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ROBUST TRANSMISSION EXPANSION PLANNING CONSIDERING INTERMITTENT RENEWABLE ENGRGY GENERATION

Mr. Rongrit Chatthaworn

A Dissertation Submitted in Partial Fulfillment of the Requirements
for the Degree of Doctor of Philosophy Program in Electrical Engineering
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รองฤทธิ์ ฉัตรถาวร : การวางแผนขยายระบบส่งไฟฟ้าแบบคงทนโดยพิจารณากำลังผลิตของพลังงานหมุนเวียนแบบไม่ต่อเนื่อง (ROBUST TRANSMISSION EXPANSION PLANNING CONSIDERING INTERMITTENT RENEWABLE ENGRGY GENERATION) อ.ที่ปรึกษาวิทยานิพนธ์หลัก: ผศ. ดร. สุรชัย ชัยทัศนีย์, 192 หน้า.

วิทยานิพนธ์นี้นำเสนอวิธีการแก้ปัญหาสำหรับการวางแผนขยายระบบส่งไฟฟ้าแบบคงทนโดยพิจารณากำลังผลิตของพลังงานหมุนเวียนแบบไม่ต่อเนื่อง รวมไปถึงความไม่ต่อเนื่องของความต้องการไฟฟ้า โดยที่ผ่านมาปัญหาการวางแผนขยายระบบส่งไฟฟ้าแบบคงทนมักถูกจำลองโดยแบบจำลองกระแสตรง ทว่าในวิทยานิพนธ์นี้ได้ใช้แบบจำลองกระแสสลับแทน ซึ่งเงินลงทุนในการสร้างสายส่งและต้นทุนสำหรับการปฏิบัติการของเครื่องกำเนิดไฟฟ้าได้ถูกนำมาพิจารณาเป็นเป้าหมายสูงสุดในการวางแผน โดยวิทยานิพนธ์นี้ได้นำเสนอวิธีการเลือกเหตุการณ์ของกำลังผลิตของพลังงานหมุนเวียนและความต้องการไฟฟ้าที่เหมาะสมสำหรับการวางแผนขยายระบบส่งไฟฟ้าเพื่อทำให้ระบบไฟฟ้ามีความคงทนในทุกๆ เหตุการณ์ของกำลังผลิตของพลังงานหมุนเวียนและความต้องการไฟฟ้า โดยวิธีการค้นหาแบบตาบูเชิงปรับตัวซึ่งเป็นวิธีการหาคำตอบแบบกึ่งฮิวริสติก ได้ถูกนำมาใช้ในการแก้ปัญหาการวางแผนขยายระบบส่งไฟฟ้าแบบคงทนนี้ วิธีการค้นหาแบบตาบูเชิงปรับตัวนี้จะดำเนินการหาคำตอบของ ปัญหาหลัก (การหาค่าต่ำสุดของเงินลงทุนในการสร้างสายส่งและต้นทุนสำหรับการปฏิบัติการของเครื่องกำเนิดไฟฟ้า) และ ปัญหาย่อย (การหลีกเลี่ยงการละเมิดข้อจำกัดในการทำงานของระบบไฟฟ้าด้วยวิธีการจัดสรรกำลังการผลิตใหม่ รวมไปถึงการปลดกำลังไฟฟ้าจากแหล่งกำเนิดไฟฟ้าจากพลังงานหมุนเวียนและการปลดโหลด) โดยผลการทดสอบวิธีการวางแผนขยายระบบส่งไฟฟ้าที่นำเสนอกับระบบไฟฟ้า IEEE 24 บัส และระบบไฟฟ้าภาคตะวันออกเฉียงเหนือของประเทศไทย แสดงให้เห็นว่าผลลัพธ์ของวิธีการในการวางแผนขยายระบบส่งไฟฟ้าที่นำเสนอมีความคงทนมากกว่าผลลัพธ์ของวิธีการของงานวิจัยอื่นๆ ในอดีต

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RONGRIT CHATTHAWORN: ROBUST TRANSMISSION EXPANSION PLANNING CONSIDERING INTERMITTENT RENEWABLE ENGRGY GENERATION. ADVISOR: ASST. PROF. SURACHAI CHAITUSANEY, Ph.D., 192 pp.

This dissertation proposes a novel method for robust transmission expansion planning (RTEP) considering intermittent renewable energy generation and loads. The RTEP problem, which is generally formulated using a DC model, will be formulated in this dissertation by using an AC model. The investment cost of transmission lines and operating cost of conventional generators are considered as the objective function of the planning. This dissertation proposes the method to select the suitable scenarios for planning in order to make the robust expansion plan for all possible scenarios of renewable energy generation and loads. A metaheuristic algorithm called Adaptive Tabu Search (ATS) is employed in the proposed RTEP. 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 generation re-dispatch and curtailments of renewable energy generation and loads. The IEEE 24 buses and northeastern Thailand transmission systems are used for testing the proposed method. The results show that the proposed expansion planning is more robust than the solutions from other previous research works.

Department: Electrical Engineering Student's Signature ....
Field of Study: Electrical Engineering Advisor's Signature ....
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LIST OF ABBREVIATIONS

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k	Index of transmission line candidates
b	Index of buses
i	Index of buses or sending buses
j	Index of receiving buses
g	Index of generators
l	Index of existing transmission lines in ET_{ij}
c	Index of transmission line candidate in TD_{ij}
m	Index of existing transmission lines in the system
n	Index of all transmission lines in the system
h	Index of hours in a year
t	Index of stages in planning horizon
s	Index of scenario in the set of uncertainty
re	Index of renewable energy sources

Sets

Ω^b	Set of all buses
N_{bi}	Set of buses connected to bus i by a transmission line
U	Set of uncertainty defined by selected scenarios
Tabu_list	Set of forbidden paths
Ans_list	Set of local solutions
N_{gb}	Set of all generators connected to bus b
N_{lb}	Set of all transmission lines connected to bus b
ET_{ij}	Set of all existing transmission lines in path ij
TD_{ij}	Set of all transmission line candidates in path ij

Constant Parameters

n_{ij}	Number of transmission line or transformer candidates added to the path *ij*
n_{ij}^0	Number of existing transmission lines or existing transformers of the path *ij*
c_{ij}	Investment cost of transmission line candidate *ij* (US$)
c_g	Power generation cost of generator *g* (US$/MW)
wr_{re}	Weighting factor for the curtailment of renewable energy generation of renewable energy source *re* (US$/MW)
wd_i	Weighting factor for the curtailment of load at bus *i* (US$/MW)
$V_i^{\min}$, $V_i^{\max}$	Minimum and maximum limit of voltage magnitude at bus *i* (p.u.)
$\theta_i^{\min}$, $\theta_i^{\max}$	Minimum and maximum limits of voltage angle at bus *i* (degrees)
$S_{ij}^{\max}$	Apparent power limit of transmission line *ij* (MVA)
$\mathbf{S^{max}}$	Vector of all apparent power limits for all transmission lines (MVA)
$P_g^{\min}$, $P_g^{\max}$	Minimum and maximum limit of power generation of generator *g* (MW)
$P_R^{\min}$	The summation of power generations from all renewable energy sources at the hour that all renewable energy sources generate the minimum power (MW)
$P_R^{\max}$	The summation of power generations from all renewable energy sources at the hour that all renewable energy sources generate the maximum power (MW)
$S_D^{\min}$	The summation of apparent power demands from all buses at the hour that the apparent power demands are minimum (MVA)
$S_D^{\max}$	The summation of apparent power demands from all buses at the hour that that the apparent power demands are maximum (MVA)
$Q_g^{\min}$, $Q_g^{\max}$	Minimum and maximum limit of reactive power generation of generator *g* (MVAr)

$Q_i^{C\min}$, $Q_i^{C\max}$	Minimum and maximum limit of reactive power supply of capacitor at bus i (MVAr)
$Q_i^{IN\min}$, $Q_i^{IN\max}$	Minimum and maximum limit of reactive power consumption of inductor at bus i (MVAr)
$\mathbf{u}$	Vector of uncertain parameters which represents the intermittent renewable energy generation and loads
r_{ij}	Series resistance in the π-model of transmission line ij (p.u.)
rx_{ij}	Series reactance in the π-model of transmission line ij (p.u.)
g_{ij}	Series conductance in the π-model of transmission line ij (p.u.)
b_{ij}	Series susceptance in the π-model of transmission line ij (p.u.)
b_i^{sh}	Shunt susceptance in the π-model of bus i (p.u.)
b_{ij}^{sh}	Shunt susceptance in the π-model of transmission line ij (p.u.)
nc	Number of transmission line candidates
ng	Number of generators
nre	Number of renewable energy sources
nb	Number of buses
nl	Number of existing transmission lines in the system
anl	Number of all transmission lines in the system
ns	Number of stages
ny	Number of years for each stage
nu	Number of scenarios in the set of uncertainty U
el	Expected life time of transmission line (year)
r	Interest rate (% per year)
dr	Demand growth rate (% per year)
sv	Salvage value of the transmission line (US$)
c_{inv}	Investment cost of transmission lines (US$)
c_{opr}	Operating cost of conventional generators (US$)
pv_{inv}	Present value of investment cost subtracted by its salvage value (US$)
pv_{opr}	Present value of operating cost of conventional generators (US$)
H	Number of hours that renewable energy generation and load are not curtailed

nhy	Number of hours in a year
S_0	The initial solution of adaptive tabu search
f_max	The maximum number of solution repetitions
$iter\_max$	The maximum number of iterations
$num\_neighbor$	The maximum number of neighbor solutions
I_{ref}	Reference bus
R	Search radius
SP	Solution point
NS	The number of testing scenarios generated by TOAT
F	The number of factors and the number of columns in array
B	The number of factor levels
$SSIRG$	Scenario selection indicator of renewable energy generation
$SSIL$	Scenario selection indicator of loads
G_{std}	Solar radiation in the standard environment (W/m^2)
R_c	Certain radiation point (W/m^2)
P_{sn}	Equivalent rated capacity of solar source (W)
V_{CI}	Cut in wind speed (km/hr)
V_r	Rated wind speed (km/hr)
V_{CO}	Cut off wind speed (km/hr)
P_{rated}	Rated wind power (W)

Variables

$\mathbf{x}$	Vector of investment variable in $\{0,1\}^{nc}$ (binary variable) representing a decision on the selection of transmission line candidates into the expansion plan, i.e. $x_{ij}^k = 1$ if the transmission line candidate k which connects between bus i and bus j is selected, otherwise it is not selected
x_{ij}	Investment variable (binary variable) representing a decision on the selection of transmission line candidates ij into the expansion plan
P_i	Net real power at bus i (MW)

Q_i	Net reactive power at bus i (MW)
$\mathbf{P^G}$	Vector of real power generation for all generators (MW)
$\mathbf{Q^G}$	Vector of reactive power generation for all generators (MW)
P_g, Q_g	Real power and reactive power generation of generator g, (MW, MVAr)
P_{re}^R	Real power of renewable energy source re (MW)
P_i^D	Real power demand at bus i (MW)
Q_i^G, Q_i^D	Reactive power supply and demand at bus i (MVAr)
$\mathbf{Q^C}$	Vector of reactive power supply of capacitor for all buses (MVAr)
$\mathbf{Q^{IN}}$	Vector of reactive power consumption of inductor for all buses (MVAr)
Q_i^C, Q_i^{IN}	Reactive power supply and consumption of capacitor and inductor at bus i (MVAr)
$\mathbf{P^{DC}}$	Vector of real power demand curtailment for all buses (MW)
$\mathbf{Q^{DC}}$	Vector of reactive power demand curtailment for all buses (MVAr)
P_i^{DC}, Q_i^{DC}	Real power demand and reactive power demand curtailments at bus i, (MW, MVAr)
$\mathbf{P^{RC}}$	Vector of real power curtailment for all renewable energy sources (MW)
P_{re}^{RC}	Real power curtailment of renewable energy source re (MW)
S^{fr}	Apparent power flow from “from” bus (MVA)
S^{to}	Apparent power flow from “to” bus (MVA)
S_{ij}^{fr}	Apparent power flow from “from bus” of transmission line ij (MW)
S_{ij}^{to}	Apparent power flow from “to bus” of transmission line ij (MW)
P_{ij}, Q_{ij}	Real power and reactive power flows from bus i to bus j (MW, MVAr)
P_{ij}^{fr}, Q_{ij}^{fr}	Real power and reactive power flow from “from bus” of transmission line ij (MW, MVAr)

P_{ij}^{to}, Q_{ij}^{to}	Real power and reactive power flow from “to bus” of transmission line ij (MW, MVAr)
$\mathbf{V}$	Vector of voltage magnitude for all buses (p.u.)
V_i, V_j	Voltage magnitude at bus i and voltage magnitude at bus j (p.u.)
$\boldsymbol{\theta}$	Vector of voltage angle for all buses (degrees)
θ_i	Voltage angle at bus i (degrees)
S_{best}	The best solution of each iteration during adaptive tabu search process
N_S	Neighbor solution around S_{best}
N_S_{best}	The best solution of all neighbor solutions around S_{best}
P_{pv}	Output power of solar source (W)
G_{bh}	Hourly solar radiation (W/m^2)
P_{wind}	Output power of wind source (W)
V_{SP}	Wind speed (km/hr)

Functions

f_g^P	Cost function of real power generation from generator
f_{re}^{RC}	Cost function of curtailment of real power generated from renewable energy source
f_i^{DC}	Cost function of curtailment of real power demand

Abbreviations

ABC	Artificial bee colony
AC	Alternating current
AEDP	Alternative energy development plan
ATS	Adaptive tabu search
BSB2	Bulk power supply project for the greater Bangkok area phase 2
BSB3	Bulk power supply project for the greater Bangkok area phase 3
COD	Commercial operation date
CPF	Chronological power flow

CS	Cuckoo search
DBLS	Discrepancy bounded local search
DC	Direct current
DE	Differential evolution
DEDE	Department of alternative energy development and efficiency
EGAT	Electricity generating authority of Thailand
ERC	Energy regulatory commission
EWES	Expected wind energy spilled
FA	Firefly algorithm
FACTS	Flexible AC transmission system
GA	Genetic algorithm
GIS	Geographic information system
GRASP	Greedy randomized adaptive search procedure
HBA	Honey bee algorithm
HBMO	Honey-bee mating optimization
HMCR	Harmony memory considering rate
HS	Harmony search
IPP	Independent power producers
KCL	Kirchhoff’s current law
LANL	Los Alamos national laboratory
MEA	Metropolitan electricity authority
MINLP	Mixed integer nonlinear programming
OPF	Optimal power flow
PAR	Pitch adjustment rate
PDP	Power development plan
PDR	People's democratic republic
PSO	Particle swarm optimization
RETA	Renewable energy transmission authority
RETI	Renewable energy transmission initiative
RPS	Renewable portfolio standard
RTEP	Robust transmission expansion planning
SA	Simulated annealing

SPP	Small power producer
SSI	Scenario selection indicator
STEP	Single stage TEP
TEP	Transmission expansion planning
TL	Transmission line
TOAT	Taguchi’s orthogonal array testing
TS	Tabu search
VBA	Virtual bee algorithm
VSPP	Very small power producer

CHAPTER 1
INTRODUCTION

This chapter starts with the problem statement which identifies the problem to be solved in this dissertation. After that, objective, scope, steps of study, and expected benefits are described. Finally, the dissertation structure is presented.

1.1 Problem Statement

Due to the electrical load growth, transmission expansion is needed to resolve the electricity inadequacy problem by the minimal associated investment and operating costs, while system operating constraints are not violated and system reliability should be acceptable [1-3]. Apart from this, 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 13,927 MW in the year 2021 [4]. Although this kind of power generation can help reduce fossil fuel consumption and CO_2 emission, its intermittent attributes, 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 expansion planning (TEP) for integrating these intermittent power generations has to be revised in order to ensure the secured system operation among intermittent renewable energy generations and loads. In addition, a robust transmission expansion planning (RTEP) which provides the robust planning scheme is extremely significant.

Practically, transmission expansion planning is generally planed based on the experiences of system planners. The method is generally based on the minimum cost solution techniques [5-7]. A set of alternatives of expansion plans in the planning period is selected from the set of all feasible plans. The number of alternatives should be reasonable for the implementation in the next steps. The computational tool employed in the process is only power system analysis software based on the Newton-Raphson algorithm [8] for solving a set of nonlinear power flow equations. After that, the suitable plan is selected from a set of alternative plans by the planners based on theirs experiences together with the results from power flow solutions.

From the literature reviews, TEP methods can be classified into 3 methods consisting of mathematical programming method, heuristic method, and metaheuristic method [9]. For the mathematic programming method, optimization techniques such as bender decomposition [10], linear programming [11], dynamic programming [12], nonlinear programming [13] and mixed integer programming [14] are mostly used for TEP. For the heuristic method, a sensitivity analysis is used to allocate the additional transmission lines [15]. Some researches use the sensitivity index with respect to the load curtailment or other indices of the system behavior [16] with respect to transmission line (TL) reinforcement. For the metaheuristic method, a simulated annealing (SA) approach is proposed for long-term TEP [17], a new variant of tabu search is presented for static or single stage TEP (STEP) [18]. A genetic algorithm (GA) based approach for multistages and coordinated planning of transmission expansions is presented in [19].

For the TEP considering the renewable energy generation, generation and transmission planning with renewable energy source integration using discrepancy bounded local search (DBLS) algorithm which is the heuristic algorithm is proposed [20]. The weak point is the quality of the solution because there is no method to prove that the solution from heuristic algorithm is global. The research work [21] models the TEP problem by using mixed-integer linear program which the impact of wind power operation in the system security and the reserve market are incorporated. In [22], ant colony optimization for TEP integrating renewable energy sources, especially large wind power, is presented. Research work [23] proposes a heuristic method of TEP by using chronological power flow in order to cope with the uncertain power of wind power resource. However, research works [21]-[23] model the TEP problem by DC model which some parameters are neglected. Therefore, the obtained solution may infeasible in practice.

For the method to design the expansion plan that can operate without any violation of system operation under the uncertain or intermittent of renewable energy generation and loads, stochastic programming is applied to model the uncertainties by random variables. Therefore, the planning solution has higher probability for supporting renewable energy generation and loads without system constraint violation. For example, research work [24] applies a stochastic programming called chance-constrained programming to formulate the TEP with consideration of the uncertainties of load and wind turbine generation. This formulation gives system-decision maker an opportunity to compromise between the investment and overload probability. However, there is the limitation because it needs an accurate probability distribution of the uncertain parameters which is difficult to obtain in practice. In addition, chance-constrained programming, with a wind turbine generator output probability density function (PDF), is further complicated by requiring the computation of the convolution of the PDFs which are approximated using discrete methods. The accurate computation of the convolution calls for the use of a small step size, which itself requires a large number of Monte Carlo simulations to determine the wind turbine generator output PDF.

Another method to design the expansion plan with the uncertain parameters is robust optimization; this optimization is widely used for making decision under uncertainty not only for system planning [25] but also system operation [26-28]. For the advantage of this optimization, the requirement is only the range of variation of uncertain parameters differing from the stochastic optimization which requires an accurate probability distribution of the uncertain parameters that is difficult to obtain in practice as mentioned before. For the works of TEP using robust optimization which is known as robust transmission expansion planning (RTEP), reference [29] uses Taguchi’s orthogonal array testing (TOAT) for selecting the optimal scenarios of uncertain renewable energy generation and loads and uses genetic algorithm to find the optimal solution. However, TOAT does not fully cover the range of all uncertain parameters and therefore results in the obtained solution may not be exactly robust. While reference [30] defines the uncertainties of renewable energy generation and loads into the maximum, and minimum values and uses mixed integer linear programming based on bender decomposition to find the optimal solution. Moreover, another research works [31] considers the uncertainties of estimated investment costs of candidate transmission lines and the forecasted electricity demands in RTEP which using mixed integer linear programming to solve the problem. The values of uncertain parameters are defined as the maximum, and minimum values as the same as [30].

Nevertheless, the maximum and minimum values may not fully cover all uncertain parameters which result in the obtained solution is not exactly robust.

From the literature reviews, most of the problems of TEP and RTEP are formulated by DC model because the problem based AC model is very complicated due to the fact that both integer programming and nonlinear programming are incorporated. In addition, some research works solve the TEP and RTEP problems by heuristic method which has no algorithm to prove that the obtained solution is optimal. Some research works solve the problem by mathematical method. Big practical obstacles appear to obtain the “optimal” solution when mathematical optimization techniques are used for solving the TEP or RTEP problems, which are nonlinear and nonconvex in nature. This is mostly due to the intrinsic limitation of the optimization process itself, for example, convergence problems when DC model is used. Finally, in the RTEP viewpoint, both scenarios selection by TOAT and maximum and minimum values of renewable energy generation and loads cannot guarantee the robustness of the obtained solution at 100% (No curtailment of renewable energy generation or curtailment of loads during system operation).

As a result, this dissertation proposes a method for robust transmission expansion planning considering intermittent renewable energy generation and loads. This dissertation proposes the scenario selection method in order to make the robust expansion plan for all possible scenarios based on intermittent renewable energy generation and loads in a year. The RTEP problem is formulated based on AC model. Adaptive tabu search (ATS) is employed in the proposed RTEP in order to obtain the global optimum or the best of local optimum. It iterates between the main problem, which minimizes the investment cost and operating cost, and the subproblem, which minimizes the total power generation of conventional generators and curtailments of renewable energy generation and loads.

The main contribution of this dissertation can be concluded as follows:

(a) The calculation of operating cost which is rarely considered in previously RTEP works is presented and is included with the investment cost in the objective function.

(b) According to [29-31], the defined scenarios of uncertain parameters for robust planning cannot guarantee the robustness of the system at 100% based on the renewable energy generation and loads profile in a target year. Consequently, the algorithm based on the maximum curtailments of renewable energy generation and loads for selecting the suitable scenarios of renewable energy generation and loads is proposed in order to plan the system with 100% robustness.

(c) Most of the problems of TEP and RTEP are formulated by DC model which is usually solved by linear programming. In order to obtain more accurate solution, this dissertation formulates TEP and RTEP by AC model which is solved by ATS.

1.2 Objective

(a) To propose an improved RTEP method considering intermittent renewable energy generation and loads in order to design the system with 100% of robustness.

(b) To show that the expansion plan from the proposed method is more robust than the expansion plan from the other methods.

(c) To show the effect of renewable energy source on cost of planning.

1.3 Scope of Research Work and Limitations

The detailed scope and limitations of this dissertation are listed as shown below.

(a) The proposed RTEP method is solved based on adaptive tabu search for both single stage and multistage planning.

(b) The problem of RTEP is divided into 2 problems consisting of main problem and subproblem. The objective function of main problem is minimizing the investment cost of transmission line and the operating costs of conventional generators whereas the objective function of subproblem is minimizing the operating cost of conventional generators and the curtailments of renewable energy generation and loads in order to avoid the violation of system operation.

(c) N-1 security constraint is not taken into account in the planning.

(d) Only solar and wind sources which generates uncertain output power are considered as the renewable energy sources in the planning.

(e) Uncertainty of the forecasted values of renewable energy generation and load is not taken into account.

(f) The pattern of solar radiation and wind speed are assumed to be the same for all planning period.

1.4 Steps of Study

(a) Studying transmission expansion planning in Thailand.

(b) Studying transmission expansion planning in other countries.

(c) Studying the works of literatures related to the transmission expansion planning.

(d) Studying the works of literatures related to the optimization technique.

(e) Studying the works of literatures related to the transmission expansion planning with renewable energy generation.

(f) Studying the works of literatures related to the robust transmission expansion planning.

(g) Developing and formulating the RTEP with renewable energy generation and loads.

(h) Simulating the proposed method on the test systems.

1.5 Dissertation Structure

The rest of this dissertation is organized as follows. In the next chapter, the review of TEP in Thailand and other countries and the literature review of TEP methods are presented. Chapter 3 shows the information of renewable energy sources in Thailand. In Chapter 4, the review of various methods of metaheuristic optimization and adaptive tabu search using in the dissertation are presented. In

Chapter 5, the proposed RTEP considering intermittent renewable energy generation is introduced in order to improve the robustness of the expansion plan. After that, this proposed RTEP is tested with the IEEE 24 buses [32] and the northeastern Thailand systems [10] in Chapter 6. Finally, the conclusions and future aspect of this dissertation are summarized.

CHAPTER 2

TRANSMISSION EXPANSION PLANNING (TEP)

This chapter presents the review of transmission system status and planning when renewable energy generation is taken into account in Thailand. Then, the methods for solving TEP in Thailand and other countries are reviewed. Moreover, general method, transmission network model, solving method and the problem formulations for transmission expansion planning are presented. Lastly, the literature review of TEP method is described. The structure of this chapter is organized as shown below.

Firstly, Thailand's transmission system status is presented in Section 2.1. Secondly, impact of renewable energy generation to transmission system in Thailand is presented in Section 2.2. Thirdly, general method of TEP is illustrated in Section 2.3. Fourthly, the transmission network model is presented in Section 2.4. Fifthly, the solving method of TEP is shown in Section 2.5. Sixthly, the problem formulation of TEP and RTEP is illustrated in Section 2.6. Finally, international review of TEP method considering renewable energy source is illustrated in the Section 2.7.

2.1 Transmission System Status and Planning in Thailand

The transmission system data of electricity generating authority of Thailand (EGAT) can be shown in Table 2.1 [33]. In addition, transmission system development projects/expansion plans in the annual report 2014 of EGAT [34] are shown in the following subsections.

<u>On-going Transmission System Projects</u>

2.1.1 Bulk Power Supply for the Greater Bangkok Area Phase 2

The bulk power supply project for the greater Bangkok area phase 2 (BSB2) is successive from the phase 1 project. The project comprises the construction of new transmission lines and the upgrade of existing lines totaling 89.025 circuit-kilometers, installation of transformers totaling 10,600 MVA, and voltage control equipment totaling 384.0 MVAr. In December 2014, the progress of the project was 85.07 percent. This project was scheduled to be completed in 2017.

Table 2.1 Transmission substations and transmission lines status (April 2015)

Voltage levels (kV)	Transmission substation		Transmission line (circuit-kilometers)
	Number	Transformer capacity (MVA)	
500	13	21,849.99	4,388.97
300 (DC line)	-	388.02	23.07
230	75	54,260.04	14,691.07
132	-	133.40	8.71
115	128	14,579.99	13,830.97
69	-	-	19.00
Total	216	91,211.44	32,961.79

2.1.2 Transmission System Expansion Project No.11 (TS.11)

Being a successive scheme of the TS.10, TS.11 covers the transmission system expansion and reinforcement projects in all provincial areas countrywide to strengthen system reliability and support the expansion plan of the new delivery points of the Provincial Electricity Authority (PEA) to assure the power sufficiency and power quality to the end-users. The TS.11 project consists of the construction of transmission lines totaling a distance of approximately 2,014 circuit-kilometers, 10 new substations, the installation of transformers of 15,950 MVA, and voltage control equipment of 1,738 MVAr. As of December 2014, the overall project achieved 94.29 percent progress. It was scheduled to be completed in 2015.

2.1.3 Transmission System Development for Power Purchase from Nam Ngum 3 and Nam Theun 1 Hydropower Plant Project

This transmission system project is to accommodate the power purchase from Nam Ngum 3 and Nam Theun 1 and/or other potential projects in Lao PDR, such as Nam Ngiep 1 Hydropower Project and Xayaburi Hydropower Project. The project consists of the construction of new 500 kV transmission lines Nam Phong 2 – Chaiyaphum 2 - Tha Tako connected with the existing Ban Na Bong (Lao PDR) – Udon Thani 3 – Nam Phong 2 lines (currently operating at 230 kV) to be the 500 kV

Ban Na Bong – Udon Thani 3 – Chaiyaphum 2 – Tha Tako line, the construction of the 230 kV Chaiyaphum 2 – Chaiyaphum line, with a total length of approximately 1,492 circuit-kilometers, a new substation, and the installation of transformers of 4,000 MVA. As of December 2014, the progress of the project was 4.58 percent. The project was scheduled to be completed in 2017.

2.1.4 Transmission System Development for Power Purchase from Theun Hinboun Hydroelectric Power Plant Expansion Project

The project includes the construction of the 230 kV Nakhon Phanom 2 Substation and relevant transmission lines with a total distance of approximately 114 circuit-kilometers. This transmission system project is to receive more electric power of 220 MW (additional to the former 220 MW) from the Expansion Project of Theun Hinboun Expansion Hydroelectric Power Plant situated in Lao PDR. The whole project was completed in September 2014.

2.1.5 Transmission System Development Project for Power Purchase from Independent Power Producers

This transmission system project serves electric power purchase from four awarded IPPs' power plants, totaling approximately 4,400 MW installed capacity. The progress of each transmission system sub-project is as follows:

1) The transmission system for the Gheco-One Power Plant was completed and connected to the grid system since February 11, 2013.
2) The transmission system for the National Power Supply Co., Ltd. will begin at the year 2016. This project is expected to be completed in 2017.
3) The progress of the transmission system for the Gulf JP UT Co., Ltd. was completed in August 2014.
4) The progress of transmission system for the Gulf JP NS Co. Ltd. was 93.45 percent (December 2014). It was scheduled to be completed in 2015.

2.1.6 Transmission System Development for Power Purchase from Hongsa Lignite-Fired Thermal Power Plant Project

This project is to accommodate the power purchase from Hongsa Lignite-Fired Thermal Power Plant Project in Lao PDR, the country's first lignite-fired power plant of the capacity of 3 × 626 MW, which will supply 1,473 MW of power to Thailand. This transmission system project consists of the construction of new 500 kV transmission lines from Thai/Lao border (Nan Province) to 500/230/115 kV Nan Substation to be connected with 500 kV transmission line to the main system in Mae Moh 3 Substation, renovation of related transmission lines with a total length of approximately 1,192 circuit-kilometers, a new substation, and the installation of transformers of 1,150 MVA. As of December 2014, the progress of project was 75.88 percent. The project is scheduled to be completed in 2015.

2.1.7 Transmission System Expansion and Renovation Project Phase 1: Substation

This project involves the improvement/replacement of aged substation equipment and control systems at EGAT's 15 substations and other miscellaneous transmission system expansion. The project aims to increase the availability, reliability, and security of transmission. As of December 2014, the progress of the project was 10 percent. The project was scheduled for completion in 2017.

2.1.8 The Development of Transmission System for Chana Power Plant Block 2 Project

This new transmission system project aims to serve 800 MW power from EGAT's new Chana Power Plant Block 2 Project. The project comprises the construction of 230 kV Chana power plant – Chana Junction – Khlong Ngae lines, with a total distance of 90 circuit-kilometers, and the construction and expansion of two existing substations. As of December 2014, the progress of this project was 97.32 percent. It was scheduled to be completed in 2015.

