	Total cost ($\times10^6$ US$)	Robustness (%)	Calculation time (min)
RTEP_MIN_MAX	$n_{6\text{-}10}$=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	4	477.95	4985.23	5463.18	74.50	155.79
RTEP_TOAT	$n_{6\text{-}10}$=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	32	509.28	5224.79	5734.06	87.48	1068.79
RTEP_PROPOSED	$n_{6\text{-}10}$=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	2	536.96	6696.52	7233.48	100	67.04

Table 6 Results of RTEP_RE

Case	Solution	pv_{inv} ($\times10^6$ US$)	pv_{opr} ($\times10^6$ US$)	Total cost ($\times10^6$ US$)	Robustness (%)
RTEP_PROPOSED-1	$n_{6\text{-}10}$=1, $n_{7\text{-}8}$=1, $n_{2\text{-}8}$=1, $n_{8\text{-}9}$=1, $n_{4\text{-}9}$=1, $n_{10\text{-}11}$=1, $n_{1\text{-}5}$=2, $n_{8\text{-}10}$=3, $n_{5\text{-}10}$=1, $n_{15\text{-}16}$=1, $n_{12\text{-}13}$=1, $n_{14\text{-}16}$=1	382.50	8419.50	8802.00	100
RTEP_PROPOSED-2	$n_{6\text{-}10}$=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	536.96	6696.52	7233.48	100
RTEP_PROPOSED-3	$n_{7\text{-}8}$=2, $n_{1\text{-}5}$=1, $n_{20\text{-}23}$=2, $n_{2\text{-}4}$=1, $n_{17\text{-}18}$=1, $n_{16\text{-}17}$=1, $n_{2\text{-}8}$=2, $n_{12\text{-}13}$=1, $n_{15\text{-}16}$=1, $n_{9\text{-}11}$=1, $n_{3\text{-}9}$=1, $n_{2\text{-}6}$=1, $n_{13\text{-}14}$=1, $n_{14\text{-}16}$=3, $n_{8\text{-}9}$=1	551.53	6030.14	6581.67	100

from the other generators and power loss when transmitting the power through a long transmission line. Therefore, the pv_{opr} of RTEP_PROPOSED-3 was lower than that of RTEP_PROPOSED-2.

Finally, for comparison of the total cost, Table 6 shows that the total cost of RTEP_PROPOSED-2 and RTEP_PROPOSED-3 was lower than that of RTEP_PROPOSED-1. This implies that the installation of a generator, either a conventional generator or a renewable energy source, can reduce the total cost, especially the operating cost. If considering only the total cost, the total cost of RTEP_PROPOSED-3 was lower than that of RTEP_PROPOSED-2. This implies that even if the power from a renewable energy source is clean and has no operating cost, its uncertainties still require high compensation from other conventional generators and result in a higher total cost. A system planner should take this aspect into account before deciding to accept a renewable energy source into the system.

4.4 Discussions of test results

From the results shown in Tables 2 and 4, we conclude that the robustness of RTEP results is higher than that of TEP results. This is because the number of scenarios considered for TEP (only one scenario) is less than that for RTEP. Therefore, the expansion plan of TEP is less likely to cover all of the uncertainties than the expansion plan of RTEP. This indicates that RTEP is more suitable than TEP when considering intermittent renewable energy generation and loads.

With RTEP, the different methods for selecting scenarios of renewable energy generation and loads led to different results. The robustness of the result from the proposed method was higher than that of the other methods. We conclude that the scenarios obtained by the proposed method should be more suitable for planning than those obtained by the methods of Yu *et al.* (2011) and Jabr (2013).

The calculation time of the TEP method was lower than that of RTEP, because the TEP method considers only one scenario for planning while the RTEP method considers more than one scenario, depending on the method for scenario selection. In RTEP calculation, the calculation time of the TOAT method was higher than that of the other methods, because the number of scenarios considered by the TOAT method was the highest.

Lastly, the impact of an intermittent renewable energy source on TEP was evaluated. The results show that the installation of a renewable energy source in the system, instead of a conventional generator, will increase the cost of the expansion plan.

5 Conclusions

In this paper, we propose an approach to evaluate the impact of an intermittent renewable energy source on TEP. For the objective function of the planning, the operating cost is presented in addition to the investment cost. Nonlinear programming based on the interior point method is used to solve the subproblem which is formulated by an AC model to obtain a more accurate result. The proposed robust optimization approach can guarantee a 100% system robustness of the expansion planning, among the intermittent renewable energy generation and loads, while the robustness of the expansion plans of other methods is less than 100%. Moreover, the impact of an intermittent renewable energy source on TEP was evaluated. The results show that the installation of a renewable energy source in a system will increase the cost of the expansion plan compared with the cost arising from installing a conventional generator.

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