2.1.9 Main Transmission System Expansion Project for Power Purchase from Small Power Producer Cogeneration Power Plants, Based on Request for Proposal 2010

This project is the expansion of major transmission system to accommodate the increasing power purchase from SPP's cogeneration power plants in line with the resolution of the National Energy Policy Council (NEPC) of November 25, 2010 to strengthen the stability of the power system and reduce the loss of power in supplying and purchasing. The project involves the construction of new 230 kV transmission lines between Ayutthaya 4 and Sikhio 2 Substation, renovation of related transmission lines with the distance of 507 circuit-kilometers, a new substation, the installation of transformers of 2,900 MVA, and the improvement of relevant transmission system. As of December 2014, the progress of the project was 16.14 percent. The project will be completed in 2019.

2.1.10 Transmission System Renovation and Expansion Project Phase 1: Transmission Line

This transmission system renovation and expansion project aims to reduce the power loss from the blackout caused by the old transmission line so as to increase the continuity and efficiency in power supply and to enhance the reliability of the power system and the performance index of the transmission system. It involves the replacement and upgrade of 15 transmission line routes and other miscellaneous transmission system expansion. As of December 2014, the progress of this project was 2.10 percent. This project was planned for completion by 2021.

2.1.11 The Project of Transmission System Expansion for North Bangkok Power Plant 2

This project comprises the construction of 230 kV underground lines north Bangkok power plant – north Bangkok with a total distance of 500 meters and expansion of north Bangkok substation. As of December 2014, the progress of this project was 84.34 percent. This project was planned for completion by 2015.

2.1.12 Transmission System Renovation and Expansion Project Phase 2

The Transmission System Renovation and Expansion Project Phase 2, a successive scheme of Phase 1 involves the renovation and expansion of the existing 19 substations and 11 transmission lines and other miscellaneous work related to the transmission system. As of December 2014, the progress of this project was 0.66 percent. This project was planned for completion by 2019.

2.1.13 Bulk Power Supply for the Greater Bangkok Area Phase 3 (BSB3)

Being a successive project of BSB2, BSB3 comprises several subprojects to respond to the increasing demand for electricity in the Greater Bangkok area, to maintain the stability of the power system and the continuity of the power supply according to the standard, and to cope with the malfunction problem of the western natural gas pipelines as well as providing the security of the power system of the country as a whole. The project comprises the construction of 172 circuit-kilometer transmission lines, two new substations, the installation of transformers of 10,200 MVA, and the voltage control equipment of 96 MVAr. As of December 2014, the progress of this project was 2.12 percent. This project was planned for completion by 2018.

2.1.14 Bulk Power Supply for the Greater Bangkok Area Phase 3 (BSB3)

This project is processed for developing the control and protection system of 500/230/115 kV Thatako Substation. This project was completed by 2014.

Transmission System Projects That Still Do Not Perform

2.1.15 Transmission System Development in the Area of Loei, Nong Bua Lam Phu, and Khon Kaen Provinces for Power Purchase from Lao PDR Project

This transmission system project is to receive imported electric power from the Xayaburi Hydroelectric Power Plant Project in Lao PDR which will supply power of 1,220 MW to Thailand. It is scheduled that all units will supply power commercially within October 2019. The project involves the construction of 500 kV double-circuit transmission lines from Thai/Lao border in Loei Province to the new Tha Li Substation (distance of approximately 5 kilometers) and from Tha Li Substation to the new Khon Kaen 4 Substation (distance of approximately 225 kilometers) totaling 460 circuit-kilometers of transmission lines (only in Thai territory). The project also includes two new substations and installation of transformer of 1,000 MVA. The project was initially planned to begin in 2015. This project was planned for completion by 2018.

2.1.16 Transmission System Development in the Area of Ubon Ratchathani, Yasothon, and Amnat Charoen Provinces for Power Purchase from Lao PDR Project

This project is intended to accommodate the power purchase from Xepian-Xenamnoy Hydropower Plan Project which has the generating capacity of 3×130 MW, and to receive more power from other potential projects from the Southern part of Lao PDR. The project consists of the construction of new 500 kV transmission lines from Thai/Lao Border at Ubon Ratchathani Province to the new Ubon Ratchathani 3 Substation with the distance of 90 kilometers, initially energized at 230 kV, and the improvement of other transmission lines (in Thai territory only) with a total of 440 circuit-kilometers. The project also includes the construction of a new substation and the installation of transformers of 400 MVA. The project was initially planned to begin in 2015. This project was planned for completion by 2018.

2.1.17 Transmission System Improvement Project in Eastern Region for System Security Enhancement

This transmission system project aims to improve the system security in the Eastern part of Thailand to continuously serve the growing electricity demand and also receive the electric power from the new power plants. The project consists of the construction of the transmission lines totaling 358 circuit-kilometers, two new substations, and the installation of additional transformers of 4,000 MVA. The project was initially planned to begin in 2015. This project was planned for completion by 2019.

2.1.18 Transmission System Expansion Project No. 12 (TS.12)

Being a successive scheme of the project TS.11, the project TS.12 covers the transmission system expansion and reinforcement projects in all provincial areas countrywide to cope with the increasing demand for electricity and to support the expansion plan of the new delivery points of the Provincial Electricity Authority (PEA). The project TS.12 consists of the construction of the transmission lines of the distance of approximately 2,791.7 circuit-kilometers, 7 new substations, the installation of transformers of 9,300 MVA, and the voltage control equipment of

2,322 MVAr. The project was initially planned to begin in 2015. This project was planned for completion by 2020.

2.1.19 Transmission System Improvement Project in Western and Southern Regions to Enhance System Security

The project involves the construction of the 500 kV transmission lines and the renovation of 230 kV transmission systems to cope with the increasing power demand in the Southern part of Thailand in the long run and to increase the capability of the transmission system from the West/Central of Thailand to the South in order to promote the growth of business, industry, and tourism sectors of southern Thailand, including remedy in the power outage in the South. The project was initially planned to begin in 2016. This project was planned for completion by 2022.

2.1.20 Transmission System Expansion for the Replacement of Mae Moh Power Plant Units 4-7

The project was initially planned to begin in 2016. This project was planned for completion by 2016.

2.1.21 New Transmission System Interconnection Project between Su-ngai Kolok Substation (EGAT) and Rantau Panjang Substation (TNB)

This new transmission system project helps strengthen the system’s security and reliability in the Narathiwat Province by increasing imported power from Malaysia and promote the cooperation between Malaysia and Thailand. The construction will start after the interconnection agreement between EGAT and Tenaga Nasional Berhad (TNB) is achieved.

Transmission System Projects in an Approval Process

2.1.22 Substation and Transmission Line Expansion for the Project of Lumtakong Wind Power Plant 2

This project is successive scheme of the Lumtakong wind power plant 1 project. This project was planned for completion by 2017.

2.1.23 Transmission System Improvement Project in Northeastern, North, Central and Bangkok Regions to Enhance System Security

This project is to develop the transmission system around northeastern, north, central and Bangkok regions in order to support the incoming of renewable energy sources and ASEAN power grid. This project was planned for completion by 2023.

2.1.24 Transmission System Improvement Project in North Regions to Enhance System Security

The project comprises the construction of new transmission lines 420 circuit-kilometers. This project was planned for completion by 2021.

2.2 Effect of Renewable Energy Generation on Transmission System in Thailand

An example of renewable energy generation which affects transmission system in Thailand is presented in this section. From the purchase of renewable energy in the North, Northeast and Central regions of Thailand studied in the year 2012 by transmission system development group in EGAT, the study assumes that renewable energy sources operate at 100 percent of their capacity and electrical power from IPP, SPP and Lao PDR is fully purchased at 100 percent according to electric power purchase agreement. Consequently, 4 transmission lines which composed of “230 kV Khon Kaen 3 - Lom Sak”, “230 kV Roi Rt - Khon Kaen 3”, “230 kV Khon-Kaen 3 - Chaiyaphum” and “230 kV Chaiyaphum - Thatako” are affected caused renewable energy as illustrated in Figure 2.1 [35].

From the study, EGAT’s system in the north eastern and the north of Thailand cannot support more purchase of electric power because over limit violation of TL occur when TL “230 kV Khon Kaen 3 – Chaiyaphum” or TL “230 kV Khon Kaen 3 -

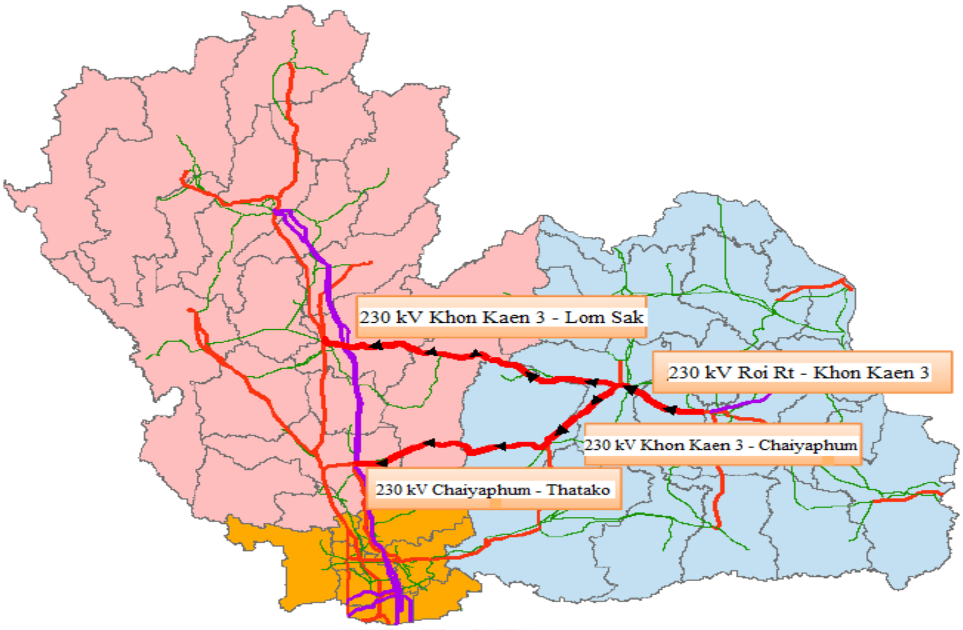

Figure 2.1 Affected TLs from renewable energy

Lom Sak” out of the network. Consequently, EGAT has been finding the solution by constructing a new TL “500 kV Udonthani 3 – Chaiyaphum 2 - Thatako” which is approved by Thailand cabinet. It can be said that, TEP is one of the solution to solve renewable energy penetration problem.

Additional information from the planner of transmission line expansion division in EGAT, when the renewable energy seller request for selling the energy, the planner will examine that renewable energy source can be integrate into the EGAT’s system or not. For the solar and wind sources, their maximum output powers are considered. For the other renewable energy sources, the committed output powers are considered. The criteria for examining such as line limit, voltage limit, short circuit current limit, etc. are used. If that renewable energy source cannot integrate into the system, EGAT may reject or postpone that renewable energy source. However, because of the policy from the ministry of energy (Thailand) which is mentioned in section 1.1, EGAT has to develop the system in order to meet the renewable energy target in the forthcoming decade. Therefore, the renewable energy zoning which is the zone of the system that allows the renewable energy to be installed will be established and officially announced in the near future [36].

2.3 General Methods of TEP

In Thailand, TEP is generally planed based on experiences of system planners. The method is based on the minimum cost solution techniques [5-7]. A set of alternatives of long term expansion plans in the planning period is chosen from the set of all feasible plans. The number of alternatives should be reasonable for manual implementation in the next steps. The computational tool employed in the process is only power system analysis software based on the Newton-Raphson algorithm for solving a set of nonlinear power flow equations. After that, the suitable plan in a set of alternative plans is chosen by planners based on the experience and results from power flow solutions. The process is performed in an iterative manner. By starting from the base case of the considered scenario, if the system is not feasible (the planning criteria are not satisfied; for example, the system violates the voltage limit, line limit, generator limit, n-1 security constraint, etc.) transmissions or transformers candidates will be selected into the considered plan. The power flow equation is solved again to verify the feasibility. The process is performed until the candidates provide the feasibility [10].

The process for selecting of the alternative plans is illustrated in Figure 2.2. After feasible alternative plans are obtained, their costs of the planning period are compared with each other. Time value of money should be taken into account according to economic aspect. Then the minimal cost plan is selected.

In addition, the TEP methods of other countries are reviewed. In South Korea, the power system is operated at such a high reliability level that it never allows the loss of load on systems other than the one where a disturbance (including the failure of 1 route (2 circuits) 345 kV line) occurs. Therefore, they define the performance criteria for transmission system planning to assure the previous principle. The performance criteria are determined based on the extent that the transmission system can keep supplying electricity to loads when a disturbance occurs. The performance criteria can be divided into 2 parts. Firstly, performance criteria for normal state (state where all system elements are in service after the power system is adjusted to supply load following specified operating procedures and no faults or outages occur) is determined.

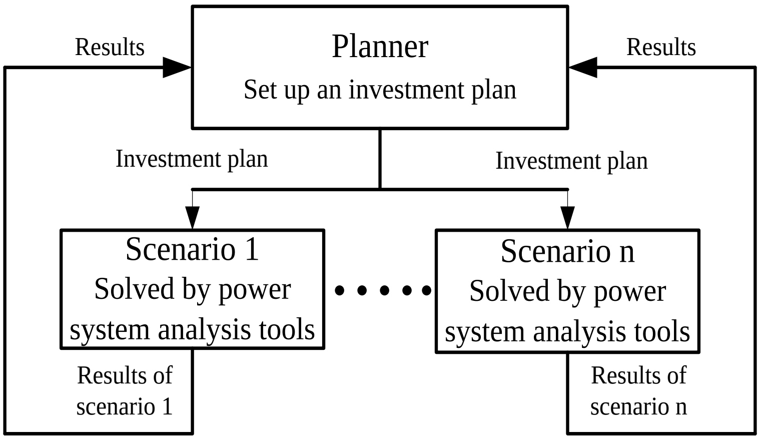

Figure 2.2 General method for solving TEP

Secondly, performance criteria for abnormal state based on the allowable actions or conditions on systems other than the one where a disturbance occurs. Reliability criteria principle that is applied to South Korean power system operation, any loss of load is not allowed in all performance levels [37].

For the TEP of China, usually regional grid companies are responsible for transmission planning between provinces (usually 500 kV or above); provincial power companies are responsible for transmission planning in their provinces (usually 220 kV). Based on local load forecast and the national economic growth rate, and generation planning in the whole region, they would work out several transmission schemes, such as pure alternating current (AC) or direct current (DC), or hybrid AC/DC, what voltage level should be adopted, etc. for each scheme, technical and economical analysis will be made, such as load flow analysis, n-1 security analysis, transient stability analysis and dynamic stability analysis, etc. By comparison of technical and economical results of several feasible schemes, the best scheme will be determined [37].

In Europe, the basic method of transmission grid planners can be summarized as follows: to forecast the power and energy flows on the transmission network, drawing upon a set of scenarios of generation/demand evolution for the targeted period; to check whether acceptable technical limits might be exceeded, in standard conditions as well as in contingency cases; to devise a set of possible strategies/solutions to overcome the criticalities and to select the options having the best cost-benefit performance. A review of current transmission planning practices, based on deterministic and probabilistic approaches, as implemented by the transmission system operators, is then executed in view of the new proposed approach, whose main focus relates to the cost-benefit analysis of the different transmission reinforcement options. Towards this scope, it is crucial to quantitatively assess the various benefits provided by transmission expansion: this task, especially in a liberalized power system, generally represents a rather complicate stage as the evaluation strongly depends on the viewpoint taken for each considered benefit. The benefits provided by transmission expansion can be grouped as: system reliability improvement; quality and security increase; system losses reduction; market benefits; avoidance/postponement of investments; more efficient reserve management and frequency regulation; environmental sustainability benefits; improved coordination of transmission and distribution grids [38].

Lastly, in United States, the current state of the art in transmission planning is able to address power systems on an independent system operator level, including moderate levels of uncertainty on a scenario basis. However, current methods have not dealt with planning over the larger geographic areas and with the increasing levels of uncertainty that must be considered to integrate substantial renewable generation efficiently. Today, the transmission system is planned using expert judgment supported by technical models. The general procedure is to forecast demand 5-10 years into the future and simulate the system performance at that time. Complex simulations identify reliability issues and potential economic improvements. If the simulations indicate a problem, system reinforcements or other remedies are developed. Next, the simulations are re-run to ensure that the reinforced system meets the prescribed reliability requirements and delivered energy costs are reduced [39].

From above review, the general TEP in many countries generally based on experiences of system planners including Thailand as mentioned in the beginning of this section. For the planning horizon, TEP can be mainly categorized into 2 methods, single stage TEP and multistage TEP as presented in following subsections.

2.3.1 Single Stage TEP

Single stage TEP [18] is the planning considering all the expansion in a single stage of planning horizon. For instance, if the transmission system for using in the period of 15 years is considered, all of the data at 15th year (amount of load, load location, transmission line capacity, etc.) will be utilized for solving the optimal planning only one time. From the review of TEP in Europe [40], the process of the TEP can be summarized as illustrated in Figure 2.3. It can be noticed that the average duration of TEP process is about 6.5 years.

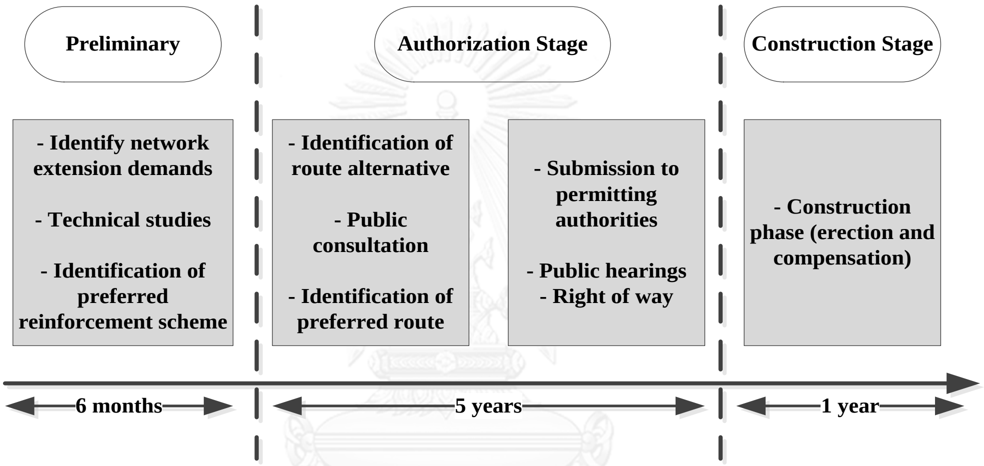

Figure 2.3 Detail and average duration of the TEP process

2.3.2 Multistage TEP

Multistage TEP is considered as a sequence of the single stage TEP [18]. From Figure 2.3, the average duration of TEP process is about 6.5 years. It means that the planning period should not less than 6.5 years. Therefore, it can be assumed that the planning period is 15 years which is divided into 3 stages. The planning period and the expansion plan corresponding to each stage of the multistage TEP are demonstrated in Figure 2.4.

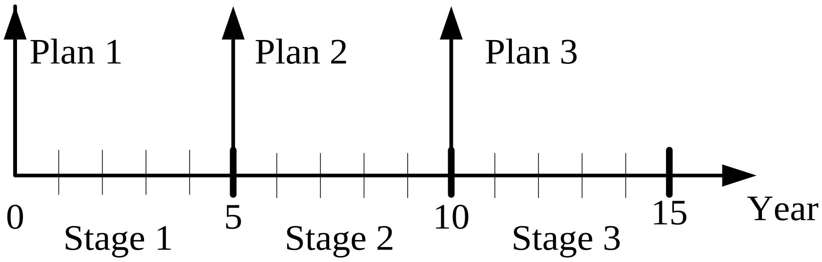

Figure 2.4 Example of multistage planning period

In this dissertation, consecutively single stage planning is used for solving multi stage planning. Therefore, the formulation of the multistage planning is based on the formulation of the single stage planning which is presented in Section 2.6. The example of consecutively single stage planning is explained below.

The plan is determined at the beginning of each stage in order that the increased load in the corresponding stage can be served. The plans obtained from the previous stages will be considered as the existing system at the present stage. For example, at first, the plan is determined at the 0th year for stage 1 in order to supply the peak load of stage 1 which certainly occurs at the last year of the stage (5th year). Hereafter, the plan is determined again at the 5th year for stage 2 by using the system obtained from stage 1 in order to supply the peak load of stage 2 (10th year). This phenomenon will continue until the end of planning. It is noted that the load used in the problem formulation for each stage can be determined from the forecasted peak value of the stage.

2.4 Transmission Network Model

The electric power transmission network, in some aspects, is similar to roads in a transportation system. The main concept of both systems is to transfer commodities from suppliers to consumers. Nevertheless, transmission networks should follow some electrical rules whereas there is no such restriction for transportation system. These electrical rules governing the power system express the relationships among variables in a power system such as voltage magnitude, voltage angles, active and reactive powers. Depending on how accurately the power system is modelled, different levels of simplification can be made in the mathematical relationships among network variables while still concerning the electrical rules that govern power flow. Generally, for transmission planning studies, the power system can be modelled with one of the three following models:

1) Alternating Current (AC) model [10], [13], [15], [32]
2) Direct Current (DC) model [1, 2], [14], [16-19], [21], [23, 24]
3) Transportation model [41-43]

The transportation model is the least accurate model and usually used in cases meant to give a general insight to the transmission expansion or a rough estimation of the power flows, whereas the AC model is the most accurate which all details are considered. Therefore, AC model is applied for modelling the TEP problem in this dissertation. These three models are presented as follows.

2.4.1 AC Model

In the AC model, nonlinear relation between variables in a power system exists. The real power and reactive power flowing in a transmission line between bus *i* and bus *j* are written by (2.1) and (2.2), respectively.

$$P_{ij} = V_i^2 g_{ij} - V_i V_j \left(g_{ij} \cos\theta_{ij} + b_{ij} \sin\theta_{ij} \right) \tag{2.1}$$

$$Q_{ij} = -V_i^2 \left(b_{ij}^{sh} + b_{ij} \right) - V_i V_j \left(g_{ij} \sin\theta_{ij} - b_{ij} \cos\theta_{ij} \right) \tag{2.2}$$

If r_{ij} is the resistance and rx_{ij} is the reactance of the transmission line connecting bus *i* and *j*, then g_{ij} and b_{ij} is mathematically expressed as follows.

$$g_{ij} + jb_{ij} = \frac{r_{ij}}{r_{ij}^2 + rx_{ij}^2} - j\frac{rx_{ij}}{r_{ij}^2 + rx_{ij}^2} \tag{2.3}$$

Equations (2.1) and (2.2) are nonlinear constraints to a transmission planning problem which considers the AC model for the network which turn the transmission planning problem into a nonlinear optimization problem. Nonlinearity of power system variables is one of the issues that challenges the transmission planners.

The advantages of this model can be summarized as follows.

(a) Using an integrated mathematical model that allows TEP problems and the optimal allocation of reactive power simultaneously.

(b) Incorporating the determination of the transmission system’s precise real losses in a trivial way.

(c) Incorporating other nonlinear operation characteristic devices in the TEP problem, for example, the FACTS controllers.

(d) The possibility of carrying out other types of studies, after solving the AC integrated TEP problem, for example: voltage stability, nodal analysis, transient stability analysis and so on.

The disadvantages of this model can be summarized as follows.

(a) Difficult to develop an efficient optimization technique to solve TEP problem with AC model which is mixed integer nonlinear programming (MINLP).

(b) Since all parameters such as voltage magnitude, voltage angles, active and reactive powers are considered in AC model, the computation time will be higher than other models.

2.4.2 DC Model

Due to the AC model is complicated, it leads the transmission planning problem to expensive time consumption in optimization. The DC model can be considered as a linearized version of AC model. The DC model expresses the fundamental relationships of parameters in the power system while it offers a relatively simple model. Simplicity of DC model is the reason that it is widely used in transmission planning studies. The three main assumptions in the DC model are as follows:

1) The voltage magnitude of all buses is equal to 1 p.u. (V_i = 1 p.u.).

2) In the transmission network, reactance is much greater than resistance ($rx_{ij} >> r_{ij}$).

3) The difference between voltage angles of two endings of a transmission line is quite small ($\cos(\theta_i - \theta_j) = 1$, $\sin(\theta_i - \theta_j) = (\theta_i - \theta_j)$).

Using these three assumptions gives a linear form of AC model. Therefore, Equations (2.1) and (2.2) can be changed to linear Equations (2.4) and (2.5), respectively.

$$P_{ij} = \frac{1}{rx_{ij}}\left(\theta_i - \theta_j\right) \tag{2.4}$$

$$Q_{ij} = 0 \tag{2.5}$$

Another necessary constraint in the DC model is the power balance at each bus, this implies the Kirchhoff's current law (KCL). For bus *b*, the KCL can be written in (2.6).

$$\sum_{g \in N_{gb}} P_g + \sum_{m \in N_{lb}} P_{ij,m} - P_b^D = 0 \tag{2.6}$$

It can be seen from equations (2.4) and (2.5) that a transmission planning study which considers DC model does not consider the reactive power and voltage magnitude. Therefore, the AC model study needs to examine the voltage and reactive power requirements [44]. In other words, for long term planning, as most researches present, a linear DC model is a usable solution. However, the final proposed network which has been determined by using DC model should be examined with the AC model study in order to make sure that violations do not exist in the network. The final network topology should fulfill all operational criteria. Figure 2.4 shows the procedure of a transmission planning using both DC model and AC model. From Figure 2.5, for a given demand and generation scheme as well as possible candidate transmission lines in a horizon year, the transmission expansion planning is studied using DC model. Next, considering the proposed expansion, the possible network violations are examined with the AC model. If there is any violation, reactive power

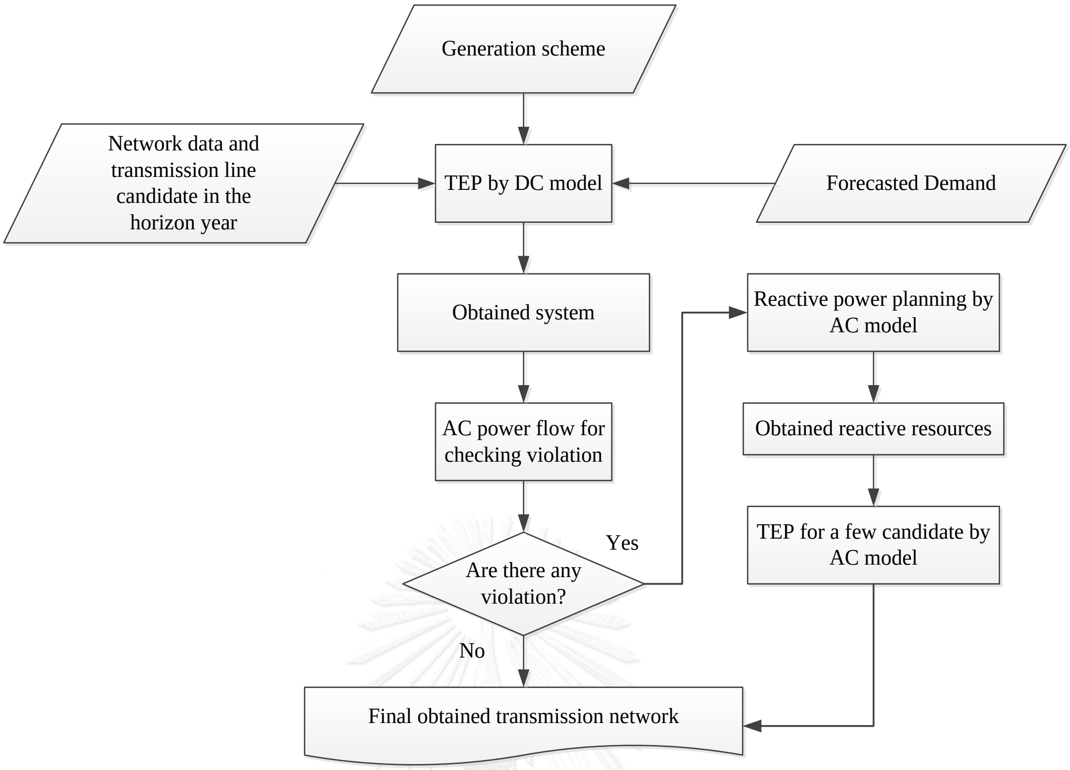

Figure 2.5 Procedure of TEP using both DC model and AC model

resources or in some cases some transmission lines may be suggested to install so that the final plan fulfills all essential security criteria.

The advantages of DC model:

a) Easy to develop an efficient optimization technique to solve TEP problem with DC model which is mixed integer linear programming.

b) Since the voltage magnitude and reactive powers are neglected, computation time will be lower than AC model.

The disadvantages of DC model:

a) The TEP problem must be separated from the reactive power allocation problem

b) DC model does not consider the reactive power and voltage magnitude. Therefore, it needs AC model to examine the voltage and reactive power requirements.

c) Nonlinear operation characteristic devices in the TEP problem, for example, the FACTS controllers cannot incorporated in DC model.

2.4.3 Transportation Model

Transportation model which is also called the network flow model is the least accurate model of the transmission network. This model consists of a source node representing system generation, a sink node representing system load, and a network of branches of finite capacities representing the transmission system. Flows in the network are constrained KCL which states that the net flows into or out of a node is zero except the source and sink nodes. All other constraints are omitted. Application of transportation model is to find those transmission corridors which can be considered as transmission expansion candidates in transmission planning studies [42]. Mutale et al. used transportation model as a model for fully flexible network where power flows can be fully controlled by flexible AC transmission system (FACTS) devices.

The advantage of transportation model is easy to formulate in TEP problem and low computation time. The disadvantage is similar as DC model but transportation model relaxes the θ_i and θ_j. Therefore, the obtained solution needs more examination than the obtained solution from DC model.

2.5 Solving Methods of TEP

In addition to the two methods of TEP based on the planning horizon as mentioned in Section 2.3, TEP can be categorized according to the solving methods. Mathematical method, heuristic method and metaheuristic method are generally using for solving TEP [9].

2.5.1 Mathematical Method

The mathematical method finds an optimum expansion plan by using a calculation procedure that solves a mathematical formulation of the problem. Due to the impossibility of considering all aspects of TEP problem, the obtained plan is the optimum only under the large simplifications and should be technically, financially and environmentally verified among other tests before the planner makes a decision.

In the formulation of these methods, the transmission planning is considered like an optimization problem with an objective function (a criterion to measure in the same way the goodness of each expansion option), subject to a set of constraints. These constraints try to model great part of the technical, economic and reliability criteria defined in the power system expansion. Several methods have been proposed to obtain the optimum solution for the transmission expansion problem, mostly using classical optimization techniques like linear programming [11], dynamic programming [12], nonlinear programming [13] and mixed integer programming [14]. Optimization techniques like Benders [45] and hierarchical [42] decomposition have been also used, as well as the combination of decomposition techniques with other approaches, solving the problem with a "branch and bound" algorithm [46]. Usually, large practical obstacles appear to obtain the "optimal" solution when mathematical optimization techniques are used for solving the transmission planning problem, which is nonlinear and non-convex in nature. This is mostly due to the intrinsic limitation of the optimization process itself, for example, convergence problems when DC load flow network model or a more detailed model is used, unreasonably large computational times when discrete variables are used for modeling the investments and when stochastic modeling is used for planning under uncertainty.

2.5.2 Heuristic Method

The term "heuristic" (to invent, to create) is used to describe all those techniques that, instead of using a classical optimization approach, go step-by-step generating, evaluating and selecting expansion options, with or without the user's help (interactive or non-interactive). To do this, the heuristic models perform local searches with the guidance of logical or empirical rules and/or sensitivities (heuristic rules). These rules are used to generate and classify the options during the search. The heuristic process is carried out until the generation algorithm of the plan is not able to find anymore a better plan considering the assessment criteria that were settled down. These criteria usually include investment-operating costs, overloads and unserved power.

One of the first heuristic approaches that tried to solve the transmission expansion problem was proposed by Fischl et al. [47]. Fischl introduced the "adjoin network” concept combined with DC power flow model to produce the necessary continuous susceptance change to minimize the investment cost. A procedure called “nearest neighbor method” was used to find the closest discrete value of the susceptances.

A common heuristic procedure is to allocate the additional circuits using a sensitivity analysis [15]. Some of these models deal with purely electric sensitivities, Bennon et al. [48], with procedures to remove overloads. Others use the sensitivity with respect to the load curtailment or other index of the system behavior, for example, the “least effort” criterion used by Monticelli et al. [16], with respect to susceptance reinforcement, when the DC load flow is used, Pereira et al. [49] and Dechamps et al. [50]. All of them start from an initial plan and after successive evaluations, they improve it until obtain a quasi-optimal plan.

Procedures based on the flow through imaginary lines of unlimited capacity have been also proposed. Those lines form the “overload network” used by Villasana et al. [51], Garver [52] and Levi et al. [53]. The flow through this network is penalized using the “guide numbers,” to assure that the mathematical model uses all the real circuit capacity first. These procedures combine heuristic rules with mathematical optimization algorithms (linear programming) to solve the problem. They form step-by-step the transmission expansion plan, installing a single new circuit at a time. This new circuit is added in the corridor with the largest flow through the corresponding corridor of the overload network.

Latorre *et al*. [54] proposed a heuristic method that took advantage of the natural decomposition of the transmission expansion problem in operation and investment subproblems. The investment subproblem is solved using a heuristic search procedure. The search was organized using a tree format and started from an initial solution provided by the user. The proposed model is very computationally efficient; this fact was verified on the planning of the Spanish transmission system. The use of heuristic algorithms is very attractive because good feasible solutions can be found, that is, very competitive economically, with a small computational effort. However, they cannot guarantee in an absolute way, mathematically speaking, the “optimal” transmission expansion.

2.5.3 Metaheuristic Method

Metaheuristic method is the new method which arises from the high data processing of the computer at present. There are various processes to find the solution depending on each method which do not use the mathematic optimization method. Consequently, the obtained solution may be not global optimum as the same as heuristic method. However, each of metaheuristic methods has some criteria to avoid the local optimum. Most of the criteria solve the solution by simultaneously finding many routes to reach the solution. After that, the quality for reaching the global optimum of each route is evaluated. In the view of this method, many metaheuristic techniques have been proposed for TEP in the last few years because of their ability to find global optimal solutions for such combinatorial problem. Some of them are discussed below.

A simulated annealing (SA) approach for TEP is proposed in [17] for long-term TEP. The SA approach is a generalization of Monte Carlo method for examining the equations of states and frozen states of n-body system. The concept is based on the manner in which liquids freeze or metals recrystallize in an annealing process.

A parallel Tabu search algorithm for TEP is discussed in [55]. This method is the third generation of Tabu search procedure, which includes features of a variety of other approaches such as heuristic search, SA and genetic algorithms (GAs). A new variant of Tabu search is presented in [18] for static or single stage TEP (STEP). The intensification and diversification phases are designed using medium and long-term memory concepts.

Applications of GA have been proposed by many works. An improved GA is proposed for TEP in [56]. Some special features have been added to the basic GA to improve its performance. The GA works on the set of candidate solutions known as population and performs a number of operations. These operators recombine the information contained in the individuals to create new solutions (populations). A procedure based on SA approach is implemented to improve the mutation mechanism. A GA based approach for multistage and coordinated planning of transmission expansions is presented in [19]. An efficient form of generation of initial population is used in the proposed approach. A specialized GA is proposed in [57] for single stage and multistage TEP. The proposed GA has the following special characteristic: (i) it uses fitness and unfitness functions to identify the value of objective function and unfeasibility of the tested solution; (ii) it applies efficient strategy of local improvement for each individual tested and (iii) it substitutes only one individual in the population for each iteration.

A greedy randomized adaptive search procedure (GRASP) for solving TEP is presented in [58]. GRASP is an expert iterative sampling technique that has two phases for each iteration. The first phase is construction phase that finds out the feasible solution. The second phase is a local search procedure that seeks for improvements on the construction phase solution by local search.

The application of a new discrete method in particle swarm optimization for TEP has been discussed in [59]. A new technique known as harmony search (HS) used for solving engineering optimization problems was first presented in [60]. The HS algorithm is based on the musical process of searching for a perfect state of harmony. The harmony in music is analogous to the optimization solution vector and the musician’s improvisations are analogous to local and global search schemes in optimization techniques. Instead of a gradient search, the HS algorithm uses a stochastic random search [61] based on the harmony memory considering rate (HMCR) and the pitch adjustment rate (PAR), so that derivative information is unnecessary. Compared to earlier metaheuristic optimization algorithms, the HS algorithm imposes fewer mathematical requirements and can be easily adapted for various types of engineering optimization problems. The HS algorithm has been very successful in wide variety of optimization problems [62]. An improved version of harmony search is presented in [63] which employ a novel method for generating new solution vectors that enhances the accuracy and convergence rate of the classical HS. Because there are various types of optimization method using the metaheuristic method, the detail of each type will be explained in detail in Chapter 4.

The advantages and disadvantages of mathematical, heuristic and metaheuristic methods given in different papers are now summarized as follows:

Advantages of mathematical method:

a) The optimal solution is usually accurate.
b) The computation time is low.
c) A suitable convergence is obtained.

Disadvantages of mathematical method:

a) Managing power system equations into an optimization programming model is difficult.
b) Adding a new constraint into the model is difficult because the model should be rearranged and new equations should be included.
c) The static studies can only be carried out and dynamical studies such as stability analysis cannot be performed.
d) It is high possibility to fall into the local minimum instead of the global minimum.

Advantages of heuristic method:

a) This method is easy to use and very straightforward.
b) This method is not required to convert power system model to an optimization programming set. The power system analysis (such as power flow or stability analysis) can be carried out in a power system analyzer package (such as DigSILENT power factory).

Disadvantages of heuristic method:

a) It requires a certain level of knowledge and experience to apply the heuristics effectively.
b) It is high possibility to fall into the local minimum instead of the global minimum.

Advantages of metaheuristic method:

a) It tends to move relatively quickly towards very good solutions, so it provides a very efficient way of dealing with large complicated problems.
b) It is capable to escape from a local optimum. Therefore, this method has high possibility to provide a global optimum.

c) This method is not required to convert power system model to an optimization programming set. The power system analysis (such as power flow or stability analysis) can be carried out in a power system analyzer package (such as DigSILENT power factory) and then the output responses are fed into optimization method.

Disadvantages of metaheuristic method:

a) It consumes high computation time.
b) It cannot guarantee that the best solution found will be the global optimum.

In this dissertation, since TEP and RTEP problems are formulated by AC model which are MINLP, it may easily fall into local optimum when solved by mathematical or heuristic method. Moreover, because TEP or RTEP is long term planning, the priority of computation time is not first. Therefore, a metaheuristic method is used for solving both TEP and RTEP. This dissertation selects adaptive tabu search (ATS) as the method for solving the TEP. The detail of ATS method will be explained later in Section 4.3.

2.6 Problem Formulations of TEP and RTEP

In this section, the problem formulations of single stage TEP and RTEP based on AC model is presented. Before presenting the problem formulation, the concept of investment and operating costs will be explained firstly in order to write the variables in the problem formulations.

2.6.1 Concept of Investment and Operating Costs in Planning Period

In general, the concept presented in this subsection can be used for both single stage and multistage TEP planning. However, to generalize the concept, the case of multistage TEP problem is described. The cash flow diagrams of the investment cost of transmission line and the operating cost of conventional generator in the planning period are shown in Figure 2.6 and Figure 2.7, respectively.

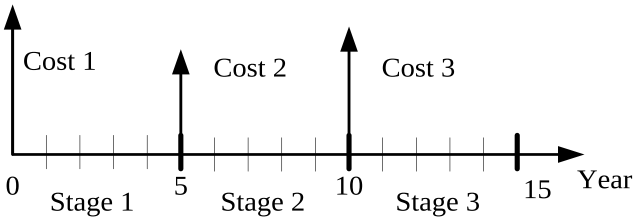

Figure 2.6 Cash flow diagrams of the investment cost of transmission line

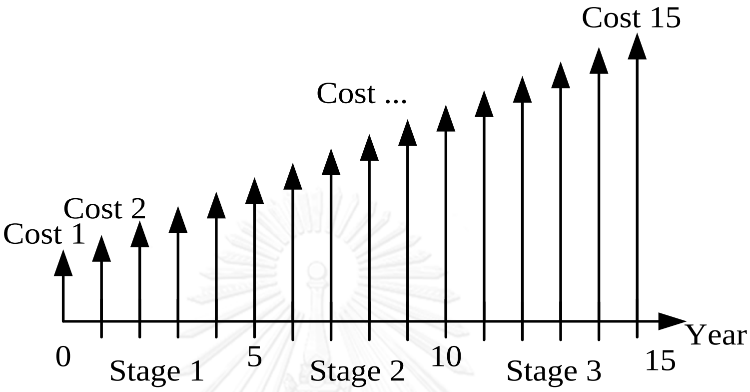

Figure 2.7 Cash flow diagrams of the operating cost of conventional generator

Since expected life time of the transmission line installed in each stage is usually longer than the considered planning period, the salvage values of these transmission lines should be considered at the end of the planning period to express the utilization of the transmission line as shown in Figure 2.8.

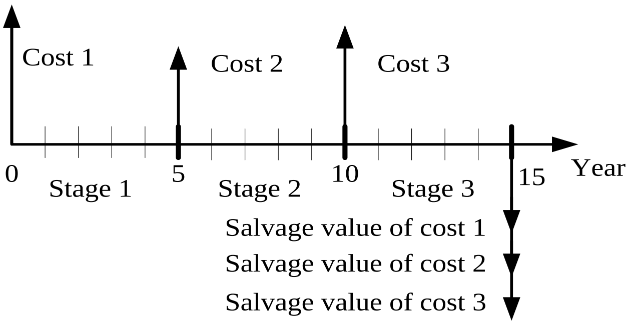

Figure 2.8 Cash flow diagram of investment cost and salvage value

The salvage value at the end of period can be estimated by a straight line method [7]. The salvage value of the equipment installed at stage *t* can be calculated by (2.7).

$$sv_t = c_{inv,t}\left(\frac{el - ny\left(ns - t + 1\right)}{el}\right) \tag{2.7}$$

Therefore, the present value of the investment cost subtracted by its salvage value can be calculated by (2.8).

$$pv_{inv,t} = c_{inv,t}\left(\frac{1}{\left(1+r\right)^{ny(t-1)}} - \frac{el - ny\left(ns - t + 1\right)}{el\left(1+r\right)^{ny \cdot ns}}\right) \tag{2.8}$$

In the case of the operating cost, it is assumed that the cost for each year increases by the same rate as the demand growth. Moreover, if the demand monotonously increases as shown in Figure 2.7, the peak demand of the last year for each stage will be applied as a representative of the demand of that stage. Therefore, the present value of the operating cost can be calculated by (2.9).

$$pv_{opr,t} = \frac{c_{opr,t}}{\left(1+r\right)^{ny(t-1)}\left(1+dr\right)^{(ny-1)}}\left(1 + \left(\frac{1+dr}{1+r}\right) + \ldots + \left(\frac{1+dr}{1+r}\right)^{ny-1}\right) \tag{2.9}$$

2.6.2 Problem Formulation of Single Stage TEP

The objective of TEP is to install the transmission lines to reliably support the loads with the minimum investment cost of transmission line and operating cost of conventional generator. The transmission line candidates are predefined based on the right of ways. Generally, the peak load scenario is selected for solving TEP. However, TEP with renewable energy generation, suitable selection of renewable energy generation values is difficult and has not been well discussed in the previous works. The general formulation of TEP is presented as follows.

Objective function:

$$Minimize\left(\sum_{k=1}^{nc} pv_{inv}^{k} x_{ij,k} + \sum_{g=1}^{ng} pv_{opr}^{g} P_g + \sum_{re=1}^{nre} wr_{re} P_{re}^{RC} + \sum_{i=1}^{nb} wd_i P_i^{DC}\right) \tag{2.10}$$

Subject to:

Real and reactive powers balance:

$$\sum_{g\in i} P_g + \sum_{re\in i}\left(P_{re}^{R} - P_{re}^{RC}\right) - \left(P_i^{D} - P_i^{DC}\right) = P_i,\quad i = 1,...,nb \tag{2.11}$$

$$\sum_{g\in i} Q_g + Q_i^{C} - Q_i^{IN} - \left(Q_i^{D} - Q_i^{DC}\right) = Q_i,\quad i = 1,...,nb \tag{2.12}$$

Bus voltage limit:

$$V_i^{\min} \le V_i \le V_i^{\max},\quad i = 1,...,nb \tag{2.13}$$

Apparent power flow limit:

$$S_{ij,m}^{fr} \le S_{ij,m}^{\max},\quad m = 1,...,nl \tag{2.14}$$

$$S_{ij,m}^{to} \le S_{ij,m}^{\max},\quad m = 1,...,nl \tag{2.15}$$

$$x_{ij,k} S_{ij,k}^{fr} \le x_{ij,k} S_{ij,k}^{\max},\quad k = 1,...,nc \tag{2.16}$$

$$x_{ij,k} S_{ij,k}^{to} \le x_{ij,k} S_{ij,k}^{\max},\quad k = 1,...,nc \tag{2.17}$$

Real and reactive power generation limit:

$$P_g^{\min} \le P_g \le P_g^{\max},\quad g = 1,...,ng \tag{2.18}$$

$$Q_g^{\min} \le Q_g \le Q_g^{\max},\quad g = 1,...,ng \tag{2.19}$$

Reactive power compensation limit:

$$Q_i^{C\min} \le Q_i^{C} \le Q_i^{C\max},\quad i = 1,...,nb \tag{2.20}$$

$$Q_i^{IN\min} \le Q_i^{IN} \le Q_i^{IN\max},\quad i = 1,...,nb \tag{2.21}$$

Curtailment of renewable energy generation and loads limit:

$$0 \le P_{re}^{RC} \le P_{re}^{R}, \quad re = 1,\ldots,nre \tag{2.22}$$

$$0 \le P_{i}^{DC} \le P_{i}^{D}, \quad i = 1,\ldots,nb \tag{2.23}$$

$$0 \le Q_{i}^{DC} \le Q_{i}^{D}, \quad i = 1,\ldots,nb \tag{2.24}$$

Investment variable limit:

$$x_{ij,k} \in \{0,\ 1\} \tag{2.25}$$

where

$$P_i = V_i \sum_{j \in \Omega^b} V_j \left(G_{ij}(\mathbf{x}) \cos\theta_{ij} + B_{ij}(\mathbf{x}) \sin\theta_{ij} \right) \tag{2.26}$$

$$Q_i = V_i \sum_{j \in \Omega^b} V_j \left(G_{ij}(\mathbf{x}) \sin\theta_{ij} - B_{ij}(\mathbf{x}) \cos\theta_{ij} \right) \tag{2.27}$$

$$G_{ij}(\mathbf{x}) = \begin{cases} G_{ij}(\mathbf{x}) = -\left(\sum\limits_{l \in ET_{ij}} g_{ij,l} + \sum\limits_{c \in TD_{ij}} x_{ij,c}\, g_{ij,c} \right) \\ G_{ii}(\mathbf{x}) = \sum\limits_{j \in N_{bi}} \left(\sum\limits_{l \in ET_{ij}} g_{ij,l} + \sum\limits_{c \in TD_{ij}} x_{ij,c}\, g_{ij,c} \right) \end{cases} \tag{2.28}$$

$$B_{ij}(\mathbf{x}) = \begin{cases} B_{ij}(\mathbf{x}) = -\left(\sum\limits_{l \in ET_{ij}} b_{ij,l} + \sum\limits_{c \in TD_{ij}} x_{ij,c}\, b_{ij,c} \right) \\ B_{ii}(\mathbf{x}) = b_i^{sh} + \sum\limits_{j \in N_{bi}} \left[\sum\limits_{l \in ET_{ij}} \left(b_{ij,l} + b_{ij,l}^{sh} \right) + \sum\limits_{c \in TD_{ij}} x_{ij,c} \left(b_{ij,c} + b_{ij,c}^{sh} \right) \right] \end{cases} \tag{2.29}$$

$$S_{ij}^{fr} = \sqrt{\left(P_{ij}^{fr} \right)^2 + \left(Q_{ij}^{fr} \right)^2} \tag{2.30}$$

$$P_{ij}^{fr} = V_i^2 g_{ij} - V_i V_j \left(g_{ij} \cos\theta_{ij} + b_{ij} \sin\theta_{ij} \right) \tag{2.31}$$

$$Q_{ij}^{fr} = -V_i^2 \left(b_{ij}^{sh} + b_{ij} \right) - V_i V_j \left(g_{ij} \sin\theta_{ij} - b_{ij} \cos\theta_{ij} \right) \tag{2.32}$$

$$S_{ij}^{to} = \sqrt{\left(P_{ij}^{to} \right)^2 + \left(Q_{ij}^{to} \right)^2} \tag{2.33}$$

$$P_{ij}^{to} = V_j^2 g_{ij} - V_i V_j \left(g_{ij} \cos\theta_{ij} - b_{ij} \sin\theta_{ij} \right) \tag{2.34}$$

$$Q_{ij}^{to} = -V_j^2\left(b_{ij}^{sh} + b_{ij}\right) + V_i V_j\left(g_{ij}\sin\theta_{ij} + b_{ij}\cos\theta_{ij}\right) \tag{2.35}$$

2.6.3 Problem Formulation of Single Stage RTEP

In the RTEP, the uncertainties of renewable energy generation and loads are treated as the considered scenarios in the planning which is solved by one optimization formulation. For example, minimum and maximum values of renewable energy generation and loads are treated as the considered scenarios in the planning. The obtained expansion plan must satisfy all constraints for all considered scenarios. For easier writing, the vector **u** is defined as the uncertain parameters consisting of the renewable energy generation and loads as shown in (2.36).

$$\mathbf{u} = \left[P_i^R,\ldots,P_{nb}^R,P_i^D,\ldots,P_{nb}^D,Q_i^D,\ldots,Q_{nb}^D\right],\quad i = 1,\ldots,nb \tag{2.36}$$

For selecting the suitable values of each uncertain parameter which should be treated as the considered scenarios in the planning, research work in [29] applies Taguchi's orthogonal array testing (TOAT) to generate the suitable values and scenarios for robust planning. While, research work in [30, 31] select minimum and maximum values of renewable energy generation and loads as the suitable considered scenarios.

To generalize the formulation of RTEP, the constraints have to be adapted by adding **u** which is the subset of the set of uncertainty *U*. The set *U* is defined according to the method of scenarios selection as mentioned in the previous paragraph. The general formulation of RTEP is shown as follows.

Objective function:

$$Minimize\left(\sum_{k=1}^{nc} pv_{inv}^{k} x_{ij,k} + \sum_{g=1}^{ng} pv_{opr}^{g} P_g + \sum_{re=1}^{nre} wr_{re} P_{re}^{RC} + \sum_{i=1}^{nb} wd_i P_i^{DC}\right) \tag{2.37}$$

Subject to:

Real and reactive powers balance:

$$\sum_{g\in i} P_{g,s} + \left(u_{i,s} - \sum_{re\in i} P_{re,s}^{RC} \right) - \left(u_{nb+i,s} - P_{i,s}^{DC} \right) = P_{i,s}, \quad i = 1,...,nb,\ s = 1,...,nu \tag{2.38}$$

$$\sum_{g\in i} Q_{g,s} + Q_{i,s}^{C} - Q_{i,s}^{IN} - \left(u_{2nb+i,s} - Q_{i,s}^{DC} \right) = Q_{i,s}, \quad i = 1,...,nb,\ s = 1,...,nu \tag{2.39}$$

Bus voltage limit:

$$V_i^{\min} \le V_{i,s} \le V_i^{\max}, \quad i = 1,...,nb,\ s = 1,...,nu \tag{2.40}$$

Apparent power flow limit:

$$S_{ij,m,s}^{fr} \le S_{ij,m}^{\max}, \quad m = 1,...,nl,\ s = 1,...,nu \tag{2.41}$$

$$S_{ij,m,s}^{to} \le S_{ij,m}^{\max}, \quad m = 1,...,nl,\ s = 1,...,nu \tag{2.42}$$

$$x_{ij,k} S_{ij,k,s}^{fr} \le x_{ij,k} S_{ij,k}^{\max}, \quad k = 1,...,nc,\ s = 1,...,nu \tag{2.43}$$

$$x_{ij,k} S_{ij,k,s}^{to} \le x_{ij,k} S_{ij,k}^{\max}, \quad k = 1,...,nc,\ s = 1,...,nu \tag{2.44}$$

Real and reactive power generation limit:

$$P_g^{\min} \le P_{g,s} \le P_g^{\max}, \quad g = 1,...,ng,\ s = 1,...,nu \tag{2.45}$$

$$Q_g^{\min} \le Q_{g,s} \le Q_g^{\max}, \quad g = 1,...,ng,\ s = 1,...,nu \tag{2.46}$$

Reactive power compensation limit:

$$Q_i^{C\min} \le Q_{i,s}^{C} \le Q_i^{C\max}, \quad i = 1,...,nb,\ s = 1,...,nu \tag{2.47}$$

$$Q_i^{IN\min} \le Q_{i,s}^{IN} \le Q_i^{IN\max}, \quad i = 1,...,nb,\ s = 1,...,nu \tag{2.48}$$

Curtailment of renewable energy generation and loads limit:

$$0 \le \sum_{re\in i} P_{re,s}^{RC} \le u_{i,s}, \quad i = 1,...,nb,\ s = 1,...,nu \tag{2.49}$$

$$0 \le P_{i,s}^{DC} \le u_{nb+i,s}, \quad i = 1,...,nb,\ s = 1,...,nu \tag{2.50}$$

$$0 \le Q_{i,s}^{DC} \le u_{2nb+i,s}, \quad i = 1,...,nb,\ s = 1,...,nu \tag{2.51}$$

Investment variable limit:

$$x_{ij,k} \in \{0,\ 1\} \tag{2.52}$$

The variables $P_{i,s}$, $Q_{i,s}$, $S_{ij,s}^{fr}$ and $S_{ij,s}^{to}$ can be defined by (2.26)-(2.35) according to the change network parameters depending on scenario *s*.

However, the defined scenarios of research works [29-31] cannot guarantee the robustness percentage of the system at 100 based on the renewable energy generation and loads profile in a target year. Therefore, the method for selecting the most suitable considered scenario in order to plan the system with 100 percent robustness is proposed as presented in Chapter 5. The details of scenarios selection method, minimum and maximum [30, 31] and TOAT [29] are presented in Subsection 2.6.3.1 and 2.6.3.2 respectively.

2.6.3.1 Scenario Selection Method by Selecting Minimum and Maximum Values

From the assumption of this method that if the solution can satisfy all boundary values, it can satisfy all values within the boundary as well. Consequently, the set of uncertainty *U* is defined by the minimum and maximum values of renewable energy generation and loads. Therefore, the number of combinations is four which can be written as follows: $P_R^{\min}$ and $S_D^{\min}$, $P_R^{\min}$ and $S_D^{\max}$, $P_R^{\max}$ and $S_D^{\min}$, and $P_R^{\max}$ and $S_D^{\max}$.

The considered scenarios for robust planning which are contained in the set of uncertainty *U* can be defined as shown in (2.53).

$$U = \begin{bmatrix} P_R^{\min} \text{and } S_D^{\min} \\ P_R^{\min} \text{and } S_D^{\max} \\ P_R^{\max} \text{and } S_D^{\min} \\ P_R^{\max} \text{and } S_D^{\max} \end{bmatrix} \tag{2.53}$$

2.6.3.2 Scenario Selection Method by TOAT

In this method, the set of uncertainty *U* is defined based on the Taguchi's orthogonal arrays testing (TOAT). TOAT method was proposed by Dr. Genichi

Taguchi in order to obtain robust solutions of experimental design problems in manufacturing [64]. The importance of TOAT and implementation of TOAT are presented below.

Importance of TOAT

The TOAT is a systematic, statistical way of testing pair-wise interactions. It provides representative (uniformly distributed) coverage of all variable pair combinations. Dr. Genichi Taguchi was one of the first presenters of orthogonal arrays in test design. His techniques, known as Taguchi methods, have been a mainstay in experimental design in manufacturing fields for decades.

Orthogonal arrays are two dimensional arrays of numbers which possess the interesting quality that by choosing any two columns in the array you receive an even distribution of all the pair-wise combinations of values in the array. Some nomenclature for working with orthogonal arrays followed by an example array $L_{NS}(B^F)$ with following definitions.

- Number of testing scenarios (*NS*): the number of rows in the array. This directly translates to the number of test scenarios which will be generated by the TOAT technique.
- Number of factors (*F*): the number of columns in an array. This directly translates to the maximum number of variables that can be handled by this array.
- Number of Levels (*B*): the maximum number of values that can be taken on by any single factor.

An example of orthogonal arrays $L_4(2^3)$ is shown in Table 2.2.

Table 2.2 Example of orthogonal array $L_4(2^3)$

No. of testing scenarios	Variable level		
	x_1	x_2	x_3
1	1	1	1
2	1	2	2
3	2	1	2
4	2	2	1

The orthogonal array characteristics are shown as follows [29].

1) For the factor in each column, every level occurs *NS/B* times. For example, $L_4(2^3)$, therefore, “1” and “2” occur 4/2 = 2 times in each column.
2) In any 2 columns, the combination of any 2 factor levels occurs the same times. For example, in any 2 columns of $L_4(2^3)$, the each combinations of 2 variable levels (“11”, “12”, “21”, “22”) appears only one time.
3) The combinations determined by orthogonal array are uniformly distributed of all possible combinations. For example, the combinations of $L_4(2^3)$ are shown in Figure 2.9 [29].

The advantage of TOAT can be concluded as presented below [65].

1) TOAT guarantees testing the pair-wise combinations of all the selected variables.
2) TOAT creates an efficient and concise test set with many fewer test cases than testing all combinations of all variables.
3) TOAT creates a test set that has an even distribution of all pair-wise combinations.
4) TOAT is simpler to generate.

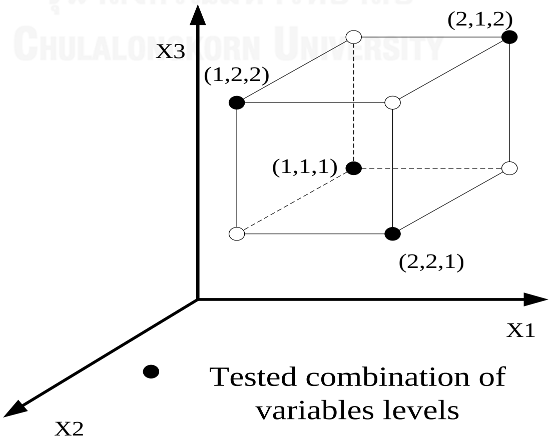

Figure 2.9 Combinations of $L_4(2^3)$

Implementation of TOAT

The TOAT technique is simple and straightforward. The steps are outlined below [65].

Step 1: Decide how many independent variables will be tested for interaction. This will map to the factors of the array.

Step 2: Decide the maximum number of values that each independent variable will take on. This will map to the levels of the array.

Step 3: Find a suitable orthogonal array with the smallest number of the number of testing scenarios from the orthogonal arrays library [66]. A suitable array is one that has at least as many factors as needed from Step 1 and has at least as many levels for each of those factors as decided in Step 2.

Step 4: Map the factors and values onto the array.

Step 5: Choose values for any "left over" levels.

Step 6: Add any particularly suspicious combinations that aren't generated.

A Simple Example

Consider a web page with three distinct sections (Top, Middle, and Bottom) that can be individually shown or hidden by the user. The interactions of the different sections need to be tested. Following the instructions from previous mention, create a test set for the system.

1) There are three independent variables (the sections of the page).
2) Each variable can take on two values (hidden or visible).
3) An $L_4(2^3)$ orthogonal array will be chosen. Two levels for the values and three factors for the variables. Note that the number of scenarios is not necessary to choose an appropriate array.
4) Mapping the values onto the array would look like Table 2.3 where Hidden=0 and Visible=1.

Table 2.3 Mapping values onto the array

Orthogonal array before mapping factors

Testing scenarios	**Factor 1**	**Factor 2**	**Factor 3**
1	0	0	0
2	0	1	1
3	1	0	1
4	1	1	0

Orthogonal array after mapping factors

Testing scenarios	**Top**	**Middle**	**Bottom**
1	Hidden	Hidden	Hidden
2	Hidden	Visible	Visible
3	Visible	Hidden	Visible
4	Visible	Visible	Hidden

5) There are no "left over" levels. In other words, there is a value mapped to every level in the array.
6) Taking the test case values from each run, you end up with four test cases. That is all that is needed to test all of the pair-wise interactions amongst the three variables. The test cases might transcribe to:

A. Display the home page and hide all sections.
B. Display the home page and show all but the Top section.
C. Display the home page and show all but the Middle section.
D. Display the home page and show all but the Bottom section.

Note that not all of the possible combinations are tested. It would take 8 test cases to test all of the combinations. Test cases that are particularly suspicious can be added. For example, a test case that all factors are “Visible” can be added if there is a strong possibility of error with those particular combinations.

An example that does not fit the array

Here is an example introducing the case that the problem does not fit the array. Assume a system with three independent variables (A, B and C). Each variable has three possible values. To test all of the possible combinations, it would take a test set containing 27 test cases (3 × 3 × 3 = 27).

Ideally, an array that contains three levels and three factors (an $L_?(3^3)$) should be used. However, no such published array exists. Therefore, the smallest array that will handle this problem needs to be looked for. An orthogonal array $L_9(3^4)$ can work. It has the three levels for the values and four factors which is more than enough for the three variables. The values onto the array can be shown in Table 2.4. There are no "left over" levels. However, it can be noticed that there was an extra factor in the original array. This factor can simply be ignored. It does not change the properties of the test set generated from the array. Distribution of the pair-wise combinations is still obtained.

Table 2.4 Mapping value of example which does not fit the array

Orthogonal array before mapping factors				
Testing scenarios	**Factor 1**	**Factor 2**	**Factor 3**	**Factor 4**
1	0	0	0	0
2	0	1	1	2
3	0	2	2	1
4	1	0	1	1
5	1	1	2	0
6	1	2	0	2
7	2	0	2	2
8	2	1	0	1
9	2	2	1	0
Orthogonal array after mapping factors				
Testing scenarios	**A**	**B**	**C**	
1	A1	B1	C1	
2	A1	B2	C2	
3	A1	B3	C3	
4	A2	B1	C2	
5	A2	B2	C3	
6	A2	B3	C1	
7	A3	B1	C3	
8	A3	B2	C1	
9	A3	B3	C2	

A Complex, Multi-Level Example

Here is a more complex example that introduces the concept of mixed-level orthogonal arrays. Assume that a system has five independent variables (A, B, C, D and E). Variables A and B each have two possible values (A1-2 and B1-2). Variables C and D each have three possible values (C1-3 and D1-3). Variable E has six possible values (E1-6). To test all of the possible combinations, it would take a test set containing 216 test cases (2 x 2 x 3 x 3 x 6 = 216). This example shows how using the TOAT technique which can reduce the number of test cases to 18 in order to test all the pair-wise combinations.

The easiest way to find a suitable orthogonal array is to go to the library of arrays and look for an array that has at least six levels (the maximum level for any of our variables) and at least five factors. The smallest array with a consistent number of levels you will find is probably the orthogonal array $L_{49}(7^8)$. This array would generate a test set containing 49 tests. That's a lot better than 216, but it is still a lot of tests. It can be noticed the phrase "consistent number of levels". This is important because there happen to be a few orthogonal arrays that have a mixed number of levels. One such array is the orthogonal array $L_{18}(3^6 6^1)$. The naming of this array means that there are 18 scenarios for seven factors, six of which contain three levels and one of which contains six levels. This problem happens to fit inside of this array and the test set goes from 49 with the first array that is identified down to 18. That is a lot better than 216 tests.

Like the previous example, this array has extra factors that are not needed. They can be safely ignored and are grayed out in Table 2.5. This array has "left over" levels. Variables A and B both have three levels specified in the original array, but there are only two possible values for each variable. This has caused a level to be left over for variables A and B after mapping the factors. These left over values have been crossed out in Table 2.5.

Table 2.5 Mapping value of multi-level example 1

Orthogonal array before mapping factors							
Testing scenarios	**Factor 1**	**Factor 2**	**Factor 3**	**Factor 4**	**Factor 5**	**Factor 6**	**Factor 7**
1	0	0	0	0	0	0	0
2	0	1	2	2	1	1	1
3	0	2	1	2	0	0	2
4	0	1	1	0	2	2	3
5	0	2	0	1	1	1	4
6	0	0	2	1	2	2	5
7	1	1	1	1	1	1	0
8	1	2	0	0	2	2	1
9	1	0	2	0	1	1	2
10	1	2	2	1	0	0	3
11	1	0	1	2	2	2	4
12	1	1	0	2	0	0	5
13	2	2	2	2	2	2	0
14	2	0	1	1	0	0	1
15	2	1	0	1	2	2	2
16	2	0	0	2	1	1	3
17	2	1	2	0	0	0	4
18	2	2	1	0	1	1	5

Orthogonal array after mapping factors							
Testing scenarios	**A**	**B**	**C**	**D**			**E**
1	A1	B1	C1	D1			E1
2	A1	B2	C3	D3			E2
3	A1	~~2~~	C2	D3			E3
4	A1	B2	C2	D1			E4
5	A1	~~2~~	C1	D2			E5
6	A1	B1	C3	D2			E6
7	A2	B2	C2	D2			E1
8	A2	~~2~~	C1	D1			E2
9	A2	B1	C3	D1			E3
10	A2	~~2~~	C3	D2			E4
11	A2	B1	C2	D3			E5
12	A2	B2	C1	D3			E6
13	~~2~~	~~2~~	C3	D3			E1
14	~~2~~	B1	C2	D2			E2
15	~~2~~	B2	C1	D2			E3
16	~~2~~	B1	C1	D3			E4
17	~~2~~	B2	C3	D1			E5
18	~~2~~	~~2~~	C2	D1			E6

In order to have fully specified test cases for the scenarios that have left over levels, a value in the cell must be provided. The choice of the value is generally arbitrary, but it usually makes good sense to add as much variety to the test cases as possible in order to enlist chance on your side to help find errors. A good way of doing this is to simply start at the top of a column and cycle through the possible values when filling in the left over levels. Table 2.6 shows the table after filling in the remaining levels by italic number using the cycling technique mentioned. As mentioned before, 18 test sets out of the 216 possible test sets are obtained. These 18 test sets will be tested for all of the pair-wise combinations of the independent variables. This demonstrates a significant saving in testing effort over the all combinations.

Table 2.6 Mapping value of multi-level example 2

Orthogonal array after mapping factors						
Testing scenarios	**A**	**B**	**C**	**D**		**E**
1	A1	B1	C1	D1		E1
2	A1	B2	C3	D3		E2
3	A1	*B1*	C2	D3		E3
4	A1	B2	C2	D1		E4
5	A1	*B2*	C1	D2		E5
6	A1	B1	C3	D2		E6
7	A2	B2	C2	D2		E1
8	A2	*B1*	C1	D1		E2
9	A2	B1	C3	D1		E3
10	A2	*B2*	C3	D2		E4
11	A2	B1	C2	D3		E5
12	A2	B2	C1	D3		E6
13	*A1*	*B1*	C3	D3		E1
14	*A2*	B1	C2	D2		E2
15	*A1*	B2	C1	D2		E3
16	*A2*	B1	C1	D3		E4
17	*A1*	B2	C3	D1		E5
18	*A2*	*B2*	C2	D1		E6

To apply TOAT for RTEP, renewable energy sources and loads are treated as the variables. The level of each variable can be defined according to the expected significant values such as the maximum and minimum values. For example, if the system has one renewable energy source and five loads, the zero and maximum capacity values are considered as the level of renewable energy source and the maximum and minimum values of each load are considered as the level of each load. Therefore, there are six variables and each variable has two levels. Consequently, the orthogonal array $L_8(2^7)$ is selected to generate the considered scenarios of RTEP. The orthogonal array of this example can be shown in Table 2.7.

Table 2.7 Eight considered scenarios for sample system

Orthogonal array before mapping factors							
Testing scenarios	**Factor 1**	**Factor 2**	**Factor 3**	**Factor 4**	**Factor 5**	**Factor 6**	**Factor 7**
1	1	1	1	1	1	1	1
2	2	1	2	1	2	1	2
3	1	2	2	1	1	2	2
4	2	2	1	1	2	2	1
5	1	1	1	2	2	2	2
6	2	1	2	2	1	2	1
7	1	2	2	2	2	1	1
8	2	2	1	2	1	1	2
Orthogonal array after mapping factors							
Testing scenarios	**Renew-able energy source 1**	**Load 1**	**Load 2**	**Load 3**	**Load 4**	**Load 5**	
1	zero	min	min	min	min	min	
2	max	min	max	min	max	min	
3	zero	max	max	min	min	max	
4	max	max	min	min	max	max	
5	zero	min	min	max	max	max	
6	max	min	max	max	min	max	
7	zero	max	max	max	max	min	
8	max	max	min	max	min	min	

Note: ignore column 7 because there are only 6 variables

2.7 International Review of TEP Considering Renewable Energy Generation

The structural changes in power systems in the last few years, due to the installation of renewable energy sources, as well as the expected amount of renewable energy source for the future, send a strong signal to system planners and operators about the need for developing new tools and methodologies for planning and operating of the power systems. Consequently, there are several TEP reports and research papers considering renewable energy penetration as presented below.

Reference [67] presents transmission expansion planning framework in United States which can reduce the impact of the uncertainty in the renewable source development; hence accelerating the process of transmission expansions that are needed for meeting the RPS (renewable portfolio standard, which has been approved by 27 states and D.C.) requirement. The roles of different assessment methods, including deterministic reliability, probabilistic reliability and economic assessments are discussed and demonstrated. This framework enables coordination of the different assessment approaches in transmission planning processes so that the impacts of renewable integration on the power system reliability performance can be assessed accurately.

California agencies in reference [68] form a stakeholder planning process, the renewable energy transmission initiative (RETI) in 2007. RETI identified and ranked renewable energy zones in California and neighboring regions, using both economic and environmental criteria, determined the transmission needed, based on least-regrets transmission planning principles, to access and deliver target renewable energy and prepared a statewide conceptual transmission plan.

Reference [69] proposes a planning method for power systems with renewable energy penetration. In this method, a large region that needs to be planned is partitioned into multiple subregions. Each subregion is modeled as 2 optimization models. One is an hour-level model with the goal to minimize the power price volatility caused by imbalance of load and supply and the CO_2 emission at hour level. Another is a year-level model with the goal to minimize the investment cost of transmission, operation and fossil/clean power capacity expansion at year level. The year-level model needs to satisfy the RPS requirements because it is a year-level policy.

Reference [70] which is the renewable energy study report by Los Alamos national laboratory (LANL) and New Mexico renewable energy transmission authority (RETA) analyzes a variety of possible transmission upgrades over the next 20 years in order to export power generated by 5,200 MW of renewable capacity. Two renewable energy development plans are analyzed by applying LANL's independent technical judgment, tools and expertise. Both plans identify opportunities to invest in grid upgrades and to create substantial economic development. They are intended to serve as examples of different design approaches: a looped transmission design identified by RETA (Collector Plan 1) which consists of upgrades to 345 kV lines, shunts and transformers; design goals are discussed. A radial transmission design identified by LANL (Collector Plan 2) consists of upgrades to 115, 230 and 345 kV lines, shunts and transformers; design goals are discussed. Each plan is built out over 5, 10 and 20 year time horizons through a phased series of transmission upgrades. Both plans are judged to be technically feasible designs which can potentially create immediate economic opportunities for New Mexico.

Reference [71] provides an overview of generation and transmission planning studies in Australia to meet renewable energy target by year 2020. Evaluation of the effectiveness of dispersed energy storage, non-schedulable peaking plants wide area controls and load management techniques are discussed to aid the penetration of renewable energy.

CHAPTER 3

RENEWABLE ENERGY SOURCES IN THAILAND

At present, Thailand generates electric power by using natural gas, which is exhaustible, more than 60% of all generated electric power. The natural gas comes from domestic excavations and import from other countries. The latest version of alternative energy development plan (AEDP) [4] which is studied by the department of alternative energy development and efficiency (DEDE), ministry of energy, Thailand, mentions that Thailand considerably imports electric power from other countries which is equivalent to about 1,125 billion baht in the year 2011. In order to decrease the imported electric power from other countries, renewable energy is greatly encouraged to be used for generating the electric power.

In this section, there are three subsections which consist of (1) prominent power plan development in Thailand, (2) renewable energy situation in Thailand and (3) renewable energy potential in Thailand.

3.1 Prominent Power Development Plan in Thailand

For developing and planning electrical power system in Thailand including renewable energy, maneuver of the plans for guidelines of public and private sector is very significant. Examples of the prominent plans are presented below.

3.1.1 Thailand Power Development Plan 2010 Revision 3

Thailand power development plan 2010 revision 3 (PDP 2010 Rev.3) [72] which is the latest power development plan in Thailand is cited in this dissertation. PDP 2010 Rev.3 is created by the collaboration of ministry of energy and EGAT. The main purpose of PDP 2010 Rev. 3 is to plan the electric power plants for supporting the next 20 years load sufficiently.

Moreover, PDP 2010 Rev.3 have adopted renewable energy target from AEDP which defines renewable energy use by 25% instead of fossil fuels within the year 2021. Consequently, some fossil fuel power plants from PDP 2010 Rev. 2 such as coal power plants and biogas power plants are replaced by renewable energy power plants as presented in Table 3.1 [72]. Nevertheless, cumulative installed capacity of renewable energy power plants between AEDP and PDP 2010 Rev. 3 are different because AEDP considers the use of renewable energy in both electric power generation and transportation system (compensate oil usage) while PDP 2010 Rev. 3 only considers the use of renewable energy in electric power generation. Moreover, hydro power plant in PDP 2010 Rev. 3 has incorporated domestic hydro power plant with hydro power plant purchased from other countries.

Power generation from renewable energy categorized by fuel type from PDP 2010 Rev. 3 and cumulative installed capacity of renewable energy power plants from AEDP at the year 2021 is shown in Table 3.2 [4], [72].

3.1.2 Alternative Energy Development Plan

Alternative Energy Development Plan (AEDP) is the plan studied by ministry of energy in Thailand for establishing the framework and direction of renewable energy development. The target of this plan is to encourage the use of renewable energy by 25% instead of fossil fuels within the year 2021. The renewable energy in this AEDP consists of solar power, wind power, hydro power, power from waste, biomass power, biogas power and the new type of power such as geothermal power, wave and ocean current power, hydrogen power, and power from storage system. For the installed capacity target of renewable energy in the year 2021 categorized by the fuel type is shown in Table 3.3 [4].

Table 3.1 Installed capacity of power plants from PDP 2010 Rev. 2 and PDP 2010 Rev. 3 during the year 2012-2030

Type of power plant	Installed capacity (MW)	
	PDP 2010 Rev. 2	PDP 2010 Rev. 3
Renewable energy power plant	4,433	9,481
Cogeneration power plant	8,319	6,476
Combined cycle power plant	18,400	25,451
Clean coal power plant	7,740	4,400
Nuclear power plant	4,000	2,000
Gas turbine power plant	-	750
Purchasing from other countries	10,982	6,572
Total	53,874	55,130

Table 3.2 Cumulative installed capacity of renewable energy categorized by fuel type from PDP 2010 Rev. 3 during the year 2012-2021

Plan	Year	Power generation of renewable energy (MW)							
		Solar power	Wind power	Hydro power	Biomass power	Biogas power	Power from waste	New type power	Total
PDP 2010	Installed capacity 2011	138.0	3.0	5,322.5	747.3	106.0	21.4	2.0	6,340.2
	2012	164.9	246.9	250.5	280.5	4.2	1.0	-	948.0
	2013	375.8	14.0	19.2	574.5	-	56.0	-	1,039.5
	2014	181.1	263.6	0.5	206.8	1.2	12.8	-	666.0
	2015	191.1	302.9	51.8	180.5	2.3	22.8	-	751.4
	2016	130.1	641.8	5.2	176.8	2.3	32.8	-	989.0
	2017	130.1	163.1	522.0	175.3	2.3	41.8	-	1,034.6
	2018	130.0	7.4	682.6	184.5	2.4	41.8	-	1,048.7
	2019	151.0	117.8	1,223.5	179.8	2.4	41.8	-	1,716.3
	2020	151.0	8.2	4.7	234.0	2.5	41.9	-	442.3
	2021	201.0	8.6	301.5	186.0	2.5	41.9	-	741.5
	Overall installed capacity until 2021	1,944.1	1,777.3	8,384.0	3,126.0	128.1	356.0	2.0	15,717.5
AEDP	Overall installed capacity until 2021	1,800.0	3,000.0	1,608.0	4,800.0	3,600.0	400.0	3.0	15,211.0

Table 3.3 Installed capacity target of renewable energy at the year 2021

Solar power (MW)	Wind power (MW)	Hydro power (MW)	Biomass power (MW)	Biogas power (MW)	Power from waste (MW)	New type of power (MW)	Total (MW)
1,800	3,000	1,608	4,800	3,600	400	3	15,211

3.2 Renewable Energy Situation in Thailand

Nowadays, using renewable energy for electric power generation is very popular in Thailand. The types of generation supplier which use renewable energy as fuel consist of (1) independent power producer: IPP (the amount of electric power generation is more than 90 MW) (2) small power producer: SPP (the amount of electric power generation is not more than 90 MW) and (3) very small power producer: VSPP (the amount of electric power generation is not more than 10 MW).

Overall data of IPP, SPP and VSPP are accumulated by energy regulatory commission (ERC). The role of ERC is to regulate the energy industry operation in order to establish a secure energy system that is reliable, efficient and fair for both energy consumers and energy industry operators. ERC has separated theirs responsible areas into 13 regions as described below [73]. The overall data of IPP and SPP using renewable energy as fuel are shown in Table 3.4.

1) Regional office 1 (Chiang Mai) covers 6 provinces composed of Chiang Rai, Lamphun, Phayao, Chiang Mai, Lampang and Mae Hon Son.
2) Regional office 2 (Phitsanulok) covers 8 provinces composed of Phrae, Uttaradit, Phitsanulok, Kamphaeng Phet, Sukhothai, Tak, Phichit and Nan.
3) Regional office 3 (Nakhon Sawan) covers 6 provinces composed of Phetchabun, Nat, Nakhon Sawan, Singburi, Uthai Thani and Lopburi.
4) Regional office 4 (Khon Kaen) covers 7 provinces composed of Nong Khai, Nong Bua-Lamphu, Loei, Sakon Nakhon, Nakhon Phanom, Khon Kaen and Udon Thani.
5) Regional office 5 (Ubon Ratchathani) covers 8 provinces composed of Kalasin, Mukdahan, Yasothon, Amnat Charoen, Maha Sarakham, Ubon Ratchathani, Roi Et and Sisaket.
6) Regional office 6 (Nakhon Ratchasima) covers 4 provinces composed of Chaiyaphum, Buriram, Nakhon Ratchasima and Surin.
7) Regional office 7 (Saraburi) covers 7 provinces composed of Ang Thong, Nakhonnayok, Ayutthaya, Prachinburi, Saraburi, Sa Kaeo and Pathum Tha.

8) Regional office 8 (Chonburi) covers 5 provinces composed Chachoengsao, Chanthaburi, Trat, Rayong and Chonburi.
9) Regional office 9 (Kanchanaburi) covers 4 provinces composed of Kanchanaburi, Nakhon Pathom, Suphanburi and Samut Sakhon.
10) Regional office 10 (Ratchaburi) covers 6 provinces composed of Ratchaburi, Prachuap Khiri Khan, Samut Songkhram, Phetchaburi, Chumphon and Ranong.
11) Regional office 11 (Surat Thani) covers 6 provinces composed of Surat Thani, Phang Nga, Krabi, Nakhon Si Thammarat, Phuket and Trang.
12) Regional office 12 (Songkhla) covers 6 provinces composed of Phatthalunge, Satun, Pattani, Yala, Songkhla and Narathiwat.
13) Regional office 13 (Bangkok) covers 3 provinces composed of Bangkok Nonthaburi and Samutprakarn.

Table 3.4 Overall data of IPP, SPP and VSPP which use renewable energy for generating electricity

Regional office	IPP		SPP		VSPP		Total	
	No. of projects	MW	No. of projects	MW	No. of projects	MW	No. of projects	MW
1) Chiang Mai	0	0.00	2	137.84	106	347.20	108	485.042
2) Phitsanulok	0	0.00	7	206.170	152	894.932	159	1,362.922
3) Nakhon Sawan	0	0.00	29	1,593.126	154	1,075.472	183	2,668.598
4) Khon Kaen	0	0.00	10	302.600	228	975.948	238	1,278.548
5) Ubon Ratchathani	0	0.00	18	819.850	183	1,112.027	201	1,931.877
6) Nakhon Ratchasima	0	0.00	62	3,362.456	236	1,258.083	298	4,620.539
7) Saraburi	3	4,881.658	43	3,803.578	180	961.933	226	9,647.169
8) Chonburi	11	10,369.080	55	6,378.854	83	422.234	149	17,170.168
9) Kanchanaburi	0	0.000	14	366.300	196	1,232.282	210	1,598.582
10) Ratchaburi	7	5,916.100	25	1,880.703	116	523.843	148	8,320.646
11) Surat Thani	4	1,750.000	8	231.200	161	681.608	173	2,662.808
12) Songkhla	0	0.000	14	566.312	82	444.462	96	1,010.774
13) Bangkok	1	400.680	5	553.500	58	64.795	64	1,018.975
Total	26	23,317.518	292	20,202.489	1,935	10,256.640	2,253	53,776.647

Note: 1) These data have been accepted as commercial operation date (COD) already

2) These data are accumulated on 6th May 2015

From Table 3.4, the data can be categorized by the 6 of fuel types which consist of solar power, wind power, hydro power, biomass power, biogas power and power from waste along 6 regions of Thailand as shown in Table 3.5 [73].

Table 3.5 Installed capacity of renewable energy categorized by fuel type and region

Region	Fuel type (MW)						
	Solar	Wind	Water	Biomass	Biogas	Waste	Total
Central	697.54	0.00	0.80	543.00	31.13	43.30	1,315.77
North	148.15	0.00	1.18	42.56	1.06	2.10	195.06
Northeast	388.43	213.90	0.00	649.45	76.75	0.80	1,329.33
South	0.03	1.75	0.00	115.13	98.15	23.82	238.87
East	66.91	0.00	0.00	77.00	19.60	4.90	168.41
West	89.13	0.05	0.00	263.00	18.99	0.00	371.16
Total	1,390.18	215.70	1.98	1,690.14	245.67	74.92	3,618.59

Note: 1) These data have been accepted as COD already

2) These data are accumulated on 6th May 2015

3.3 Renewable Energy Potential in Thailand

Because solar and wind output powers are eminently depending on their installed location, this section presents the potential of solar and wind energies of Thailand.

3.3.1 Potential of Solar Energy

Solar energy is unlimited energy which can be found every area of Thailand. The solar radiation map of Thailand collected by DEDE is shown in Figure 3.1 [74].

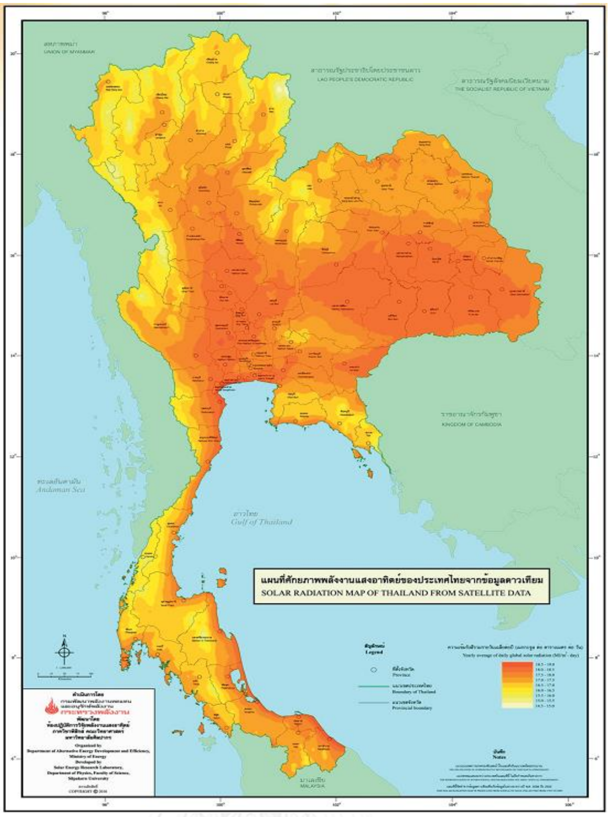

Figure 3.1 The solar radiation map of Thailand in the year 2013

A report of Thailand renewable energy situation in the year 2013 which is studied by the DEDE [74] mentioned that the annual average of solar intensity in Thailand is 17.4 MJ/m^2-day which equals the energy potential 505,867.15 thousand ton comparing crude oil. The highest annual average of solar intensity province is Pattani which has the annual average of solar intensity 18.6 MJ/m^2-day which equals the power potential 2,931.43 thousand ton comparing crude oil.

3.3.2 Potential of Wind Energy

Wind energy is the popular one of renewable energy. The wind speed map of Thailand at 90 meters above the ground is shown in Figure 3.2 [74].

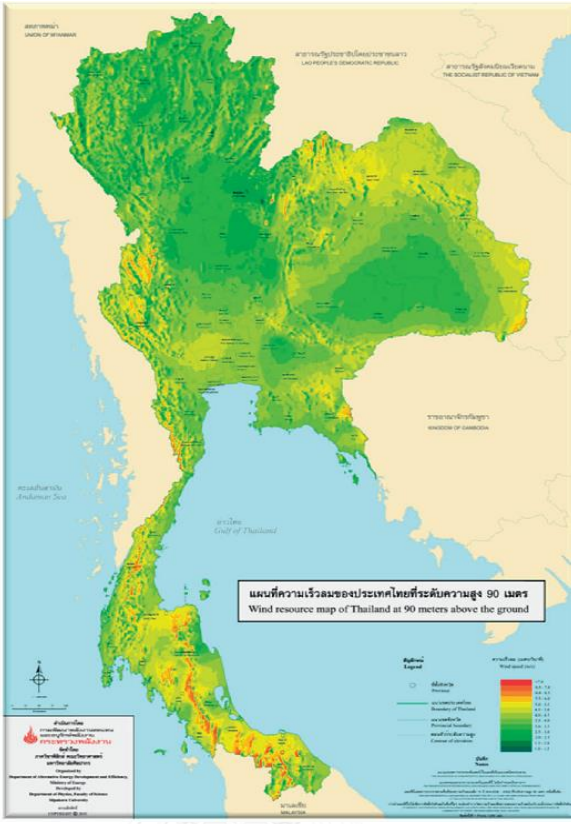

Figure 3.2 The wind speed map of Thailand at 90 meters above the ground

The wind resource assessment of Thailand report which is studied by DEDE [75] mentioned that wind energy potential in Thailand is in a pleasant level. The average of annual wind speed is not less than 6.4 m/s. From November to the end of March, the wind speed will increase because of northeastern storm coming from South China Sea. The affected provinces from this storm are Nakhon Si Thammarat, Songkla and Pattani. From May to the middle of October, the wind will increase because of southwestern storm. The affected provinces from this storm are Phetchaburi and Kanchanaburi. Moreover, the areas which have high wind speed all the year are Gaeng Grung national park in Surat Thani and Sri Phang Nga national park in Phang Nga.

3.3.3 Performance Evaluation of Renewable Energy Sources

Some types of renewable energy sources, such as solar and wind sources generate intermittent power to the interconnecting power system. In order to estimate the intermittent power from solar and wind sources, accurate models are needed. In this dissertation, the models of solar and wind power as shown in (3.1)-(3.3) from [76] and (3.4)-(3.7) from [77], respectively are used.

Solar model

$$P_{pv} = P_{sn} \times \frac{G_{bh}^2}{G_{std} \times R_c} \qquad ;0 \le G_{bh} < R_c \qquad (3.1)$$

$$P_{pv} = P_{sn} \times \frac{G_{bh}}{G_{std}} \qquad ;R_c \le G_{bh} < G_{std} \qquad (3.2)$$

$$P_{pv} = P_{sn} \qquad ;G_{std} < G_{bh} \qquad (3.3)$$

Wind model

$$P_{wind} = 0 \qquad ;0 < V_{SP} < V_{CI} \qquad (3.4)$$

$$P_{wind} = P_{rated} \frac{\left(V_{SP}^3 - V_{CI}^3\right)}{\left(V_r^3 - V_{CI}^3\right)} \qquad ;V_{CI} < V_{SP} < V_r \qquad (3.5)$$

$$P_{wind} = P_{rated} \qquad ;V_r < V_{SP} < V_{CO} \qquad (3.6)$$

$$P_{wind} = 0 \qquad ;V_{SP} > V_{CO} \qquad (3.7)$$

CHAPTER 4
METAHEURISTIC OPTIMIZATION

According to the solving methods as mentioned in Section 2.5, TEP method can be classified into 3 methods. Metaheuristic optimization which is one of the methods is adopted in this dissertation. At first, various methods of metaheuristic optimization are presented in Section 4.1. After that, the reason for selecting Tabu search to solve TEP is presented in Section 4.2. Finally, the algorithm of adaptive tabu search (ATS) used in this dissertation is explained in detail in Section 4.3.

4.1 Review of Metaheuristic Optimization

Various metaheuristic algorithms exist in literatures such as simulated annealing, ant colony, particle swarm, etc. The most popular metaheuristic algorithms for optimization are briefly introduced in this dissertation.

4.1.1 Simulated Annealing

The origins of the simulated annealing (SA) method are in statistical mechanics [78]. SA was first proposed by Kirkpatrick et al. [79], and independently by Cerny [80]. SA is inspired by the annealing technique which is used by the metallurgists to obtain a ‘‘systematical’’ solid state of minimal energy (while avoiding the ‘‘metastable’’ structures, property of the local minima of energy). This technique consists in carrying a material at high temperature until melting point. After that, leave it lowering its temperature slowly, then the robust material will be obtained. From the experiment, it can be said that more cooling time more obtained robust material. The process of the annealing to the solution of an optimization problem is transposed by SA. The objective function of the problem, similar to the energy of a material, is then minimized by introducing an imaginary temperature which is a simple controllable parameter of this algorithm.

4.1.2 Genetic Algorithms

Genetic algorithms (GAs) are probably the most popular evolutionary algorithms with a diverse range of applications. Moreover, GAs are population-based and many modern evolutionary algorithms are directly based on or similar to GAs.

GAs developed by John Holland and his collaborators in the 1960s and 1970s, are a model of biological evolution based on Charles Darwin's theory of natural selection [81]. Holland was the first to utilize crossover, recombination, mutation and selection in the study of adaptive and artificial systems. These genetic operators are the essential components of genetic algorithms as a problem-solving strategy. Many variants of genetic algorithms have been developed and applied to a wide range of optimization problems, from discrete systems (such as the travelling salesman problem) to continuous systems (e.g., the efficient design of airfoil in aerospace engineering) and from financial markets to multi-objective engineering optimization. The main matter of genetic algorithms concerns the encoding of solutions as bits arrays or character strings (chromosomes), the manipulation of these strings by genetic operators and a selection based on their fitness to find a solution of a problem. This is the following procedure: 1) definition of an encoding scheme 2) definition of a fitness function 3) creation of a population of chromosomes 4) evaluation of the fitness of every chromosome in the population 5) creation of a new population by performing fitness-appropriate selection, crossover and mutation 6) replacement of the old population by the new population. Steps 4), 5) and 6) are repeated for a number of generations. At the end, the best chromosome is decoded to obtain a solution of the problem.

4.1.3 Differential Evolution

Differential evolution (DE) algorithm is one of the most popular algorithms for the continuous global optimization problems. It was proposed by Storn and Price in the 90’s [82] in order to solve the Chebyshev polynomial fitting problem and has proven to be a very reliable optimization strategy for many different tasks. DE is a vector-based evolutionary algorithm and can be considered as a further development of genetic algorithms. Unlike genetic algorithms, DE carries out operations over each component (or each dimension of the solution). Almost everything is done in terms of vectors, and DE can be viewed as a self-organizing search, directed towards the optimum. For each generation of the evolution process, new individuals are created by applying reproduction operators (crossover and mutation). The fitness of the solutions is evaluated and each individual (target individual) of the population competes against a new individual (trial individual) to determine which one will be maintained into the next generation. The trial individual is created by recombining the target individual with another individual created by mutation.

4.1.4 Ant Colony Optimization

Ant colony optimization is created by Marco Dorigo in 1992 and is inspired by the food exploration behavior of social ants. When searching for food, these ants initially explore the area around their nest by performing a random walk. Along their path between food source and nest, ants deposit a chemical pheromone trail on the ground in order to mark some favorable path that should guide other ants to the food source [83]. After some time, the shortest path between the nest and the food source presents a higher concentration of pheromone and, therefore, attracts more ants. Ant colony optimization employed this characteristic of real ant colonies to build solutions to an optimization problem and exchange information on their quality through a communication scheme that is reminiscent of the one adopted by real ants [84].

4.1.5 Bee Algorithms

Bee algorithms inspired by the food exploration behavior of bees are another class of metaheuristic algorithms. A few bee algorithms exist in the literature such as honeybee algorithm, artificial bee colony, bee algorithm, virtual bee algorithm, and honeybee mating algorithms [81].

Honey bees live in a colony and they forage and store honey in their colony. Honey bees can communicate the others by pheromone and “wobble dance”. For example, an alarming bee may release a pheromone to stimulate the attack response in other bees. Moreover, when a good food source is found and some honey is brought back to the honeycomb, they will inform the location of the food source by performing the so-called wobble dance as a signal. The signal dances vary from species to species. However, they are aimed at recruiting more bees by using directional dancing with varying strength so as to communicate the direction and distance of the food source.

For many food sources such as flower patches, studies illustrate that a bee colony seems to be able to allocate forager bees among different flower patches in order to maximize their total honey initiative (Moritz and Southwick 1992).

Honey bee algorithm (HBA) was first formulated around 2004 by Craig A Tovey in collaboration with Sunil Nakrani as a method to allocate computers among different clients and web-hosting servers. Later in 2004 and in early 2005, Xin-She Yang developed a virtual bee algorithm (VBA) to solve continuous optimization problems. At about the same time, Pham *et al*. (2005) developed the bee algorithms. A little later in 2005, a honey-bee mating optimization (HBMO) algorithm which was subsequently applied to reservoir modeling and clustering is presented by Haddad and Afshar and their colleagues. Around the same time, an artificial bee colony (ABC) algorithm for numerical function optimization is developed by D. Karabogo in Turkey. In conclusion, bee algorithms are more suitable for discrete and combinatorial optimization and have been applied in a wide range of applications.

4.1.6 Particle Swarm Optimization

Kennedy and Eberhart developed particle swarm optimization (PSO) in 1995 based on swarm behavior observed in nature such as fish and bird schooling. Particle swarm optimization (PSO) was developed by Kennedy and Eberhart in 1995, based on swarm behavior such as fish and bird nature. From that time on, PSO has generated a lot of attention, and forms an exciting, ever-expanding research subject in the field of swarm intelligence. PSO has been applied to almost every area in optimization, computational intelligence, and scheduling applications. There are at least 22 of PSO variants, as well as hybrid algorithms obtained by combining PSO with other existing algorithms which are also further renowned.

PSO searches the space of an objective function by adjusting the trajectories of individual agents called particles. Each particle detects a piecewise path which can be modeled as a time-dependent positional vector. The motion of a swarm particle composes of 2 major components: a stochastic component and a deterministic component. Each particle is attracted toward the position of the current global best and its own best known location, while exhibiting at the same time a tendency to randomly move.

When a particle finds a location which is better than every previously found location, it updates this location as the new current best for particle. There is a current best for all particles at any time of each iteration. The aim is to find the global best among all the current best solutions until the objective no longer improves.

4.1.7 Tabu Search

Tabu search (TS) was formed in 1986 by Glover [85]. TS was designed to manage an embedded local search algorithm. It evidently uses the history of the search, both to escape from local minima and to implement an explorative strategy. Its major characteristic is based on the mechanisms which are inspired by the memory of human. As most algorithms are memory less or only use results of the last or 2 last steps, it is initially difficult to see the advantage of using the search history. The fragility of memory and history could introduce too many degrees of freedom, and a mathematical analysis of the algorithm behavior becomes unamenable. However, TS remains one of the most successful and widely used metaheuristics in optimization.

In essence, tabu search can be considered as a massive local search and the proper use of search history which can avoid revisiting local solutions by recording recently tried solutions in tabu lists. Over a large number of iterations, these tabu lists could conserve an essential amount of computing time which lead to improvements in search efficiency. For example, studies show that the use of tabu lists with integer programming compared with standard integer programming can save computing effort by at least 2 orders of magnitude for a given problem [81] (Glover 1986, Glover and Laguna 1997).

4.1.8 Harmony Search

Harmony search (HS) is a new heuristic optimization algorithm which is developed by Z. W. Geem *et al*. in 2001 [81]. Harmony search is related to the improvisation process of a musician. When a musician is improvising, he or she has 3 possible choices: 1) play any famous piece of music (a series of pitches in harmony) exactly from his or her memory 2) play something similar to a known piece (thus adjusting the pitch slightly) and 3) compose new or random notes. If these 3 options for optimization are formalized, 3 corresponding components: usage of harmony memory, pitch adjustment, and randomization are obtained.

4.1.9 Firefly Algorithm

The firefly algorithm (FA) was developed by Xin-She Yang (Yang 2008) and is based on the flashing patterns and behavior of fireflies. In matter, FA uses the following 3 idealized rules:

1) Fireflies are unisex in order to one firefly will be attracted to other fireflies regardless of their sex
2) The attractiveness is proportional to the brightness and both decrease as the distance between 2 fireflies increases. Therefore, for any 2 glittering fireflies, the brighter firefly will attract the other one. If neither one is brighter, a random move is performed.
3) The brightness of a firefly is determined by the landscape of the objective function.

4.1.10 Cuckoo Search

Cuckoo search (CS) is one of the latest nature-inspired metaheuristic algorithms developed by Xin-She Yang and Suash Deb in 2009. CS is based on the brood parasitism of some cuckoo species (Yang and Deb 2009). In addition, this algorithm is supplemented by the so-called Levy flights, rather than by simple isotropic random walks (Pavlyukevich 2007). Recent studies show that CS is potentially far more efficient than PSO and genetic algorithms (Yang and Deb 2010).

Cuckoos are charming birds, not only because of the beautiful sounds they make, but also because of their aggressive reproduction strategy. Some species named ani and Guira lay their eggs in communal nests, though they may remove others' eggs to increase the hatching probability of their own eggs. Quite a number of species engage in the mandatory brood parasitism by laying their eggs in the nests of other host birds (often other species).

4.2 The Reasons for Selecting Tabu Search to Solve TEP

Since the problem of TEP with AC model is nonconvex, the global optimum is very difficult to obtain. Both mathematical and heuristic methods cannot guarantee a global optimum because these methods are easily trapped in local optimum. It seems that this is an inevitable characteristic of the TEP problem when the AC model is applied. To overcome this difficulty without relaxing the model of TEP problem, metaheuristic method should be employed. Some types of metaheuristic method are appropriate for nonconvex problems since they have mechanisms to escape the local optimum. Consequently, the metaheuristic method is used to solve TEP with AC model.

From the review of metaheuristic optimization methods, this dissertation selects tabu search method for solving both TEP and RTEP because of the following advantages.

Advantages of tabu search:

1) Tabu search is formulated by the idea that “the intelligent search has to consider the adaptive memory” while the other metaheuristic optimizations do not consider about this.
2) Tabu search uses the responsive exploration which means that “sometimes, a bad path may give more information to the better path than a good path give”.
3) Tabu search uses the sensibility and diversity formulation by increasing the sensibility around the good solution which is previously found and additional searching a new path which differs from the path that the previously found the good solution.
4) Tabu search can alleviate the local optimal solutions and can continuously execute the solution search until the global optimal solution or the approximate global optimal solution is obtained.

From these advantages, this dissertation selects tabu search method for solving both TEP and RTEP problems with AC model which are MINLP. Moreover, for increasing the search efficiency, some techniques are supplemented to the original tabu search. Adaptive tabu search (ATS) is a new name after these techniques are included. The details of ATS are explained in Subsection 4.2.3. In order to better understand, the original tabu search algorithm has to be explained firstly as presented in the next section.

4.3 Tabu Search Algorithm

Tabu search is an efficient method for combinatorial optimization [86-88]. At present, tabu search is generally accepted as the best method to alleviate local optimal solution and can continuously execute the solution search until the global optimal solution is obtained. In addition, tabu search can be simply adopted in various works because the principal and mechanism of tabu search are not complicated compared with other metaheuristic optimizations.

From many advantages of tabu search, tabu search is widespread popularity tool for various optimization problems such as applied science in business or engineering etc.

4.3.1 Basic Principle of Tabu Search

Tabu means “forbidden” according to dictionary. There is element which composed of forbidden status in the tabu search infrastructure. However, this element is not necessary to preserve this forbidden status forever but this status can change in accordance with the time and differential system status. The procedure of tabu search uses the previously mentioned principle for considering the expected path that can lead to the optimal solution. Tabu search can avoid local optimal solution which is the point that no other paths around this point can give better solution than the present solution.

According to Figure 4.1, the surface in this figure is defined as the results from evaluation of the objective function which are the maximum values from the surface. The calculation for searching a new solution from any present solution point will uses the operation called “move operator” or “walk operator” which changes the state of the solution depend on the path of moving. For general search called “local search” or “neighborhood search”, tabu search will select the better solution around the present

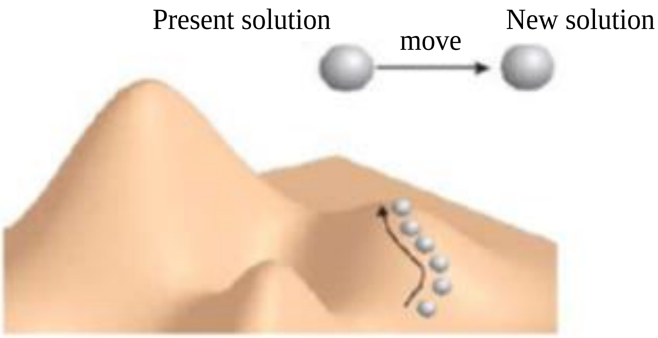

Figure 4.1 "Move operator" for searching a new solution from present solution [89]

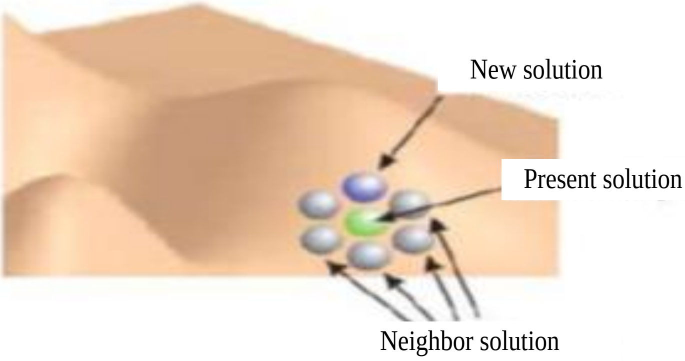

Figure 4.2 Searching for local optimal solution [89]

solution by move operator for evaluating the value of neighbor solutions, and then select the best solution as a new solution which is shown in Figure 4.2.

Define solution search as the optimal solution search of the objective function $f(s)$ and $s \in S$ where $f(s)$ is any linear function or non-linear function, s is a present solution, S is a set of all possible solutions. Neighbor solutions around present solution can be defined as $N \subset S$. The optimal solution can be defined as shown below.

1) If s is a global optimal solution, it can be said that,

   $f(s) \geq f(y)$ for $\forall y \in S$ (in the case of maximization)

   $f(s) \leq f(y)$ for $\forall y \in S$ (in the case of minimization)

2) If s is a local optimal solution, it can be said that,

   $f(s) \geq f(y)$ for $\forall y \in N(S)$ (in the case of maximization)

   $f(s) \leq f(y)$ for $\forall y \in N(S)$ (in the case of minimization)

4.3.2 Basic Element of Tabu Search

Tabu search supplements the procedures and conditions for moving except searching around neighbor area in order to:

1) Avoidance from the local optimal solution

If a new solution is better than a present solution, the search direction will move to a new solution path. If no neighbor solution is better than a present solution, the search of new better solution will be terminated. The last 2 sentences is a step during the searching of neighbor solution process. The obtained solution is a local optimal solution. However, tabu search allows change of the search direction to the worse search direction as illustrated in
Figure 4.3 in order to escape from the local optimal solution.

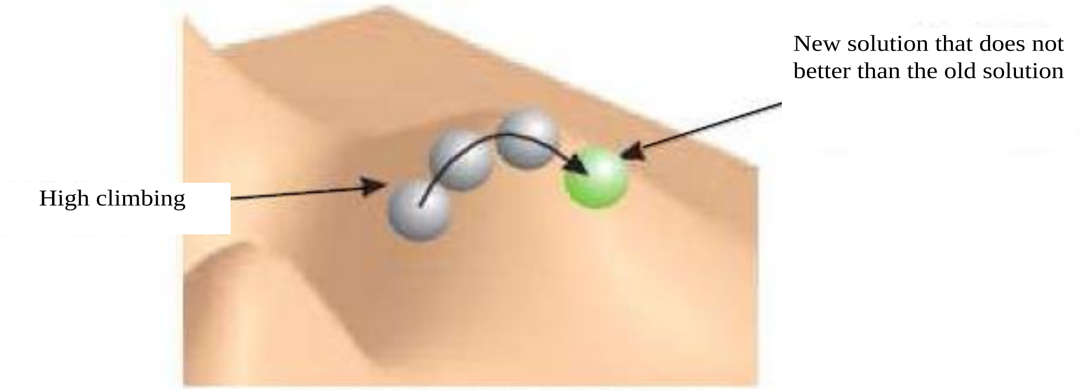

Figure 4.3 Avoidance from local optimal solution [89]

2) Avoidance from the loop path

Some path can lead to the loop path that cause the solution cannot escape from the present state. For example, the property of some path is “inverse move” which effect to the unlimited “go and back” event. Therefore, tabu search set status of the previously used path as “tabu status” in order to avoid this path within a defined period of time. After the time past the defined period of time, the tabu status of that path will be cancel.

From the above mentioned ability of tabu search, the old data are used for making the decision of the solution search direction. The elements which are the important parts of tabu search structure in order to increase the efficiency of solution search are shown below.

- Recency condition

The using of recency condition is the tracking of solution search in the past period of time. When the solution is found, the status of the paths which lead to that solution will be set to forbidden. Consequently, the found solution from this moving is a last solution and will not be found again within a defined period of time because the status of paths which lead to this solution are still set as forbidden. After past a defined period of time, the status of these paths will be set as normal. Therefore, during the solution search process, tabu search will force the solution search to move to the other solutions that their statuses are normal. This mechanism of tabu search can avoid the local optimal solution and can continuously search the new better solution although sometimes, a new solution is worse than an old solution. That is to say, this mentioned condition is probably called the tabu procedure as well.

- Frequency condition

Frequency condition is the condition for avoiding the loop searching. This condition can help the solution to leave a local optimal solution. For example, when the solution reaches to the solution that expected to be the local optimum, the algorithm will check whether this solution is the local optimum in its search space or not by finding the new better solutions around this solution. If the obtained solutions are the same and the number of these repetitive solutions equal to the defined maximum repetitive number, this solution will be set as local optimum. After that, the algorithm will collect this solution and leave from this solution for avoiding the loop searching.

There are other elements which affect the selecting of solution search path as explained below:

- Intensification

Intensification is the solution search that emphasizes the good solution area by using the previously collected data. Intensification of tabu search will go back to the area which provides the good solutions and intensively search the solution in this area again.

- Diversification

Diversification is the mechanism that encourages tabu search to explore the previously unexplored area. Diversification can cause obtained solution probably differs from the previous solutions. Sometimes, selection of unexplored and different area may cause to meet the better solution.

- Aspiration criterion

Aspiration criterion is the condition that can force the solution to move into the desired path, although the status of that path is still "forbidden". This criterion will be allowed to use when the obtained solution is better than overall previously obtained solutions.

4.3.3 Adaptive Tabu Search Method

In many cases, the efficiency of original tabu search is not sufficient to adopt in some applications. Accordingly, the structure of tabu search is developed which is called "adaptive tabu search (ATS)". The algorithm of ATS is developed by the researchers in department of electrical engineering, Suranaree University of Technology [88]. This development supplements 2 mechanisms in an original tabu search. These mentioned mechanisms are "back tracking" and "adaptive radius" as shown below.

1) Back tracking

Back tracking is the procedure which allows the search direction to go back to the old searched paths. When the solution cannot escape from the local optimal solution point within the defined maximum number of repetition, the algorithm will select the initial solution as the starting point for the next step calculation as shown in Figure 4.4.

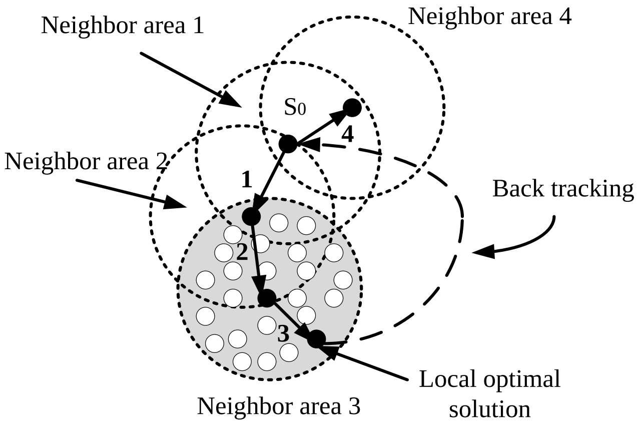

Figure 4.4 Back tracking mechanism

2) Adaptive radius

Adaptive radius will reduce the search radius during searching process. The search radius will continuously reduce until the searching approaches to the global optimal solution as illustrated in Figure 4.5. Generally, wide search radius can result in the unsuitable solution. On the other hand, narrow search radius resulting in more suitable solution but the searching time will be greater. Especially, if the search radius is too narrow, it will not cover all of solution area. Therefore, the optimal adjustment of search radius for a specific problem can increase the efficiency of a search solution. In ATS, the adjustment of search radius is optimally developed as presented in Figure 4.5 by using the solution value. For example, when present solution gives the higher value of the solution, the search radius will be decreased as presented in (4.1).

$$New\_radius = \frac{Old\_radius}{DF} \tag{4.1}$$

where *DF* is a decreasing factor.

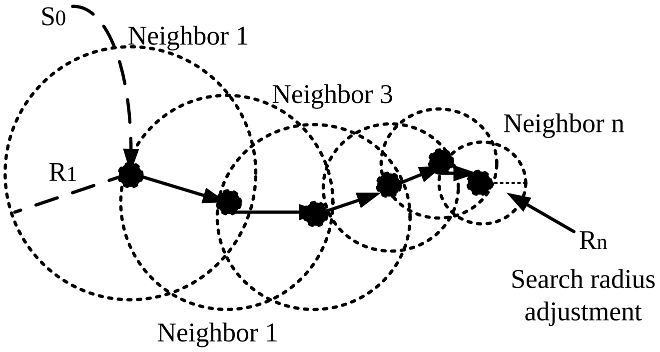

Figure 4.5 Adaptive radius mechanism

4.3.4 Adaptive Tabu Search Procedure

ATS is the search solution method developed from TS [87, 88]. The two supplemented mechanisms of this method compose of back tracking and adaptive radius mechanisms which increase the speed and accuracy of search solution process. The procedure of ATS algorithm is explained below.

1) Define the search space, search radius (*R*), number of neighbor solutions (*N*), maximum number of search iteration (*iter_max*), maximum number of solution repetitions (*f_max*) and the limitation time of "forbidden" status of the path.

2) Randomize the initial solution (S_0) in the search space by define S_0 as the best neighbor solution at present as illustrated in Figure 4.6.

3) Generate the neighbor solution of S_0 by randomization under search radius (*R*) for *N* solutions then collect all solution into $S_1(r)$. After that, evaluate all of solution in $S_1(r)$ according to the objective function (the minimum value). Define S_1 (best_neighbor1) as the solution that gives the minimum value as shown in Figure 4.7.

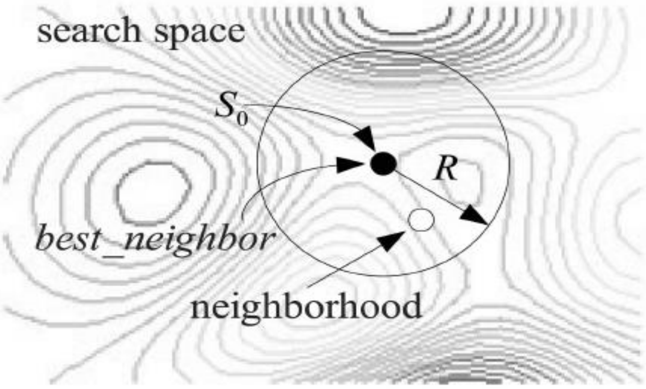

Figure 4.6 Randomization of initial solution (S_0) [89]

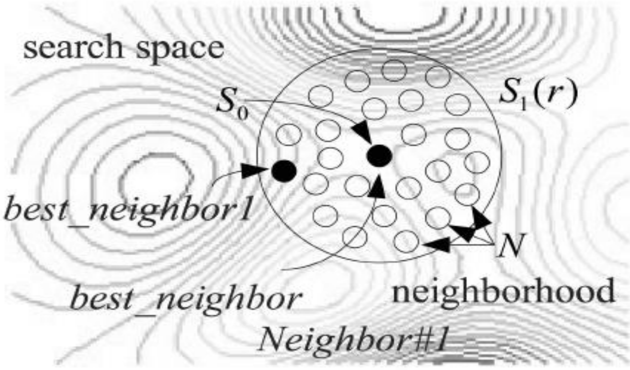

Figure 4.7 Neighbor solutions from randomization [89]

(4) If quality of S_1 is better than S_0, collect S_0 into Tabu list and then set S_0 equals to S_1; otherwise, if quality of S_0 is better than S_1, collect S_1 into Tabu list as illustrated in Figure 4.8.

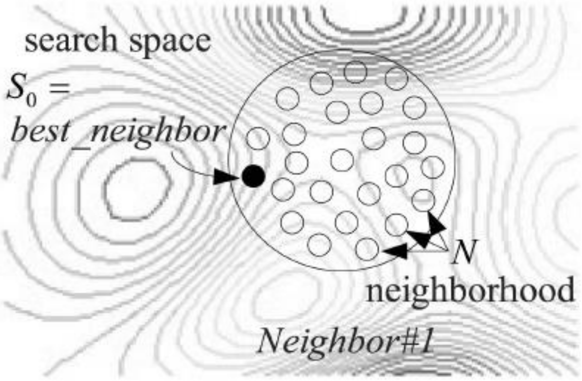

Figure 4.8 Comparing and setting S_0 as the best solution [89]

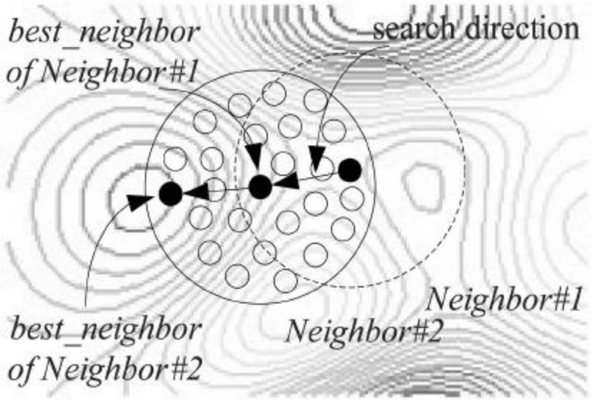

Figure 4.9 The step of moving [89]

5) Use the back tracking mechanism in the case that the number of the obtained solution which is repetitive more than *f_max* (all neighbor solutions are not better than the present solution) in order to escape from local optimal solution as shown in Figure 4.10.
6) Examine the number of iteration is complete according to the *iter_max*. If it is complete, stop the search and then define S_0 as the optimal solution. Otherwise, go to next step.
7) Use the search radius adjustment when the search process close to the optimal solution as illustrated in Figure 4.11.
8) Supplement the iteration by one and then return to (3) for searching the next iteration. Normally, ATS algorithm will be terminated when the iteration reaches to the defined maximum iteration or the percentage of discrepancy is acceptable.

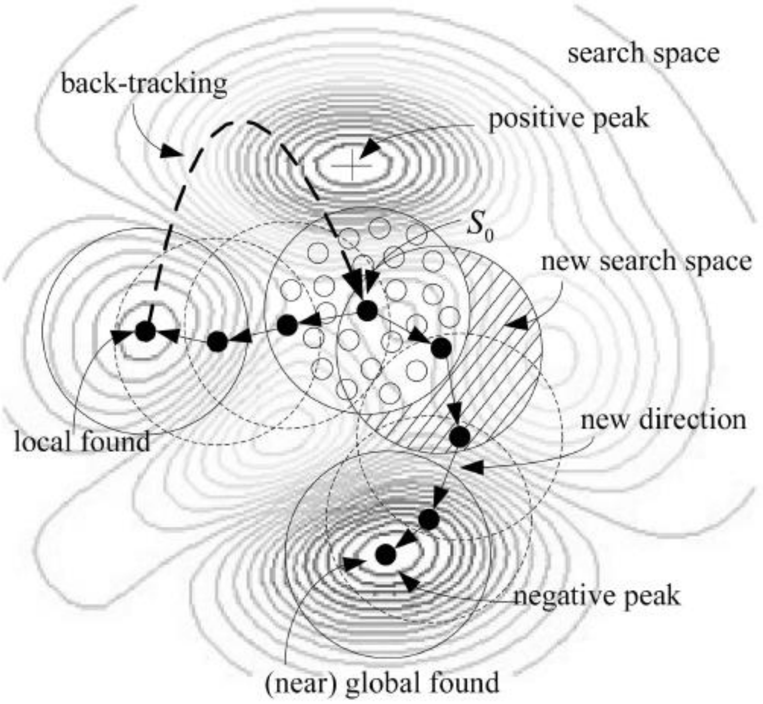

Figure 4.10 Using a back tracking mechanism [90]

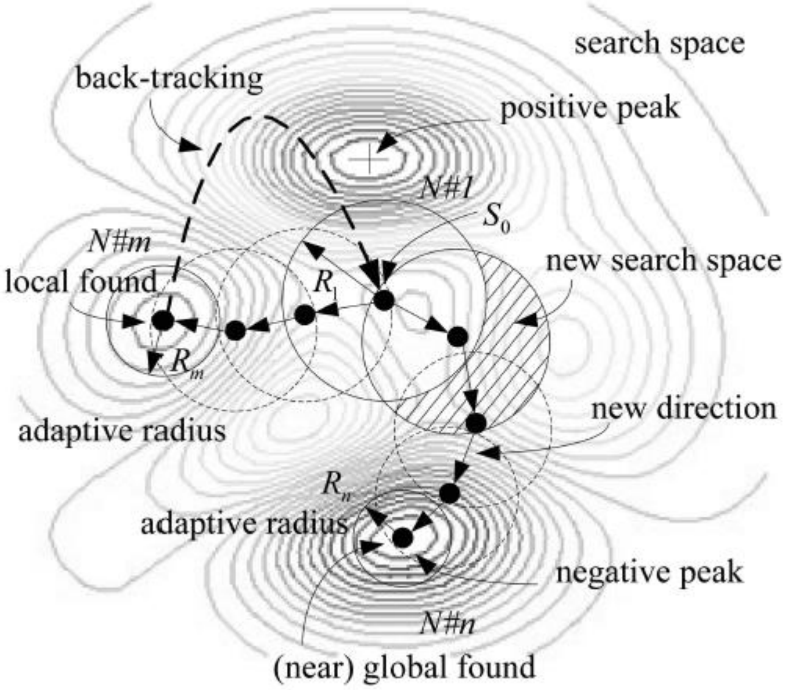

Figure 4.11 Using both back tracking and search radius adjustment mechanisms [90]

CHAPTER 5

PROPOSED FORMULATION AND METHODOLOGY

In this chapter, the proposed scenarios selection method is presented in Section 5.1 in order to design the system with high robustness. In addition, the procedure of ATS based method for solving both TEP and RTEP problems are proposed in Section 5.2. After that, the evaluation of expansion plan robustness is presented in Section 5.3. Finally, the method to ensure the system robustness is presented in Section 5.4.

5.1 Proposed Scenario Selection Method

From the assumption that if the system can satisfy the most severe scenario, it may satisfy other scenarios which their severity are lower as well. Consequently, in order to plan the system with high robustness, the expansion plan should satisfy the most severe scenario.

To determine what values of renewable energy generation and loads that should be considered as the most severe scenario. The severity of every hourly forecasted value of the actual renewable energy generation and loads in a target year must be determined. The severity of each hourly value can be measured by the scenario selection indicator (SSI) which is calculated based on the curtailments of renewable energy generation and loads. These curtailments are obtained by solving the formulation in (5.1)-(5.13).

Objective function:

$$Minimize\left(\sum_{g=1}^{ng} c_g P_g + \sum_{re=1}^{nre} wr_{re} P_{re}^{RC} + \sum_{i=1}^{nb} wd_i P_i^{DC}\right) \tag{5.1}$$

Subject to:

Real and reactive powers balance:

$$\sum_{g\in i} P_g + \sum_{re\in i}\left(P_{re}^{R} - P_{re}^{RC}\right) - \left(P_i^{D} - P_i^{DC}\right) = P_i, \quad i = 1,\dots,nb \tag{5.2}$$

$$\sum_{g\in i} Q_g + Q_i^C - Q_i^{IN} - \left(Q_i^D - Q_i^{DC}\right) = Q_i,\quad i = 1,...,nb \tag{5.3}$$

Bus voltage limit:

$$V_i^{\min} \le V_i \le V_i^{\max},\quad i = 1,...,nb \tag{5.4}$$

Apparent power flow limit:

$$S_{ij,m}^{fr} \le S_{ij,m}^{\max}\ ,\quad m = 1,...,nl \tag{5.5}$$

$$S_{ij,m}^{to} \le S_{ij,m}^{\max},\quad m = 1,...,nl \tag{5.6}$$

Real and reactive power generation limit:

$$P_g^{\min} \le P_g \le P_g^{\max},\quad g = 1,...,ng \tag{5.7}$$

$$Q_g^{\min} \le Q_g \le Q_g^{\max},\quad g = 1,...,ng \tag{5.8}$$

Reactive power compensation limit:

$$Q_i^{C\min} \le Q_i^C \le Q_i^{C\max},\quad i = 1,...,nb \tag{5.9}$$

$$Q_i^{IN\min} \le Q_i^{IN} \le Q_i^{IN\max}\ ,\quad i = 1,...,nb \tag{5.10}$$

Curtailment of renewable energy generation and loads limit:

$$0 \le P_{re}^{RC} \le P_{re}^R,\quad re = 1,...,nre \tag{5.11}$$

$$0 \le P_i^{DC} \le P_i^D,\quad i = 1,...,nb \tag{5.12}$$

$$0 \le Q_i^{DC} \le Q_i^D,\quad i = 1,...,nb \tag{5.13}$$

where

$$P_i = V_i \sum_{j\in\Omega^b} V_j \left(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}\right) \tag{5.14}$$

$$Q_i = V_i \sum_{j\in\Omega^b} V_j \left(G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}\right) \tag{5.15}$$

$$G_{ij} = \begin{cases} G_{ij} = -\left(\sum_{l \in ET_{ij}} g_{ij,l} \right) \\ G_{ii} = \sum_{j \in N_{bi}} \left(\sum_{l \in ET_{ij}} g_{ij,l} \right) \end{cases} \tag{5.16}$$

$$B_{ij} = \begin{cases} B_{ij} = -\left(\sum_{l \in ET_{ij}} b_{ij,l} \right) \\ B_{ii} = b_i^{sh} + \sum_{j \in N_{bi}} \left[\sum_{l \in ET_{ij}} \left(b_{ij,l} + b_{ij,l}^{sh} \right) \right] \end{cases} \tag{5.17}$$

The variables S_{ij}^{fr} and S_{ij}^{to} can be defined by (2.30)-(2.35). If the curtailments of renewable energy generation and loads of the considered hour are high, it means that the system cannot support the renewable energy generation and loads of this hour sufficiently. In consequence, the renewable energy generation and loads of this hour should be selected as the considered scenario for planning. On the contrary, if there is no any curtailment, the renewable energy generation and loads of this hour may be insignificant to be considered for planning. According to renewable energy generation and loads, the SSI can be separated into 2 indicators, i.e. SSI of renewable energy generation (*SSIRG*) and SSI of loads (*SSIL*) as presented below.

$$SSIRG_h = \frac{\sum_{re}^{nre} P_{re,h}^{RC}}{\sum_{re}^{nre} P_{re,h}^{R}} \tag{5.18}$$

$$SSIL_h = \frac{\sum_{i}^{nb} P_{i,h}^{DC}}{\sum_{i}^{nb} P_{i,h}^{D}} \tag{5.19}$$

After the *SSIRG* and *SSIL* of each hour are known, the next step is selecting the most severe scenario based on the hours providing the highest values of *SSIRG* and *SSIL*. It can be noticed that the maximum value of both *SSIRG* and *SSIL* of each hour cannot more than 1.

In some hours, the optimal power of MATPOWER cannot be calculated due to the failure to converge. The *SSIRG* and *SSIL* of these hours will be defined equally to 1 in order to select the values of renewable energy generation and loads of these hours as the considered scenarios for planning.

The procedure of the proposed scenario selection method can be summarized as the following steps:

Step 1: Set the index of hour (h) to 1 and create the set of considered scenarios for planning.

Step 2: Calculate $SSIRG_h$ and $SSIL_h$ of the existing system. If the OPF cannot be calculated, define the $SSIRG_h$ and $SSIL_h$ equally to 1.

Step 3: Set $h=h+1$. If h is higher than the number of hour in a year, go to step 4; if else, go to 2).

Step 4: If the *SSIRG* and *SSIL* of some hours equal to 1, add the values of the renewable energy generation and loads of these hours into the set of considered scenarios for planning. Otherwise, do nothing.

Step 5: Add the values of the renewable energy generation and loads of the hour that provides the highest *SSIRG*, excepting the hour that provides the *SSIRG* equally to 1, into the set of considered scenarios for planning. Moreover, add the values of the renewable energy generation and loads of the hour that provides the highest *SSIL*, excepting the hour that provides the *SSIL* equally to 1, into the set of considered scenarios for planning as well.

5.2 ATS Optimization for Solving TEP and RTEP

After the considered scenarios for planning are obtained, the next step is solving the expansion plan by using ATS optimization. The problem formulations of TEP and RTEP are presented in Subsection 2.6.2 and 2.6.3, respectively. The search space of ATS is all transmission line (TL) candidates. The procedure for solving TEP and RTEP can be explained as follows.

Step 1: Define ATS parameters: *f_max*, *iter_max* and *num_neighbor*.

Step 2: Define S_0 is selecting all TL candidates to install in the system and set S_0 to be the best solution (S_{best}). The format for collecting the TL candidates is shown in Table 5.1 by assuming the number of all TL candidates is three. From this table, the $x_{ij,k}$ "0" means that TL is not selected to install in the system; otherwise, the $x_{ij,k}$ "1" means that TL is selected (in this case, S_0 is defined to selecting all TL candidates; therefore, $x_{ij,1}$, $x_{ij,2}$ and $x_{ij,3}$ are "1").

Table 5.1 Example of the format for collecting the TL candidates

x^k	TL candidates	
	From bus no.	To bus no.
$x_{ij,1} = 1$	1	3
$x_{ij,2} = 1$	4	6
$x_{ij,3} = 1$	7	8

Step 3: Collect S_{best} in the *Tabu_list* as shown in Table 5.2.

Table 5.2 Format of collecting S_{best} in the *Tabu_list*

S_{best_1}
S_{best_2}
⋮
⋮
$S_{best\_iter\_max}$

Step 4: Evaluate the quality of S_{best}. The method for evaluating the quality of the solution is explained in the Subsection 5.2.1 for TEP and Subsection 5.2.2 for RTEP.

Step 5: Adjust the radius of the area around S_{best} according to the quality of the solution as called “adaptive radius” mechanism.

Step 6: Randomize the neighbor solutions *N_S* around S_{best} which the number of *N_S* equal to the *num_neighbor* and evaluate the quality of all neighbor solutions. After that, select the solution which gives the best quality (N_S_{best}).

Step 7: Compare the quality of S_{best} and N_S_{best} which can be divided into 3 cases as follows.

Case 1: If N_S_{best} quality is worse than S_{best} quality, define $S_{best} = S_{best}$.

Case 2: If N_S_{best} quality is better than S_{best} quality, define $S_{best} = N\_S_{best}$ and examine whether S_{best} is in *Tabu_list* or not. If S_{best} is in *Tabu_list*, randomize a new solution from neighbor solutions and set that solution as S_{best}.

Case 3: If N_S_{best} quality equals S_{best} quality, consider N_S_{best} as follows.

Case 3.1: If N_S_{best} is a new solution, define $S_{best} = N\_S_{best}$ and examine whether S_{best} is in *Tabu_list* or not. If S_{best} is in *Tabu_list*, randomize a new solution from neighbor solutions and select that solution as S_{best}.

Case 3.2: If N_S_{best} is an old solution, define $S_{best} = N\_S_{best}$.

Step 8: Update and examine the number of solution repetitions of S_{best}. If the number of solution repetitions of S_{best} is more than *f_max*, collect S_{best} in the *Ans_list* as shown in Table 5.3. After that, define $S_{best} = S_0$ according to the “back tracking” mechanism.

Step 9: Collect S_{best} in *Tabu_list* and then increase the iteration by one and check the iteration. If the number of iterations is more than the *iter_max*, go to Step 10; otherwise, go to Step 4.

Step10: Find the optimal solution by selecting the solution in *Ans_list* which provides the best quality.

Table 5.3 Pattern of collecting S_{best} in the *Ans_list*

Local_solution_1
Local_solution_2
⋮
⋮
Local_solution_last

From the procedure which is previously mentioned, the flowchart of the procedure can be drawn as shown in Figure 5.1.

Since the suitable *iter_max* is difficult to defined in order to obtain the expected global optimal, the convergence criterion is applied in this dissertation. The procedure can be explained as the following steps.

Step1: After the optimal solution from the ATS procedure is obtained, collect this solution and redefine the *iter_max* by multiplying the old *iter_max* by 2.

Step2: Continue the ATS process until the iteration reaches to *iter_max*.

Step3: Find the optimal solution. After that, check this solution is the same as the previous collected solution or not. If the solution is the same, increase the repetition number by 1; otherwise, define the repetition number equal to 0.

Step4: Check the repetition number. If the repetition number is equal to 3, terminate the process and define this optimal solution is expected global solution. Otherwise, go to Step1.

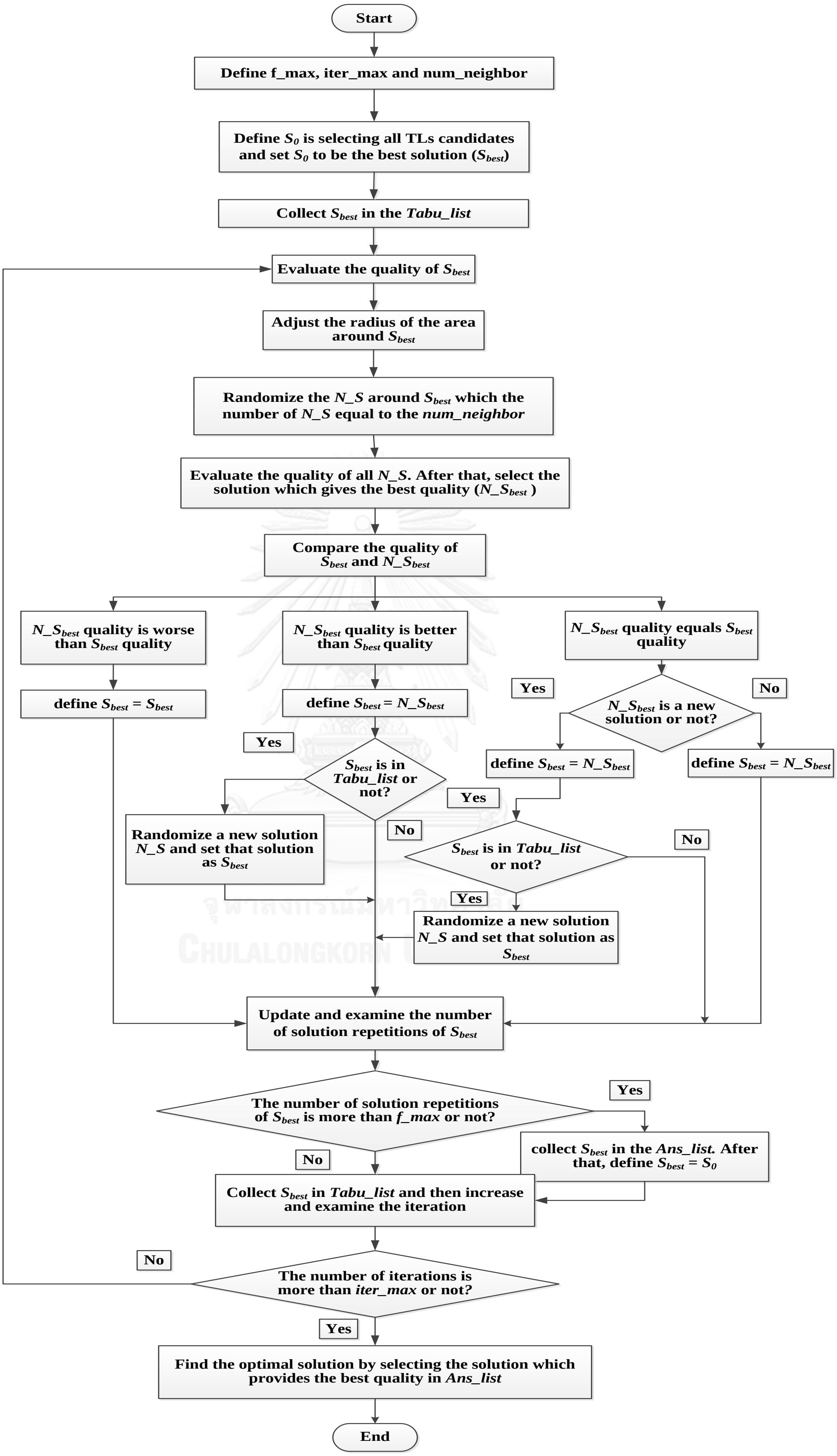

Figure 5.1 Flowchart of ATS Optimization for Solving TEP and RTEP

5.2.1 Evaluating the Solution Quality for TEP

As mentioned in the procedure showing in Figure 5.1, each obtained solution from the random process of ATS has to be evaluated the quality. The procedure for evaluating the solution quality for TEP can be explained into the following steps.

Step 1: Obtain the solution which represents the selected TL candidates.

Step 2: Update the system configuration by using the obtained solution in Step 1.

Step 3: Define the considered scenarios for TEP. For load, the peak value is selected as explained in Subsection 2.6.2. For renewable energy generation, the suitable values are not well discussed in the previous research works; consequently, the three values consisting of zero, half and full capacity will be tested in Chapter 6.

Step 4: Solve the subproblem in order to avoid the violation of system operation by generation redispatch and curtailments of renewable energy generation and loads. The subproblem formulation is presented in Subsection 5.2.3.

Step 5: Grade the quality point of this obtained solution, if the results do not cause any curtailments of renewable energy generation and loads, grade the quality point by using (5.20); else, grade the point to 0.

$$SP = 20 - \frac{\left(\sum_{k=1}^{nc} pv_{inv}^{k} x_{ij,k} + \sum_{g=1}^{ng} pv_{opr}^{g} P_g \right) \times 20}{\left(\sum_{k=1}^{nc} pv_{inv}^{k} + \sum_{g=1}^{ng} pv_{opr}^{g} P_g^{\max} \right)} \tag{5.20}$$

From (5.16), it can be noticed that the maximum point is equal to 20. If the $\left(\sum_{k=1}^{nc} pv_{inv}^{k} x_{ij,k} + \sum_{g=1}^{ng} pv_{opr}^{g} P_g \right)$ is low, the obtained solution point will be high which is in accordance with the objective function of the TEP problem as shown in Subsection 2.6.2.

5.2.2 Evaluating the Solution Quality for RTEP

Similar to the Subsection 5.2.1, each obtained solution from the random process of ATS has to be evaluated the quality. The procedure for evaluating the solution quality for RTEP can be explained into the following steps.

Step 1: Obtain the solution which represents the selected TL candidates.

Step 2: Update the system configuration by using the obtained solution in Step 1.

Step 3: Define the considered scenarios for RTEP depending on the chosen scenarios selection method as presented in Subsection 2.6.3.1, 2.6.3.2 and Section 5.1.

Step 4: Solve the subproblem as presented in Subsection 5.2.3 for each considered scenario one by one until all considered scenarios are completely solved.

Step 5: Grade the quality point of this obtained solution; if the results do not cause any curtailments of renewable energy generation and loads for all considered scenarios, grade the quality point by using (5.20) same as the case of TEP; else, grade the point to 0.

From (5.20), it can be noticed that the maximum point is equal to 20. If the $\left(\sum_{k=1}^{nc} pv_{inv}^{k} x_{ij,k} + \sum_{g=1}^{ng} pv_{opr}^{g} P_g\right)$ is low, the obtained solution point will be high which is in accordance with the objective function of the RTEP problem as shown in Subsection 2.6.3.

5.2.3 Problem Formulation of Subproblem

The objective of subproblem is to avoid the violation of system operation which is generally solved by the method of generation redispatch and load curtailment. From the literature review, many research works [1, 2], [14], [16-19], [21], [23, 24] and [29-31] solve the subproblem by using DC model instead of AC model. However, solving the problem with the DC model may not be acceptable for transmission system planning of the utilities because the obtained result may be infeasible since the DC model is relaxed by using linear equations. Currently, there are limited numbers of TEP or RTEP research solving subproblem by AC model [10], [13], [15] and [32]. Therefore, this dissertation applies AC model which the obtained result is more accurate for solving subproblem.

From the advantage of AC model previously mentioned above, this dissertation models the subproblem formulation with AC model to solve the problem. The problem formulation of the subproblem can be shown as follows.

Objective function:

$$Minimize\left(\sum_{g=1}^{ng} c_g P_g + \sum_{re=1}^{nre} wr_{re} P_{re}^{RC} + \sum_{i=1}^{nb} wd_i P_i^{DC} \right) \tag{5.21}$$

Subject to:

Real and reactive powers balance:

$$\sum_{g \in i} P_g + \sum_{re \in i} \left(P_{re}^{R} - P_{re}^{RC} \right) - \left(P_i^{D} - P_i^{DC} \right) = P_i, \quad i = 1,...,nb \tag{5.22}$$

$$\sum_{g \in i} Q_g + Q_i^{C} - Q_i^{IN} - \left(Q_i^{D} - Q_i^{DC} \right) = Q_i, \quad i = 1,...,nb \tag{5.23}$$

Bus voltage limit:

$$V_i^{\min} \le V_i \le V_i^{\max}, \quad i = 1,...,nb \tag{5.24}$$

Apparent power flow limit:

$$S_{ij,m}^{fr} \le S_{ij,m}^{\max}, \quad m = 1,...,nl \tag{5.25}$$

$$S_{ij,m}^{to} \le S_{ij,m}^{\max}, \quad m = 1,...,nl \tag{5.26}$$

$$x_{ij,k} S_{ij,k}^{fr} \le x_{ij,k} S_{ij,k}^{\max}, \quad k = 1,...,nc \tag{5.27}$$

$$x_{ij,k} S_{ij,k}^{to} \le x_{ij,k} S_{ij,k}^{\max}, \quad k = 1,...,nc \tag{5.28}$$

Real and reactive power generation limit:

$$P_g^{\min} \le P_g \le P_g^{\max}, \quad g = 1,...,ng \tag{5.29}$$

$$Q_g^{\min} \le Q_g \le Q_g^{\max}, \quad g = 1,...,ng \tag{5.30}$$

Reactive power compensation limit:

$$Q_i^{C\min} \le Q_i^{C} \le Q_i^{C\max}, \quad i = 1,...,nb \tag{5.31}$$

$$Q_i^{IN\min} \le Q_i^{IN} \le Q_i^{IN\max}, \quad i = 1,...,nb \tag{5.32}$$

Curtailment of renewable energy generation and loads limit:

$$0 \le P_{re}^{RC} \le P_{re}^{R}, \quad re = 1,...,nre \tag{5.33}$$

$$0 \le P_i^{DC} \le P_i^{D}, \quad i = 1,...,nb \tag{5.34}$$

$$0 \le Q_i^{DC} \le Q_i^{D}, \quad i = 1,...,nb \tag{5.35}$$

The variables P_i, Q_i, S_{ij}^{fr} and S_{ij}^{to} can be defined by (2.26)-(2.35). For solving problem formulation in (5.21)-(5.35), AC optimal power flow (OPF) is applied. In general, the standard version of both DC OPF and AC OPF problems can be written as follows [91].

Objective function:

$$Minimize \ f(\mathbf{w}) \tag{5.36}$$

Subject to:

$$g(\mathbf{w}) = 0 \tag{5.37}$$

$$h(\mathbf{w}) \le 0 \tag{5.38}$$

$$\mathbf{w}_{\min} \le \mathbf{w} \le \mathbf{w}_{\max} \tag{5.39}$$

For AC OPF, the optimization vector **w** from (5.37)-(5.39) consists of the $nb \times 1$ vectors of voltage angles $\boldsymbol{\theta}$, voltage magnitudes **V**, curtailment of power load $\mathbf{P^{DC}}$, curtailment of reactive power load $\mathbf{Q^{DC}}$, reactive power injection of capacitor $\mathbf{Q^{C}}$ and reactive power consumption of reactor $\mathbf{Q}^{\mathbf{IN}}$. The $nre \times 1$ vectors of curtailment of renewable energy generation $\mathbf{P}^{\mathbf{RC}}$. The $ng \times 1$ vectors of generator real and reactive power injections $\mathbf{P}^{\mathbf{G}}$ and $\mathbf{Q}^{\mathbf{G}}$, respectively. The optimization vector **w** can be written as follows.

$$\mathbf{w} = \begin{bmatrix} \boldsymbol{\theta} \\ \mathbf{V} \\ \mathbf{P}^{\mathbf{RC}} \\ \mathbf{P}^{\mathbf{DC}} \\ \mathbf{Q}^{\mathbf{DC}} \\ \mathbf{Q}^{\mathbf{C}} \\ \mathbf{Q}^{\mathbf{IN}} \\ \mathbf{P}^{\mathbf{G}} \\ \mathbf{Q}^{\mathbf{G}} \end{bmatrix} \tag{5.40}$$

The objective function (5.36) is simply a summation of individual cost functions of each generator $f_g^{\,P}$ for real power, $f_{re}^{\,RC}$ for curtailment of renewable energy generation and f_i^{DC} for curtailment of load.

$$\min_{\substack{\boldsymbol{\theta},\ \mathbf{V},\ \mathbf{P}^{\mathbf{RC}},\ \mathbf{P}^{\mathbf{DC}},\ \mathbf{Q}^{\mathbf{DC}},\\ \mathbf{Q}^{\mathbf{C}},\ \mathbf{Q}^{\mathbf{IN}},\ \mathbf{P}^{\mathbf{G}},\ \mathbf{Q}^{\mathbf{G}}}} \sum_{g=1}^{ng} f_g^P\left(P_g\right) + \sum_{re}^{nre} f_{re}^{RC}\left(P_{re}^{RC}\right) + \sum_{i}^{nb} f_i^{DC}\left(P_i^{DC}\right) \tag{5.41}$$

For the equality constraints in (5.37), they are simply the full set of 2 × nb nonlinear real and reactive power balance equations as presented below.

$$\begin{aligned} & g^P\left(\theta_i,\ V_i,\ P_g,\ P_i^{DC}, P_{re}^{RC}\right) = \\ & \qquad P_i\left(\theta_i,\ V_i\right) + P_i^D - P_i^{DC} - \sum_{g\in i} P_g - \sum_{re\in i} P_{re}^R + \sum_{re\in i} P_{re}^{RC} = 0 \end{aligned} \tag{5.42}$$

$$\begin{aligned} & g^Q\left(\theta_i,\ V_i,\ Q_g,\ Q_i^{C},\ Q_i^{IN},\ Q_i^{DC}\right) = \\ & \qquad Q_i\left(\theta_i,\ V_i\right) + Q_i^D - Q_i^{DC} - \sum_{g\in i} Q_g - Q_i^C + Q_i^{IN} = 0 \end{aligned} \tag{5.43}$$

The inequality constraints (5.38) consist of two sets of nl branch flow limits as nonlinear functions of the bus voltage angles and magnitudes, one for the “from” end and one for the “to” end of each branch.

$$h^{fr}\left(\theta_i,\ V_i\right)=\left|S^{fr}\left(\theta_i,\ V_i\right)\right|-\mathbf{S}^{\mathbf{max}}\leq 0 \tag{5.44}$$

$$h^{to}\left(\theta_i,\ V_i\right)=\left|S^{to}\left(\theta_i,\ V_i\right)\right|-\mathbf{S}^{\mathbf{max}}\leq 0 \tag{5.45}$$

The variable limits (5.39) include an equality constraint on any reference bus angle, upper and lower limits on all bus voltage magnitudes, real and reactive power limits of generators, reactive power compensation limits, curtailment of renewable energy generation and curtailments of real and reactive power demands as follows.

$$\theta_i^{\min}\leq\theta_i\leq\theta_i^{\max},\quad i\in I_{ref} \tag{5.46}$$

$$V_i^{\min}\leq V_i\leq V_i^{\max},\quad i=1,\ldots,nb \tag{5.47}$$

$$P_g^{\min}\leq P_g\leq P_g^{\max},\quad g=1,\ldots,ng \tag{5.48}$$

$$Q_g^{\min}\leq Q_g\leq Q_g^{\max},\quad g=1,\ldots,ng \tag{5.49}$$

$$Q_i^{C\min}\leq Q_i^{C}\leq Q_i^{C\max},\quad i=1,\ldots,nb \tag{5.50}$$

$$Q_i^{IN\min}\leq Q_i^{IN}\leq Q_i^{IN\max},\quad i=1,\ldots,nb \tag{5.51}$$

$$0\leq P_{re}^{RC}\leq P_{re}^{R},\quad re=1,\ldots,nre \tag{5.52}$$

$$0\leq P_i^{DC}\leq P_i^{D},\quad i=1,\ldots,nb \tag{5.53}$$

$$0\leq Q_i^{DC}\leq Q_i^{D},\quad i=1,\ldots,nb \tag{5.54}$$

For the algorithm used to solve AC OPF, various nonlinear programming for optimal power flow in MATPOWER version 5.1 are tested in order to find the minimum computation time among the all algorithms. Each algorithm of AC OPF is tested on IEEE 24 buses system [32]. The test is running on an Intel Core i5 3.0 GHz processor based computer. The results of computation time are presented as shown in Table 5.4.

Table 5.4 Computation time of various algorithms

Algorithm	Primal/dual interior point	Trust region reflective	Active set	Interior point	Sequential quadratic programming
Computation time (s)	0.140	0.789	63.962	0.431	0.364

From Table 5.4, the algorithm which provides the lowest computation time is primal/dual interior point. Therefore, this algorithm is selected for solving subproblem by AC OPF. The detail of primal/dual interior point for OPF can be investigated in [92].

5.3 Evaluation of the Expansion Plan Robustness

In the actual situation, there are various combinations of intermittent renewable energy generation and loads. Although the expansion plan from the proposed RTEP can guarantee the feasibility of all selected scenarios from the proposed scenario selection method, it does not mean that the expansion plan can guarantee the feasibility of all combinations of uncertain variables. In order to measure the number of the feasibility of each combination which is also called system robustness, this dissertation uses the renewable energy generation and loads data of each hour in a target year for evaluating the robustness of the expansion plan. To evaluate the robustness, every hourly value of renewable energy generation and loads in a target year is executed by the formulation (5.55)-(5.67).

Objective function:

$$Minimize\left(\sum_{g=1}^{ng} c_g P_g + \sum_{re=1}^{nre} wr_{re} P_{re}^{RC} + \sum_{i=1}^{nb} wd_i P_i^{DC}\right) \tag{5.55}$$

Subject to:

Real and reactive powers balance:

$$\sum_{g\in i} P_g + \sum_{re\in i}\left(P_{re}^{R} - P_{re}^{RC}\right) - \left(P_i^{D} - P_i^{DC}\right) = P_i, \quad i = 1,...,nb \tag{5.56}$$

$$\sum_{g\in i} Q_g + Q_i^C - Q_i^{IN} - \left(Q_i^D - Q_i^{DC}\right) = Q_i, \quad i = 1,...,nb \tag{5.57}$$

Bus voltage limit:

$$V_i^{\min} \le V_i \le V_i^{\max}, \quad i = 1,...,nb \tag{5.58}$$

Apparent power flow limit:

$$S_{ij,n}^{fr} \le S_{ij,n}^{\max} \;, \quad n = 1,...,anl \tag{5.59}$$

$$S_{ij,n}^{to} \le S_{ij,n}^{\max}, \quad n = 1,...,anl \tag{5.60}$$

Real and reactive power generation limit:

$$P_g^{\min} \le P_g \le P_g^{\max}, \quad g = 1,...,ng \tag{5.61}$$

$$Q_g^{\min} \le Q_g \le Q_g^{\max}, \quad g = 1,...,ng \tag{5.62}$$

Reactive power compensation limit:

$$Q_i^{C\min} \le Q_i^C \le Q_i^{C\max}, \quad i = 1,...,nb \tag{5.63}$$

$$Q_i^{IN\min} \le Q_i^{IN} \le Q_i^{IN\max}, \quad i = 1,...,nb \tag{5.64}$$

Curtailment of renewable energy generation and loads limit:

$$0 \le P_{re}^{RC} \le P_{re}^R, \quad re = 1,...,nre \tag{5.65}$$

$$0 \le P_i^{DC} \le P_i^D, \quad i = 1,...,nb \tag{5.66}$$

$$0 \le Q_i^{DC} \le Q_i^D, \quad i = 1,...,nb \tag{5.67}$$

The variables P_i and Q_i can be defined by (5.14)-(5.17) and the variables S_{ij}^{fr} and S_{ij}^{to} can be defined by (2.30)-(2.35). After all hourly values are executed; expansion plan robustness will be evaluated by (5.68).

$$Robustness(\%) = \frac{H}{nhy} \times 100 \qquad (5.68)$$

where H is the number of hours that renewable energy generation and load are not curtailed.

5.4 The Method to Ensure the System Robustness at 100 Percent

As mentioned in the previous section, although the expansion plan from the proposed RTEP can guarantee the feasibility of all selected scenarios from the proposed scenario selection method, it does not mean that the expansion plan can guarantee the feasibility of all combinations of uncertain variables. In other words, there is no evidence that the expansion plan can guarantee the system robustness at 100 percent. Therefore, the method to ensure that the expansion plan can guarantee the system robustness at 100 percent is proposed in this dissertation. The procedure of the method is described as following steps.

Step 1: After the system configuration is obtained from ATS, the system robustness is evaluated as explained in Section 5.3. If the robustness is 100 percent, terminate the process; otherwise, go to step 2.

Step 2: Collect the all hours that cause the curtailment of renewable energy generation or curtailment of loads and the hours that the calculation of OPF is failed.

Step 3: Select the values of renewable energy generation and loads of all hours obtained from Step 2 as the considered scenarios for replanning.

Step 4: Add the considered scenarios from Step 3 into the previous considered scenarios.

Step 5: Replan RTEP based ATS optimization by using the obtained system configuration from Step 1 and the new set of considered scenarios from Step 4. After that, go to Step 1.

CHAPTER 6
NUMERICAL RESULTS AND DISCUSSION

In this chapter, the ATS based method for solving both TEP and RTEP problems in this dissertation will be tested on IEEE-24 buses [32] and the modified northeastern Thailand 75 buses systems which the original one is obtained by the research work [10]. The objective of the tests is to illustrate the capability of the proposed methods to cope with TEP and RTEP. Basic configurations of the IEEE-24 buses system is shown in Figure 6.1. Detailed data of the test systems is shown in the appendix. It should be noted that the power demand and the generation capacity data are the forecasted values of a target year for planning [10], [32].

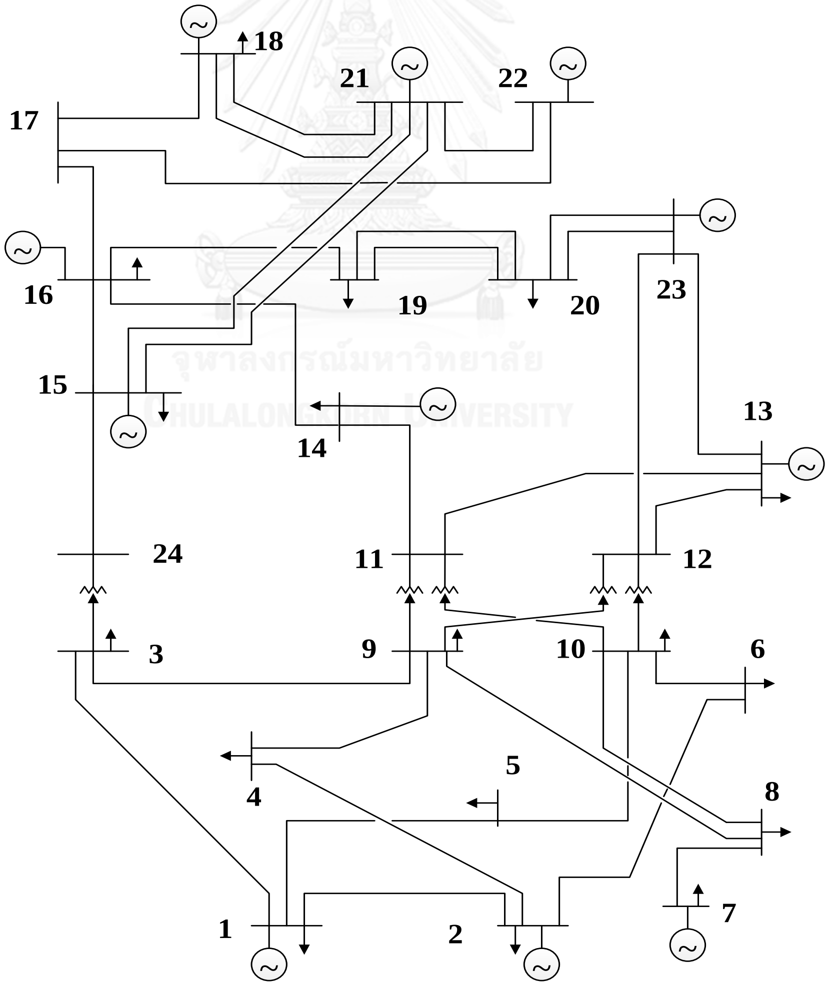

Figure 6.1 Basic configuration of IEEE-24 buses system

The life-time of all transmission line candidates is assumed to be 25 years, whereas the interest rate is 10% per year. The generation costs defined in the appendix are expressed in US$/KWh. The generated active power has to be multiplied by the plant factor before calculating the operating cost. It is assumed that the plant factor is 60%.

For intermittent renewable energy source, the parameters for evaluating the performance of each wind source are defined as follows: cut in speed (V_{CI}) is 4 m/s, rated speed (P_{rated}) is 13.62 m/s, and cut out speed (V_{CO}) is 25 m/s [29]. For solar source, the parameters are defined as follows: a certain irradiation point (R_c) is 150 W/m^2, the solar irradiation in the standard environment (G_{std}) is 1000 W/m^2 [76]. For wind speed (V_{SP}) and solar radiation (G_{bh}), the wind speed and solar radiation from Nakhon Ratchasima province, Thailand are selected for testing on both IEEE-24 buses and northeastern Thailand systems. The data of wind speed and solar radiation are obtained from the meteorological department of Thailand [93]. In this dissertation, it is assumed that the magnitude and pattern of solar radiation and wind speed for planning period. Therefore, the magnitude and pattern of solar radiation and wind speed of the future year are the same as the magnitude and pattern of solar radiation and wind speed of the present year.

For the ATS parameters, each parameter is set as follows: the number of neighbor solutions (*num_neighbor*) is 20, and the maximum repetition of the solutions (*f_max*) is 3. For solving AC OPF which is NLP problem, the AC OPF based on primal/dual algorithm which is a tool in MATPOWER version 5.1 is used as a solver. All programs are written on MATLAB R2011a which runs on an Intel Core i5 3.0 GHz processor based computer.

6.1 Single Stage TEP

Objective

The objectives of the test are listed as shown below.

(a) To illustrate the origin of the result of TEP based on ATS.
(b) To compare the result of TEP based on ATS method with the results from other methods of the previous research works.

(c) To show the benefit of cost saving when the operating cost is considered in the TEP problem.

Details of the test

The single stage TEP is formulated by using AC model as presented in Subsection 2.6.2 and solved by the proposed method based on ATS which is described in Section 5.2. For this case of the single stage TEP, it is assumed that the length of planning period is one year as same as the reference [10] in order to compare the results.

To illustrate the origin of the result of TEP based on ATS, the IEEE-24 buses system is used to explain. The test is design based on the comparison of the solution which can be measured the quality by the solution point (*SP*). The comparison of *SP* of each *iter_max* value is illustrated in Table 6.1.

Table 6.1 The comparison of *SP* of each *iter_max* value

iter_max	*SP*
250	18.6282
500	19.2455
1,000	19.7805
2,000	19.7805
4,000	19.7805
8,000	19.7805

The initial value of *iter_max* in the test is assumed to be 250. The next *iter_max* is defined based on the previous value of *iter_max* multiply by 2. This test will be stopped when the obtained solution is repeated equal to 3 times. This criterion will be applied for every test.

From Table 6.1, when the *iter_max* is increased, the *SP* will increase as well. However, when the *iter_max* is 1,000 or higher, the *SP* is still 19.7805. It can be said that, the solution which has the *SP* 19.7805 is the expected global optimal solution.

The detail of the first three local optimal solutions ranking by the *SP* when the *iter_max* is defined equal to 8,000 is illustrated in Table 6.2.

Table 6.2 Local optimal solutions from ATS

Local optimal solution	From bus	To bus	Number of lines	*SP*
1	6	10	1	19.7805
	7	8	2	
2	6	10	2	19.7074
	7	8	2	
3	6	10	2	19.2455
	7	8	2	
	11	13	1	
	1	8	1	

According to the *SP* of each local optimal solution in Table 6.2, the best local optimal solution is the local optimal solution number 1 which provides the *SP* 19.7805. Therefore, this solution is selected as the expected global optimal solution of the planning.

To compare the result of single stage TEP for IEEE-24 buses system with the results from other research works [10] and [44], the operating cost is neglected in the objective function which is same as the references [10] and [44]. Detail of the expansion plan from the proposed method is shown in the Table 6.3. The computation time is 32.92 minutes. It should be noted that the expansion plan from the proposed method is same as the result in references [10] and [44]. The comparison of the results from proposed method, references [10] and [44] is presented in Table 6.4.

For the northeastern Thailand system, the expansion plans obtained from the proposed method when neglecting operating cost in the objective function is presented in Table 6.5. The *SP* and the computation time are 19.57 and 206.67 minutes, respectively.

Table 6.3 Expansion plan of single stage TEP for IEEE-24 buses system when neglecting operating cost

From bus	To bus	Number of lines	Cost (MUS$)
6	10	1	16.00
7	8	2	32.00
Investment cost (MUS$)			48.00
pv_{inv} (MUS$)			6.11
pv_{opr} (MUS$)			1,893.70
Total cost (MUS$)			1,899.81

Table 6.4 Comparison result of single stage TEP for IEEE-24 buses system when neglecting operating cost

Result	Proposed method based on ATS	Reference [44] based on GA	Reference [10] based on decomposition method
Investment cost (MUS$)	48.00	48.00	48.00
pv_{inv} (MUS$)	6.11	6.11	6.11
pv_{opr} (MUS$)	1,893.70	-	1,893.70

Note: - means that the value does not appear on the reference

To show the benefit from cost saving when the operating cost is taken into account in the TEP problem, the single stage TEP when the operating cost is considered are solved by the proposed method on IEEE-24 buses and northeastern Thailand systems. The expansion plans of IEEE-24 buses system is shown in Table 6.6. The SP and the computation time are 7.567 and 58.86 minutes, respectively.

Table 6.5 Expansion plan of single stage TEP for northeastern Thailand system when neglecting operating cost

From bus	To bus	Number of lines	Cost (MUS$)
18	20	1	6.10
2	3	1	18.80
51	52	1	16.90
4	18	1	14.40
5	74	1	21.60
10	61	1	22.10
16	53	1	49.20
Investment cost (MUS$)			149.10
pv_{inv} (MUS$)			18.98
pv_{opr} (MUS$)			988.11
Total cost (MUS$)			1,007.09

Table 6.6 Expansion plan of single stage TEP for IEEE-24 buses system when considering operating cost

From bus	To bus	Number of lines	Cost (MUS$)
6	10	1	16.00
7	8	2	32.00
16	17	1	36.00
14	16	1	54.00
Investment cost (MUS$)			138.00
pv_{inv} (MUS$)			17.56
pv_{opr} (MUS$)			1,805.87
Total cost (MUS$)			1,823.43

For the northeastern Thailand system, the expansion plans obtained from the proposed method when considering operating cost in the objective function is presented in Table 6.7. The *SP* and the computation time are 11.43 and 432.93 minutes, respectively.

Table 6.7 Expansion plan of single stage TEP for northeastern Thailand system when considering operating cost

From bus	To bus	Number of lines	Cost (MUS$)
3	4	1	5.80
31	32	1	18.80
2	3	1	18.80
1	61	1	4.00
41	59	2	14.80
16	60	1	19.00
4	71	1	39.70
1	10	1	20.60
3	20	1	16.70
13	14	1	22.30
18	25	1	35.20
3	18	1	16.00
19	52	1	52.10
Investment cost (MUS$)			283.80
pv_{inv} (MUS$)			36.12
pv_{opr} (MUS$)			936.74
Total cost (MUS$)			972.86

Discussion

From ATS algorithm, the exactly global optimal solution cannot be guaranteed. However, the expected global optimal solution can be obtained from

ATS. The probability to obtain the global optimal solution is directly proportional to the values of *iter_max*.

From Table 6.4, the result of single stage TEP for IEEE-24 buses system when neglecting operating cost from the proposed method is same as the results from references [10] and [44]. It can be said that the proposed method based on ATS is reliable to solve TEP problem.

When operating cost is considered in the objective function of TEP problem, the power of generation is properly dispatched. Therefore, the operating cost for the IEEE-24 bus system is decreased by 4.64% compared with the TEP problem when the operating cost is neglected. The evidence of this result is shown in Table 6.3 and Table 6.6. It can be noticed that the selected transmission lines in the expansion plans of both cases are different. The investment cost in the case of neglecting operating cost is lower; however, the total cost is higher.

For the northeastern Thailand system, as the same as the IEEE-24buses system, the expansion plan of single stage TEP when neglecting operating cost differs from the expansion plan of single stage TEP when considering operating cost. As shown in Table 6.5 and Table 6.7, the operating cost of TEP problem when considering operating cost is decreased by 5.20% compared with the TEP problem when the operating cost is neglected. Even if the investment cost in the case of considering operating cost is higher than the case of neglecting operating cost, the total cost is lower. It can be conclude that the operating cost should be taken into account in the objective function of TEP problem in order to save the total cost.

6.2 Single Stage TEP with Renewable Energy Sources

Objective

The objectives of the test are listed as shown below.

(a) To compare the results of TEP when considering different values of renewable energy generation for planning

Details of the test

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 and has not been well discussed in the previous works. In order to select the suitable value, the three values of renewable energy generation consisting of zero, half and full capacity are selected to test. Therefore, there are three test cases which denoted by TEP_ZERO, TEP_HALF and TEP_FULL according to the zero, half capacity and full capacity values of renewable energy generation, respectively. It should be noted that operating cost is taken into account for all three cases. For the case of single stage TEP with renewable energy sources, it is assumed that the length of planning period is nine years.

For IEEE-24 buses system, renewable energy sources are assumed to be two wind farms as same as reference [29] and [30]. Theses wind farms are assumed to be installed instead of conventional generators at bus 7 and bus 22, respectively. The capacity of each wind farm is assumed to be 990 MW. The wind speed time frame at bus 7 is assumed to be the same as the wind speed time frame of Nakhon Ratchasima province. Meanwhile, the wind speed time frame at bus 22 is assumed to be shifted forward 1 hour compared with the wind speed time frame of Nakhon Ratchasima province.

The expansion plans of the TEP_ZERO, TEP_HALF and TEP_FULL are shown in Table 6.8, Table 6.9 and Table 6.10, respectively. The result comparison is shown in Table 6.11. The *SP*s of these three cases are 7.280, 9.621 and 11.924, respectively and the computation time of each case is 58.86 minutes.

Table 6.8 Expansion plan of single stage TEP_ZERO for IEEE-24 buses system

From bus	To bus	Number of lines	Cost (MUS$)
6	10	2	32.00
7	8	1	16.00
2	8	2	66.00
1	8	1	35.00
8	9	1	43.00
17	18	1	20.00
10	11	1	50.00
12	13	2	132.00
14	16	1	54.00
Investment cost (MUS$)			448.00
pv_{inv} (MUS$)			326.40
pv_{opr} (MUS$)			9,161.17
Wind operating cost (MUS$) [1]			3,416.06
Total cost (MUS$)			12,903.63
Robustness (%)			70.48

[1] Calculated based on Thailand feed in tariff rates of wind energy at 0.179 US$/kWhr (year 2015) [95]

Table 6.9 Expansion plan of single stage TEP_ HALF for IEEE-24 buses system

From bus	To bus	Number of lines	Cost (MUS$)
6	10	1	16.00
1	2	2	6.00
10	11	1	50.00
16	17	1	36.00
12	13	1	66.00
17	18	2	40.00
9	11	1	50.00
5	10	1	23.00
15	24	1	72.00
14	16	1	54.00
15	21	2	136.00
Investment cost (MUS$)			549.00
pv_{inv} (MUS$)			399.99
pv_{opr} (MUS$)			9,182.64
Wind operating cost (MUS$) [1]			2,958.77
Total cost (MUS$)			12,541.40
Robustness (%)			30.56

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[1] Calculated based on Thailand feed in tariff rates of wind energy at 0.179 US$/kWhr (year 2015) [95]

Table 6.10 Expansion plan of single stage TEP_ FULL for IEEE-24 buses system

From bus	To bus	Number of lines	Cost (MUS$)
7	8	1	16.00
1	2	1	3.00
6	7	1	50.00
16	17	1	36.00
3	24	1	50.00
11	13	1	66.00
9	12	1	50.00
2	8	1	33.00
14	16	1	54.00
15	21	1	68.00
12	23	1	134.00
16	23	1	114.00
Investment cost (MUS$)			674.00
pv_{inv} (MUS$)			491.06
pv_{opr} (MUS$)			9,058.70
Wind operating cost (MUS$) [1]			3,726.87
Total cost (MUS$)			13,276.63
Robustness (%)			41.86

[1] Calculated based on Thailand feed in tariff rates of wind energy at 0.179 US$/kWhr (year 2015) [95]

Table 6.11 Result comparison of single stage TEP with renewable energy for IEEE 24-buses system

Case	TEP_ZERO	TEP_ HALF	TEP_ FULL
Investment cost (MUS$)	448.00	549.00	674.00
pv_{inv} (MUS$)	326.40	399.99	491.06
pv_{opr} (MUS$)	9,161.17	9,182.64	9,058.70
Wind operating cost (MUS$) [1]	3,416.06	2,958.77	3,726.87
Total Cost (MUS$)	12,903.63	12,541.4	13,276.63
Robustness (%)	70.48	30.56	41.86
Computation time (minutes)	58.86	58.86	58.86

[1] Calculated based on Thailand feed in tariff rates of wind energy at 0.179 US$/kWhr (year 2015) [95]

For the northeastern Thailand system, wind and solar sources are considered in the planning. These data are collected from “geographic information system (GIS) for alternative energy & energy efficiency” which is invented by the department of alternative energy development and efficiency (DEDE), ministry of energy in Thailand. The accumulated date is 4th April 2015. The details of location and capacity of each wind and solar source expressed as are shown in Table 6.12. For the time frames of solar radiation and wind speed, the time frames of each bus is assumed as illustrated in Table 6.13 for solar radiation and Table 6.14 for wind speed.

Because the northeastern Thailand system given from reference [10] does not provide the hourly load data, the load data pattern of northeastern Thailand in the year 2012 [93] are used to generate the hourly load data for testing on northeastern Thailand system. The technique to generate is finding the ratio between hourly load and peak load of the year 2012. After that, the obtained ratio of each hour is multiplied by the peak load of the northeastern Thailand system to get the hourly load data.

Table 6.12 Location and capacity of each wind and solar source installed in the northeastern Thailand system

Bus	Type Solar (MW)	 Wind (MW)	Bus	Type Solar (MW)	 Wind (MW)	Bus	Type Solar (MW)	 Wind (MW)
1	3.18	0.00	26	0.00	0.00	51	3.20	0.00
2	2.94	0.00	27	0.00	0.00	52	3.20	0.00
3	1.47	0.00	28	5.88	0.00	53	0.00	0.00
4	1.47	0.00	29	5.88	0.00	54	0.00	0.00
5	0.00	0.00	30	20.27	0.00	55	5.88	0.00
6	29.00	0.00	31	20.27	0.00	56	5.88	0.00
7	0.00	0.00	32	40.53	180.00	57	16.99	0.00
8	5.88	0.00	33	0.00	0.00	58	0.00	2.50
9	6.88	0.00	34	0.00	0.00	59	4.50	0.00
10	35.76	0.00	35	0.00	0.00	60	0.00	0.00
11	5.00	2.30	36	0.00	0.00	61	5.88	0.00
12	5.00	4.60	37	0.00	0.00	62	5.88	0.00
13	0.00	0.00	38	0.00	0.00	63	0.00	0.00
14	19.64	0.00	39	2.00	0.00	64	0.00	0.00
15	0.00	0.00	40	2.01	0.00	65	5.88	0.00
16	2.90	0.00	41	0.00	0.00	66	0.00	0.00
17	0.00	0.00	42	0.00	0.00	67	0.00	0.00
18	5.88	0.00	43	0.00	0.00	68	4.87	0.00
19	12.70	0.00	44	5.88	0.00	69	4.87	0.00
20	3.92	0.00	45	0.95	0.00	70	9.74	0.00
21	11.76	0.00	46	0.00	0.00	71	7.80	0.00
22	0.00	0.00	47	0.00	0.00	72	7.80	0.00
23	0.00	0.00	48	0.00	0.00	73	0.00	0.00
24	11.76	0.00	49	5.88	0.00	74	0.00	0.00
25	1.95	0.00	50	1.60	0.00	75	0.00	0.00

Table 6.13 Time frame of solar radiation for northeastern Thailand system

Bus	Solar capacity (MW)	Shifted time frame compared with the time frame of Nakhon Ratchasima (hr.)	Bus	Solar capacity (MW)	Shifted time frame compared with the time frame of Nakhon Ratchasima (hr.)
1	3.18	0	32	40.53	+1
2	2.94	+1	39	2.00	-1
3	1.47	-1	40	2.01	0
4	1.47	0	44	5.88	+1
6	29.00	+1	45	0.95	-1
8	5.88	-1	49	5.88	0
9	6.88	0	50	1.60	+1
10	35.76	+1	51	3.20	-1
11	5.00	-1	52	3.20	0
12	5.00	0	55	5.88	+1
14	19.64	+1	56	5.88	-1
16	2.90	-1	57	16.99	0
18	5.88	0	59	4.50	+1
19	12.70	+1	61	5.88	-1
20	3.92	-1	62	5.88	0
21	11.76	0	65	5.88	+1
24	11.76	+1	68	4.87	-1
25	1.95	-1	69	4.87	0
28	5.88	0	70	9.74	+1
29	5.88	+1	71	7.80	-1
30	20.27	-1	72	7.80	0
31	20.27	0			

Note: + is “shift forward”, - is “shift backward”

Table 6.14 Time frame of wind speed for northeastern Thailand system

Bus	Wind capacity (MW)	Shifted time frame compared with the time frame of Nakhon Ratchasima (hr.)
11	2.3	0
12	4.6	+1
32	180	-1
58	2.5	0

Note: + is “shift forward”, - is “shift backward”

The expansion plans of the TEP_ZERO, TEP_HALF and TEP_FULL are shown in Table 6.15, Table 6.16 and Table 6.17, respectively. The result comparison is shown in Table 6.18. The *SP*s of TEP_ZERO, TEP_HALF and TEP_FULL are 12.40, 12.96 and 13.60, respectively and the computation time of each case is 435.87 minutes.

Table 6.15 Expansion plan of single stage TEP_ZERO for northeastern Thailand system

From bus	To bus	Number of lines	Cost (MUS$)
3	4	1	5.80
31	32	1	18.80
2	3	1	18.80
1	61	1	4.00
41	59	2	14.80
16	60	1	19.00
4	71	1	39.70
1	10	1	20.60
3	20	1	16.70
13	14	1	22.30
18	25	1	35.20
3	18	1	16.00
19	52	1	52.10
Investment cost (MUS$)			283.80
pv_{inv} (MUS$)			206.77
pv_{opr} (MUS$)			4,592.04
Wind operating cost (MUS$) [1]			116.39
Solar operating cost (MUS$) [2]			305.66
Total cost (MUS$)			5,220.86
Robustness (%)			92.85

[1] Calculated based on Thailand feed in tariff rates of wind energy at 0.179 US$/kWhr (year 2015) [95]

[2] Calculated based on Thailand feed in tariff rates of solar energy at 0.167 US$/kWhr (year 2015) [95]

Table 6.16 Expansion plan of single stage TEP_ HALF for northeastern Thailand system

From bus	To bus	Number of lines	Cost (MUS$)
3	4	1	5.80
31	32	1	18.80
2	3	1	18.80
11	12	2	37.60
41	59	1	7.40
69	70	1	18.80
4	18	1	14.40
4	67	1	12.40
4	72	1	33.90
61	62	1	18.80
36	53	1	13.20
27	65	1	16.80
21	51	1	64.80
Investment cost (MUS$)			281.50
pv_{inv} (MUS$)			205.09
pv_{opr} (MUS$)			4,458.84
Wind operating cost (MUS$) [1]			120.44
Solar operating cost (MUS$) [2]			327.04
Total cost (MUS$)			5,111.41
Robustness (%)			87.94

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[1] Calculated based on Thailand feed in tariff rates of wind energy at 0.179 US$/kWhr (year 2015) [95]

[2] Calculated based on Thailand feed in tariff rates of solar energy at 0.167 US$/kWhr (year 2015) [95]

Table 6.17 Expansion plan of single stage TEP_ FULL for northeastern Thailand system

From bus	To bus	Number of lines	Cost (MUS$)
3	4	1	5.80
2	3	1	18.80
74	75	1	18.80
1	61	1	4.00
44	54	1	21.60
25	50	1	17.60
24	37	1	32.20
18	25	1	35.20
44	72	1	41.00
Investment cost (MUS$)			195.00
pv_{inv} (MUS$)			142.07
pv_{opr} (MUS$)			4,523.86
Wind operating cost (MUS$)[1]			120.45
Solar operating cost (MUS$)[2]			327.04
Total cost (MUS$)			5,113.42
Robustness (%)			83.32

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[1] Calculated based on Thailand feed in tariff rates of wind energy at 0.179 US$/kWhr (year 2015) [95]

[2] Calculated based on Thailand feed in tariff rates of solar energy at 0.167 US$/kWhr (year 2015) [95]

Table 6.18 Result comparison of single stage TEP with renewable energy for northeastern Thailand system

Case	TEP_ZERO	TEP_ HALF	TEP_ FULL
Investment cost (MUS$)	283.80	281.50	195.00
pv_{inv} (MUS$)	206.77	205.09	142.07
pv_{opr} (MUS$)	4,592.04	4,458.84	4,523.86
Wind operating cost (MUS$) [1]	116.39	120.44	120.45
Solar operating cost (MUS$) [2]	305.66	327.04	327.04
Total Cost (MUS$)	5,220.86	5,111.41	5,113.42
Robustness (%)	92.85	87.94	83.32
Computation time (minutes)	435.87	435.87	435.87

[1] Calculated based on Thailand feed in tariff rates of wind energy at 0.179 US$/kWhr (year 2015) [95]

[2] Calculated based on Thailand feed in tariff rates of solar energy at 0.167 US$/kWhr (year 2015) [95]

Discussion

From the results of these three cases from both systems, it can be observed that considering different renewable energy values for planning can make a great difference to the planning schemes and the robustness percent. This indicates the importance of considering the intermittent renewable energy sources in the TEP problem.

For the robustness viewpoint in IEEE-24 buses system, the robustness in the case of considering the zero value of renewable energy sources is the highest. The reason can be explained by Table 6.19. It can be noticed that the number of hours that wind sources generating 0% is the highest. Consequently, the expansion plan considering the zero value of renewable energy sources can satisfy the highest number of hours as well. For the case of northeastern Thailand system, the robustness in the case of considering the zero value of renewable energy sources is the highest same as the case of IEEE-24 buses system. The reason can be explained by Table 6.20. It can be noticed that the number of hours that renewable energy sources generating between 0% to 25% is the highest and the number of hours that renewable energy sources generating 0 is the second-highest. Consequently, the expansion plan considering the zero value of renewable energy sources can satisfy the highest number of hours. However, each the robustness of the planning scheme cannot reach to 100%. It can be said that it is unsuitable to solve TEP considering intermittent renewable energy generation and loads by conventional method.

Table 6.19 The number of hours of wind sources generation for IEEE-24 buses system

Generation of wind sources (WP) compared with its maximum capacity (%)	Number of hours	Number of hours compared with total hours in a year (%)
0	3,358	39
0<WP<=25	2,205	25
25<WP<=50	525	6
50<WP<=75	196	2
75<WP<100	82	1
100	2,370	27

Table 6.20 The number of hours of renewable energy sources generation for northeastern Thailand system

Generation of renewable energy sources (RE) compared with its maximum capacity (%)	Number of hours	Number of hours compared with total hours in a year (%)
0	2,400	27
0<RE<=25	4,429	50
25<RE<=50	1,302	15
50<RE<=75	574	7
75<RE<100	79	1
100	0	0

6.3 Single Stage RTEP with Renewable Energy Sources

Objective

The objectives of this test are listed below.

(a) To show the benefit of system robustness when using RTEP instead of TEP

(b) To compare the results of RTEP when using different method for selecting scenario

Details of the test

As mentioned in Subsection 2.6.3.1, 2.6.3.2 and Section 5.1, there are three methods for selecting scenario for planning. The first method is selecting minimum and maximum values of renewable energy generation and loads. The second method is selecting the values of renewable energy generation and loads by using Taguchi's orthogonal array testing (TOAT). The third method is the proposed method which selects the values of renewable energy generation and loads based on the scenario selection indicator (SSI) as mentioned in Section 5.1. Therefore, there are three test cases according to the scenario selection methods. The three test cases are denoted by RTEP_MIN_MAX, RTEP_TOAT and RTEP_PROPOSED, respectively.

For the case of this single stage RTEP, it is assumed that the length of planning period is nine years in order to compare the result with the result from multistage RTEP which the length of planning period is assumed to be nine years as well. For IEEE-24 buses system, the location and capacity of each wind farm are adopted from the Section 6.2. The expansion plan of the RTEP_MIN_MAX is shown in Table 6.21. The *SP* and the computation time are 12.079 and 187.92 minutes, respectively.

In the case of RTEP_TOAT for IEEE-24 buses system, the total number of uncertain variables in this system is 19 consisting of 2 renewable energy sources (wind farms) and 17 loads. The level of each uncertain variable is defined to 2 (zero and maximum capacity values for renewable energy generation and minimum and maximum values for loads). Therefore, orthogonal array $L_{32}(2^{19})$ [66] is chosen to generate the scenarios. The orthogonal array after mapping factors is shown in Table

6.22. The expansion plan of the RTEP_TOAT is shown in Table 6.23. The *SP* and the computation time are 11.687 and 1,103.36 minutes, respectively.

Table 6.21 Expansion plan of single stage RTEP_MIN_MAX
for IEEE-24 buses system

From bus	To bus	Number of lines	Cost (MUS$)
6	10	2	32.00
7	8	2	32.00
2	8	2	66.00
1	8	1	35.00
8	9	1	43.00
17	18	2	40.00
10	11	1	50.00
4	9	1	27.00
1	5	2	44.00
5	10	1	23.00
15	16	1	24.00
14	16	1	54.00
6	7	2	100.00
6	10	2	32.00
Investment cost (MUS$)			656.00
pv_{inv} (MUS$)			477.95
pv_{opr} (MUS$)			8,956.25
Wind operating cost (MUS$) [1]			4,361.94
Total cost (MUS$)			13,796.14
Robustness (%)			74.50

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[1] Calculated based on Thailand feed in tariff rates of wind energy at 0.179 US$/kWhr (year 2015) [95]

Table 6.22 The orthogonal array after mapping factors for IEEE-24 buses system

Testing scenario	Load at bus 1	Load at bus 2	Load at bus 3	Load at bus 4	Load at bus 5	Load at bus 6	Load at bus 7	Load at bus 8	Load at bus 9	Load at bus 10	Load at bus 13	Load at bus 14	Load at bus 15	Load at bus 16	Load at bus 18	Load at bus 19	Load at bus 20	Wind farm at bus 7	Wind farm at bus 22
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1
3	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0
4	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
5	0	0	0	1	1	1	1	0	0	0	0	1	1	1	1	0	0	0	0
6	0	0	0	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1
7	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
8	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	1	1	1	1
9	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1
10	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1	1	1	0	0
11	0	1	1	0	0	1	1	1	1	0	0	1	1	0	0	0	0	1	1
12	0	1	1	0	0	1	1	1	1	0	0	1	1	0	0	1	1	0	0
13	0	1	1	1	1	0	0	0	0	1	1	1	1	0	0	0	0	1	1
14	0	1	1	1	1	0	0	0	0	1	1	1	1	0	0	1	1	0	0
15	0	1	1	1	1	0	0	1	1	0	0	0	0	1	1	0	0	1	1
16	0	1	1	1	1	0	0	1	1	0	0	0	0	1	1	1	1	0	0
17	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1
18	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	1	0	1	0
19	1	0	1	0	1	0	1	1	0	1	0	1	0	1	0	0	1	0	1
20	1	0	1	0	1	0	1	1	0	1	0	1	0	1	0	1	0	1	0
21	1	0	1	1	0	1	0	0	1	0	1	1	0	1	0	0	1	0	1
22	1	0	1	1	0	1	0	0	1	0	1	1	0	1	0	1	0	1	0
23	1	0	1	1	0	1	0	1	0	1	0	0	1	0	1	0	1	0	1
24	1	0	1	1	0	1	0	1	0	1	0	0	1	0	1	1	0	1	0
25	1	1	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1	0
26	1	1	0	0	1	1	0	0	1	1	0	0	1	1	0	1	0	0	1
27	1	1	0	0	1	1	0	1	0	0	1	1	0	0	1	0	1	1	0
28	1	1	0	0	1	1	0	1	0	0	1	1	0	0	1	1	0	0	1
29	1	1	0	1	0	0	1	0	1	1	0	1	0	0	1	0	1	1	0
30	1	1	0	1	0	0	1	0	1	1	0	1	0	0	1	1	0	0	1
31	1	1	0	1	0	0	1	1	0	0	1	0	1	1	0	0	1	1	0
32	1	1	0	1	0	0	1	1	0	0	1	0	1	1	0	1	0	0	1

Table 6.23 Expansion plan of single stage RTEP_TOAT
for IEEE-24 buses system

From bus	To bus	Number of lines	Cost (MUS$)
6	10	2	32.00
7	8	3	48.00
2	8	1	33.00
1	8	1	35.00
8	9	1	43.00
3	24	1	50.00
8	10	1	43.00
16	17	2	72.00
9	11	1	50.00
14	16	1	54.00
6	7	1	50.00
12	23	1	134.00
19	20	1	55.00
Investment cost (MUS$)			699.00
pv_{inv} (MUS$)			509.28
pv_{opr} (MUS$)			8,927.40
Wind operating cost (MUS$) [1]			4,392.16
Total cost (MUS$)			13,828.84
Robustness (%)			87.48

[1] Calculated based on Thailand feed in tariff rates of wind energy at 0.179 US$/kWhr (year 2015) [95]

In the case of RTEP_PROPOSED for IEEE-24 buses system, the proposed method for selecting scenarios as presented in Section 5.1 is used. The first 10 highest values of *SSIRG* and *SSIL* are shown in Table 6.24.

Table 6.24 The first 10 highest values of *SSIRG* and *SSIL* for IEEE 24-buses system

For renewable energy generation		For loads	
Hour	*SSIRG*	Hour	*SSIL*
7,787 th	0.3906	8,528 th	0.0744
4,095 th	0.3905	8,610 th	0.0692
203 th	0.3902	8,436 th	0.0687
3,783 th	0.3902	8,434 th	0.0678
4,935 th	0.3902	8,442 th	0.0652
4,119 th	0.3902	8,266 th	0.0640
3,779 th	0.3901	8,276 th	0.0640
4,931 th	0.3900	8,322 th	0.0640
4,115 th	0.3900	8,462 th	0.0635
227 th	0.3899	8,268 th	0.0624

Certainly, more scenarios are considered for planning, more robustness of the planned system will be. However, the computation time will be increased as well. Therefore, the values of renewable energy generation and loads at the hour that provides the highest *SSIRG* and the hour that provides the highest *SSIL* are selected as the considered scenarios. From Table 6.24, the renewable energy generation and loads values at hours “7,787” and “8,528” are selected as the considered scenarios for planning. The expansion plan of the RTEP_PROPOSED is shown in Table 6.25. The *SP* and the computation time are 9.681 and 178.85 minutes, respectively.

Table 6.25 Expansion plan of single stage RTEP_PROPOSED for IEEE-24 buses system

From bus	To bus	Number of lines	Cost (MUS$)
6	10	2	32.00
7	8	2	32.00
2	8	1	33.00
1	8	1	35.00
8	9	1	43.00
10	12	1	50.00
20	23	1	30.00
1	2	1	3.00
3	24	1	50.00
14	16	1	54.00
6	7	2	100.00
1	3	1	55.00
Investment cost (MUS$)			517.00
pv_{inv} (MUS$)			376.67
pv_{opr} (MUS$)			8,966.37
Wind operating cost (MUS$) [1]			4,392.16
Total cost (MUS$)			13,735.20
Robustness (%)			100

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[1] Calculated based on Thailand feed in tariff rates of wind energy at 0.179 US$/kWhr (year 2015) [95]

The comparison of the three RTEP results is shown in Table 6.26.

Table 6.26 Comparison of the three results of RTEP for IEEE 24-buses system

Case	RTEP_MIN_MAX	RTEP_TOAT	RTEP_PROPOSED
Number of considered scenario	4	32	2
Investment cost (MUS$)	656.00	699.00	517.00
pv_{inv} (MUS$)	477.95	509.28	376.67
pv_{opr} (MUS$)	8,956.25	8,927.40	8,966.37
Wind operating cost (MUS$) [1]	4,361.94	4,392.16	4,392.16
Total cost (MUS$)	13,796.14	13,828.84	13,735.20
Robustness (%)	74.50	87.48	100
Computation time (minutes)	187.92	1,103.36	178.85

[1] Calculated based on Thailand feed in tariff rates of wind energy at 0.179 US$/kWhr (year 2015) [95]

For northeastern Thailand system, the location and capacity of solar and wind sources are adopted from the Section 6.2. The expansion plan of the RTEP_MIN_MAX is shown in Table 6.27. The *SP* and the computation time are 15.289 and 1,312.58 minutes, respectively.

Table 6.27 Expansion plan of single stage RTEP_MIN_MAX
for northeastern Thailand system

From bus	To bus	Number of lines	Cost (MUS$)
3	4	1	5.80
30	31	1	7.90
18	20	1	6.10
31	32	1	18.80
18	19	1	18.80
50	51	1	18.80
74	75	1	18.80
51	52	2	33.80
16	50	1	17.40
22	31	1	21.80
4	67	1	12.40
8	46	1	17.30
26	27	1	6.80
61	62	1	18.80
4	71	1	39.70
2	21	1	21.60
11	46	1	23.50
7	38	1	18.50
2	51	1	72.90
18	46	1	30.50
Investment cost (MUS$)			430.00
pv_{inv} (MUS$)			313.29
pv_{opr} (MUS$)			4,530.21
Wind operating cost (MUS$) [1]			120.40
Solar operating cost (MUS$) [2]			327.04
Total cost (MUS$)			5,290.95
Robustness (%)			93.67

[1] Calculated based on Thailand feed in tariff rates of wind energy at 0.179 US$/kWhr (year 2015) [95]

[2] Calculated based on Thailand feed in tariff rates of solar energy at 0.167 US$/kWhr (year 2015) [95]

In the case of RTEP_TOAT for northeastern Thailand system, because the total number of uncertain variables in this system is 101 consisting of 41 solar sources, 4 wind sources and 56 loads, there is no orthogonal array that cannot fit this number of uncertain variables. Therefore, the number of uncertain variables should be reduced by choosing only the variables which are significantly affected the system. The first 6 highest values of renewable energy sources (solar and wind) and the first 6 highest values of loads are assumed to be chosen as the uncertain variables. Consequently, The orthogonal array $L_{16}(2^{15})$ [66] is chosen to generate the scenarios. The orthogonal array after mapping factors is shown in Table 6.28. The expansion plan of the RTEP_TOAT is shown in Table 6.29. The *SP* and the computation time are 13.382 and 5,120.32 minutes, respectively.

Table 6.28 The orthogonal array after mapping factors
for northeastern Thailand system

Testing scenario	Load at bus 11	Load at bus 18	Load at bus 28	Load at bus 31	Load at bus 39	Load at bus 69	Solar at bus 6	Solar at bus 10	Solar at bus 30	Solar at bus 31	Solar at bus 32	Wind at bus 32
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	1	1	1	1	1
3	0	0	0	1	1	1	1	0	0	0	0	1
4	0	0	0	1	1	1	1	1	1	1	1	0
5	0	1	1	0	0	1	1	0	0	1	1	0
6	0	1	1	0	0	1	1	1	1	0	0	1
7	0	1	1	0	0	1	1	1	1	0	0	1
8	0	1	1	1	1	0	0	1	1	0	0	0
9	1	0	1	0	1	0	1	0	1	0	1	0
10	1	0	1	0	1	0	1	1	0	1	0	1
11	1	0	1	1	0	1	0	0	1	0	1	1
12	1	0	1	1	0	1	0	1	0	1	0	0
13	1	1	0	0	1	1	0	0	1	1	0	0
14	1	1	0	0	1	1	0	1	0	0	1	1
15	1	1	0	1	0	0	1	0	1	1	0	1
16	1	1	0	1	0	0	1	1	0	0	1	0

Table 6.29 Expansion plan of single stage RTEP_TOAT for northeastern Thailand system

From bus	To bus	Number of lines	Cost (MUS$)
30	31	1	7.90
18	20	1	6.10
2	3	1	18.80
1	61	1	4.00
11	12	1	18.80
51	52	1	16.90
41	59	1	7.40
69	70	1	18.80
22	31	1	21.80
4	18	1	14.40
5	74	1	21.60
37	71	1	22.50
61	62	2	37.60
4	72	1	33.90
36	53	1	13.20
22	30	1	25.80
2	19	1	24.00
5	26	1	37.80
2	21	1	21.60
16	25	1	20.20
18	46	1	30.50
29	55	1	50.90
Investment cost (MUS$)			474.50
pv_{inv} (MUS$)			345.71
pv_{opr} (MUS$)			4,506.87
Wind operating cost (MUS$) [1]			120.45
Solar operating cost (MUS$) [2]			327.04
Total cost (MUS$)			5,300.07
Robustness (%)			96.57

[1] Calculated based on Thailand feed in tariff rates of wind energy at 0.179 US$/kWhr (year 2015) [95]

[2] Calculated based on Thailand feed in tariff rates of solar energy at 0.167 US$/kWhr (year 2015) [95]

In the case of RTEP_PROPOSED for northeastern Thailand system, the proposed method for selecting scenarios as presented in Subsection 5.1 is used. The first 10 highest values of *SSIRG* and *SSIL* are shown in Table 6.30.

Table 6.30 The first 10 highest values of *SSIRG* and *SSIL*
for northeastern Thailand system

For renewable energy generation		For loads	
Hour	*SSIRG*	Hour	*SSIL*
5,632 th	1.000	5,632 th	1.000
7,532 th	1.000	7,532 th	1.000
6,355 th	8×10^{-06}	7,556 th	0.024
6,343 th	3×10^{-06}	7,820 th	0.018
6,319 th	1×10^{-06}	2,780 th	0.016
1,963 th	1×10^{-06}	7,868 th	0.008
6,247 th	8×10^{-07}	7,843 th	0.008
1,951 th	6×10^{-07}	7,867 th	0.004
6,199 th	5×10^{-07}	7,819 th	0.003
6,235 th	5×10^{-07}	7,507 th	0.003

In this case, both hours 5,632 and 7,532 have the *SSIRG* and *SSIL* equal to 1. This means that the OPF cannot be calculated in these hours. Therefore, the values of renewable energy generation and loads of these two hours are selected as the considered scenarios for planning. In addition, as mentioned in the step 5 of Section 5.1, the values of the renewable energy generation and loads of the hour that provides the highest *SSIRG*, excepting the hour that provides the *SSIRG* equally to 1, have to be added into the considered scenarios for planning. Moreover, the values of the renewable energy generation and loads of the hour that provides the highest *SSIL*, excepting the hour that provides the *SSIL* equally to 1, have to be added into the considered scenarios as well. Therefore, the values of renewable energy generation and loads of the hours 6,355 and 7,556 are added into the considered scenarios for planning as well. In conclusion, the values of renewable energy generation and loads of the hours 5,632, 7,532, 6,355 and 7556 are selected as the considered scenarios for planning. The expansion plan of the RTEP_PROPOSED is shown in Table 6.31. The *SP* and the computation time are 13.45 and 650.12 minutes, respectively.

Table 6.31 Expansion plan of single stage RTEP_PROPOSED for northeastern Thailand system

From bus	To bus	Number of lines	Cost (MUS$)
3	4	2	11.60
18	20	1	6.10
31	32	1	18.80
2	3	1	18.80
50	51	1	18.80
47	50	1	18.40
26	27	2	13.60
6	11	1	25.60
4	71	1	39.70
3	20	1	16.70
38	72	1	17.70
18	25	1	35.20
56	61	1	19.50
21	52	1	53.90
17	57	1	24.30
Investment cost (MUS$)			338.70
pv_{inv} (MUS$)			246.77
pv_{opr} (MUS$)			4,498.14
Wind operating cost (MUS$)[1]			120.45
Solar operating cost (MUS$)[2]			327.04
Total cost (MUS$)			5,192.40
Robustness (%)			99.95

[1] Calculated based on Thailand feed in tariff rates of wind energy at 0.179 US$/kWhr (year 2015) [95]

[2] Calculated based on Thailand feed in tariff rates of solar energy at 0.167 US$/kWhr (year 2015) [95]

From Table 6.31, the robustness of the expansion plan cannot reach to 100 percent. In order to design the system with the 100 percent of robustness, the method in Section 5.4 is applied for this case. In the step 2 of the method, the hours that cause the curtailment of renewable energy generation or curtailment of loads are 7,580, 7,484, 6,380 and 6,476. Therefore, the values of renewable energy generation and loads of the four hours are added into the considered scenarios for planning. At present, all considered scenarios are consisted of the values of renewable energy generation and loads of the hours 5,632, 7,532, 6,355, 7,556, 7,580, 7,484, 6,380 and 6,476. After that, the system before expansion including an expansion plan from Table 6.31 is defined as the existing system for replanning. After replanning by using the new considered scenarios, the result is shown in Table 6.32.

Table 6.32 Expansion plan of the replanning single stage RTEP_PROPOSED for northeastern Thailand system

From bus	To bus	Number of lines	Cost (MUS$)
3	4	2	11.6
18	20	1	6.1
31	32	1	18.8
2	3	1	18.8
50	51	1	18.8
41	59	1	7.4
47	50	1	18.4
26	27	2	13.6
6	11	1	25.6
4	71	1	39.7
3	20	1	16.7
38	72	1	17.7
10	61	1	22.1
18	25	1	35.2
56	61	1	19.5
14	18	1	35.3
21	52	1	53.9
17	57	1	24.3
Investment cost (MUS$)			403.5
pv_{inv} (MUS$)			293.98
pv_{opr} (MUS$)			4,501.38
Wind operating cost (MUS$) [1]			120.45
Solar operating cost (MUS$) [2]			327.04
Total cost (MUS$)			5,242.85
Robustness (%)			100

[1] Calculated based on Thailand feed in tariff rates of wind energy at 0.179 US$/kWhr (year 2015) [95]

[2] Calculated based on Thailand feed in tariff rates of solar energy at 0.167 US$/kWhr (year 2015) [95]

The comparison of the three RTEP results is shown in Table 6.33.

Table 6.33 Comparison of the three results of RTEP for northeastern Thailand system

Case	RTEP_MIN_MAX	RTEP_TOAT	RTEP_PROPOSED
Number of considered scenario	4	16	8
Investment cost (MUS$)	430.00	474.50	403.5
pv_{inv} (MUS$)	313.29	345.71	293.98
pv_{opr} (MUS$)	4,530.21	4,506.87	4,501.38
Wind operating cost (MUS$) [1]	120.40	120.45	120.45
Solar operating cost (MUS$) [2]	327.04	327.04	327.04
Total cost (MUS$)	5,290.95	5,300.07	5,242.85
Robustness (%)	93.67	96.57	100
Computation time (minutes)	1,312.58	5,120.32	4,237.74

[1] Calculated based on Thailand feed in tariff rates of wind energy at 0.179 US$/kWhr (year 2015) [95]

[2] Calculated based on Thailand feed in tariff rates of solar energy at 0.167 US$/kWhr (year 2015) [95]

Discussion

For the case of IEEE-24 buses system, the comparison in Table 6.26 shows that only the RTEP_PROPOSED can provide the robustness at 100 percent. This means that the proposed method of RTEP is the most efficient in the term of robustness comparing with the RTEP_MIN_MAX and RTEP_TOAT from research works [30] and [29], respectively. Moreover, the pv_{inv} of RTEP_PROPOSED result is the lowest comparing with the pv_{inv} of RTEP_MIN_MAX and RTEP_TOAT results. For the computation time comparison, the computation time of the RTEP_PROPOSED is the lowest compared with the computation time of the other methods. This is because the number of considered scenarios of RTEP_PROPOSED which directly relates with the computation time is the least.

For the case of northeastern Thailand system, the robustness of this system is rather high compared with the IEEE-24 buses system as shown in Table 6.26 and

Table 6.33. This is because the number of transmission lines of the northeastern Thailand system is more than the number of transmission lines of the IEEE 24-buses system while the total power demand of the northeastern Thailand system is lower. From the result in Table 6.33, the RTEP_PROPOSED with the method in Section 5.4 can provide the robustness at 100 percent. Moreover, the total cost of RTEP_PROPOSED result is the lowest comparing with the total cost of RTEP_MIN_MAX and RTEP_TOAT results.

In addition, the comparisons of TEP and RTEP for IEEE-24 buses system and northeastern Thailand system are compared as shown in Table 6.34 and Table 6.35. The comparisons of both systems show that robustness percent of TEP results are lower than RTEP results no matter how the renewable energy output values are selected as the considered scenario for planning. This indicates that it is unsuitable to solve TEP considering intermittent renewable energy generation and loads by conventional method. Furthermore, the high robustness percent of all three cases of the RTEP results prove that RTEP is suitable than the conventional TEP when intermittent renewable energy generation and loads are considered in the planning.

Table 6.34 Comparison between TEP and RTEP results for IEEE-24 buses system

Case	TEP_ ZERO	TEP_ HALF	TEP_ FULL	RTEP_ MIN_MAX	RTEP_ TOAT	RTEP_ PROPOSED
Investment cost (MUS$)	448.00	549.00	674.00	656.00	699.00	517.00
pv_{inv} (MUS$)	326.40	399.99	491.06	477.95	509.28	376.67
pv_{opr} (MUS$)	9,161.17	9,182.64	9,058.70	8,956.25	8,927.40	8,966.37
Wind operating cost (MUS$) [1]	3,416.06	2,958.77	3,726.87	4,361.94	4,392.16	4,392.16
Total cost (MUS$)	12,903.63	12,541.4	13,276.63	13,796.14	13,828.84	13,735.20
Robustness (%)	70.48	30.56	41.86	74.50	87.48	100
Computation time (minutes)	58.86	58.86	58.86	187.92	1,103.36	118.85

[1] Calculated based on Thailand feed in tariff rates of wind energy at 0.179 US$/kWhr (year 2015) [95]

Table 6.35 Comparison between TEP and RTEP results for northeastern Thailand system

Case	TEP_ ZERO	TEP_ HALF	TEP_ FULL	RTEP_ MIN_MAX	RTEP_ TOAT	RTEP_ PROPOSED
Investment cost (MUS$)	283.80	281.50	195.00	430.00	474.50	403.5
pv_{inv} (MUS$)	206.77	205.09	142.07	313.29	345.71	293.98
pv_{opr} (MUS$)	4,592.04	4,458.84	4,523.86	4,530.21	4,506.87	4,501.38
Wind operating cost (MUS$) [1]	116.39	120.44	120.45	120.40	120.45	120.45
Solar operating cost (MUS$) [2]	305.66	327.04	327.04	327.04	327.04	327.04
Total Cost (MUS$)	5,220.86	5,111.41	5,113.42	5,290.95	5,300.07	5,242.85
Robustness (%)	92.85	87.94	83.32	93.67	96.57	100
Computation time (minutes)	435.87	435.87	435.87	1,312.58	5,120.32	2,636.64

[1] Calculated based on Thailand feed in tariff rates of wind energy at 0.179 US$/kWhr (year 2015) [95]

[2] Calculated based on Thailand feed in tariff rates of solar energy at 0.167 US$/kWhr (year 2015) [95]

6.4 Multistage RTEP with Renewable Energy Sources

Objective

The objectives of this test are listed below.

(a) To compare the result of multistage planning with the result of single stage planning

Details of the test

In the case of the multistage TEP, the length of the planning period is nine years. The planning period is divided into three stages. Each stage spans for three years. It is assumed that the power demand and the generation capacity monotonously increase throughout the planning period. Therefore, the plan established at the beginning of each stage must be able to serve the demand at the end of stage. That is why, the power demand and the generation capacities at year 3, 6 and 9 will be used as the representative values for the first, second, and third stage respectively.

For the year 9 which is the target year of planning, the power demand and the installed generation capacity are defined according to the data shown in the appendix. For the year 6 and year 3, the demand is assumed to monotonously decrease by 10% per year for both the IEEE-24 bus system and the northeastern Thailand system. The data for the first, second and third stage are summarized in Table 6.36.

Table 6.36 Assumption of power demand and generation capacities for the first, second and third stage

Description	1st stage (year 3)	2nd stage (year 6)	3rd stage (year 9)
Demand (compare with the demand of third stage)	56.45%	75.13%	100%
Generation (compare with the generation of third stage)	56.45%	75.13%	100%

It should be noted that consecutively single stage planning is used for solving multistage planning in this dissertation. The RTEP_PROPOSED is used to solve the problem in order to design the robust system.

For IEEE-24 buses system, there are two wind farms installed as mentioned in Section 6.2, the first wind farm (bus 7) is assumed to be installed at the second stage (year 6) and the second wind farm (bus 22) is assumed to be installed at the third stage (year 9). The expansion plan of the multistage RTEP_PROPOSED for IEEE-24 buses system is shown in Table 6.37. The result comparison between single stage RTEP and multistage RTEP which are solved by RTEP_PROPOSED method is shown in Table 6.38.

Table 6.37 Expansion plan of multistage RTEP_PROPOSED for IEEE-24 buses system

Stage	From bus - To bus	Number of lines	Investment cost (MUS$)	pv_{inv} (MUS$)	pv_{opr} (MUS$)	Wind operating cost (MUS$) [1]	Total cost (MUS$)	Robustness (%)
1st stage	2-8	1	158.00	115.12	2,829.08	0	2,944.20	100
	8-9	1						
	7-8	2						
	6-7	1						
2nd stage	6-10	1	123.00	52.77	2,800.40	730.18	2,853.17	100
	6-7	1						
	1-2	1						
	14-16	1						
3rd stage	6-10	1	236.00	45.14	2,757.09	1,460.36	2,802.23	100
	20-23	1						
	10-12	1						
	3-24	1						
	1-8	1						
	1-3	1						
Total investment cost (MUS$)							517	
Total pv_{inv} (MUS$)							213.03	
Total pv_{opr} (MUS$)							8,986.57	
Wind operating cost (MUS$) [1]							2,190.54	
Total cost (MUS$)							11,390.14	
Robustness (%)							100	

[1] Calculated based on Thailand feed in tariff rates of wind energy at 0.179 US$/kWhr (year 2015) [95]

Table 6.38 Result comparison between single stage RTEP and multistage RTEP for IEEE-24 buses system

	Single stage RTEP		Multistage RTEP		
	From bus - To bus	Number of lines	Stage	From bus - To bus	Number of lines
Description	6-10	2	1st stage	2-8	1
	7-8	2		8-9	1
	2-8	1		7-8	2
	1-8	1		6-7	1
	8-9	1	2nd stage	6-10	1
	10-12	1		6-7	1
	20-23	1		1-2	1
	1-2	1		14-16	1
	3-24	1	3rd stage	6-10	1
	14-16	1		20-23	1
	6-7	2		10-12	1
	1-3	1		3-24	1
				1-8	1
				1-3	1
Total investment cost (MUS$)	517		517		
Total pv_{inv} (MUS$)	376.67		213.03		
Total pv_{opr} (MUS$)	8,966.37		8,986.57		
Wind operating cost (MUS$) [1]	4,392.16		2,190.54		
Total cost (MUS$)	13,735.20		11,390.14		
Robustness (%)	100		100		

[1] Calculated based on Thailand feed in tariff rates of wind energy at 0.179 US$/kWhr (year 2015) [95]

For the northeastern Thailand system, the location and capacity of solar and wind sources are adopted from the Table 6.12, Section 6.2. At the third stage (year 9), the capacities of solar and wind sources are directly adopted from Table 6.12. For the year 6 and year 3, it is assumed that the capacity of solar and wind source monotonously decrease by 10% per year as same as the generation and demand. Therefore, the capacity percent of the first (year 3) and the second (year 6) stages are 56.45% and 75.13% of the capacity of the third stage (year 9), respectively. The expansion plan of the multistage RTEP_PROPOSED for northeastern Thailand system is shown in Table 6.39. The result comparison between single stage RTEP and multistage RTEP which are solved by RTEP_PROPOSED method is shown in Table 6.40.

Table 6.39 Expansion plan of multistage RTEP_PROPOSED for northeastern Thailand system

Stage	From bus - To bus	Number of lines	Investment cost (MUS$)	pv_{inv} (MUS$)	pv_{opr} (MUS$)	Wind operating cost (MUS$)[1]	Solar operating cost (MUS$)[2]	Total cost (MUS$)	Robustness (%)
1st stage	-		-	-	1,508.48	22.66	61.54	1,592.68	100
2nd stage	-		-	-	1,525.63	30.16	81.90	1,637.70	100
3rd stage	3-4	2	403.50	77.18	1,517.24	40.15	109.01	1,666.40	100
	18-20	1							
	31-32	1							
	2-3	1							
	50-51	1							
	41-59	1							
	47-50	1							
	26-27	2							
	6-11	1							
	4-71	1							
	3-20	1							
	38-72	1							
	10-61	1							
	18-25	1							
	56-61	1							
	14-18	1							
	21-52	1							
	17-57	1							

Total investment cost (MUS$)	403.50
Total pv_{inv} (MUS$)	77.18
Total pv_{opr} (MUS$)	4,551.35
Wind operating cost (MUS$)[1]	92.98
Solar operating cost (MUS$)[2]	252.45
Total cost MUS$)	4,896.78
Robustness (%)	100

[1] Calculated based on Thailand feed in tariff rates of wind energy at 0.179 US$/kWhr (year 2015) [95]

[2] Calculated based on Thailand feed in tariff rates of solar energy at 0.167 US$/kWhr (year 2015) [95]

Table 6.40 Result comparison between single stage RTEP and multistage RTEP for northeastern Thailand system

	Single stage RTEP		Multistage RTEP		
	From bus - To bus	Number of lines	Stage	From bus - To bus	Number of lines
Description	3-4	2	1st stage	-	
	18-20	1	2nd stage	-	
	31-32	1	3rd stage	3-4	2
	2-3	1		18-20	1
	50-51	1		31-32	1
	41-59	1		2-3	1
	47-50	1		50-51	1
	26-27	2		41-59	1
	6-11	1		47-50	1
	4-71	1		26-27	2
	3-20	1		6-11	1
	38-72	1		4-71	1
	10-61	1		3-20	1
	18-25	1		38-72	1
	56-61	1		10-61	1
	14-18	1		18-25	1
	21-52	1		56-61	1
	17-57	1		14-18	1
				21-52	1
				17-57	1
Total Investment cost (MUS$)	403.5		403.50		
Total pv_{inv} (MUS$)	293.98		77.18		
Total pv_{opr} (MUS$)	4,501.38		4,551.35		
Wind operating cost (MUS$) [1]	120.45		92.98		
Solar operating cost (MUS$) [2]	327.04		252.45		
Total cost (MUS$)	5,242.85		4,896.78		
Robustness (%)	100		100		

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[1] Calculated based on Thailand feed in tariff rates of wind energy at 0.179 US$/kWhr (year 2015) [95]

[2] Calculated based on Thailand feed in tariff rates of solar energy at 0.167 US$/kWhr (year 2015) [95]

Discussion

For the IEEE-24 buses system, the results in show that the expansion plan of single stage planning is the same as the expansion plan of multistage planning. However, the costs of both cases are different. The pv_{inv} of the multistage planning is lower than the pv_{inv} of the single stage planning because the utilization of the transmission lines of multistage case is lower than the single stage case. However, the pv_{opr} of multistage planning is higher than the pv_{opr} of the single stage planning. This is because all transmission lines of the expansion plan are installed in the system at once when using single stage planning. Meanwhile, transmission lines of the expansion plan are gradually installed in the system stage by stage when using multistage planning. Consequently, the system from single stage planning has high flexibility since the beginning of the planning period while the system flexibility from multistage planning is lower until the third stage planning. This result in the system from single stage planning has higher flexibility than the multistage planning when the whole planning period is considered.

For the northeastern Thailand system, the results in Table 6.40 show that the expansion plan of single stage planning is the same as the expansion plan of multistage planning. However, the expansion is not necessary in the first and second stages because the system meets the 100 percent of robustness. For cost comparison, the costs of single stage and multistage planning are different in the same way as the IEEE 24-buses system case. The pv_{inv} of the multistage planning is lower than the pv_{inv} of the single stage planning while the pv_{opr} of multistage planning is higher than the pv_{opr} of the single stage planning.

6.5 The Effect of Renewable Energy Sources on Cost of Planning

Objective

The objectives of this test are listed below.

(a) To study the effect of renewable energy sources on cost of planning

Details of the test

To study the effect of renewable energy sources on cost of planning for the IEEE-24 buses system, the original load values of IEEE-24 buses system as shown in the appendix is used [94]. For renewable energy sources, 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 to 20 MW to study the effect of renewable energy sources on planning. In addition, the proposed RTEP method which can provide the 100 percent of robustness is applied in this study. The result of this study is shown in Table 6.41 which can be plotted as illustrated in Figure 6.2.

Table 6.41 Effect of wind farms on planning cost for IEEE-24 buses system

Each wind capacity (MW)	Total wind capacity (MW)	pv_{inv} (MUS$)	pv_{opr} (MUS$)	Wind operating cost (MUS$) [1]	Total cost (MUS$)
0	0	Unnecessary to expand transmission line because the system can satisfy 100% of robustness			
1	7				
2	14				
3	21				
4	28				
5	35				
6	42				
7	49				
8	56				
9	63				
10	70				
11	77				
12	84				
13	91				
14	98				
15	105				
16	112	55.91	3,067.02	103.06	3,225.99
17	119	60.31	3,065.12	109.51	3,263.01
18	126	84.37	3,063.10	115.95	3,294.06
19	133	157.90	3,060.85	122.39	3,331.14
20	140	170.18	3,054.49	128.83	3,356.50

[1] Calculated based on Thailand feed in tariff rates of wind energy at 0.179 US$/kWhr (year 2015) [95]

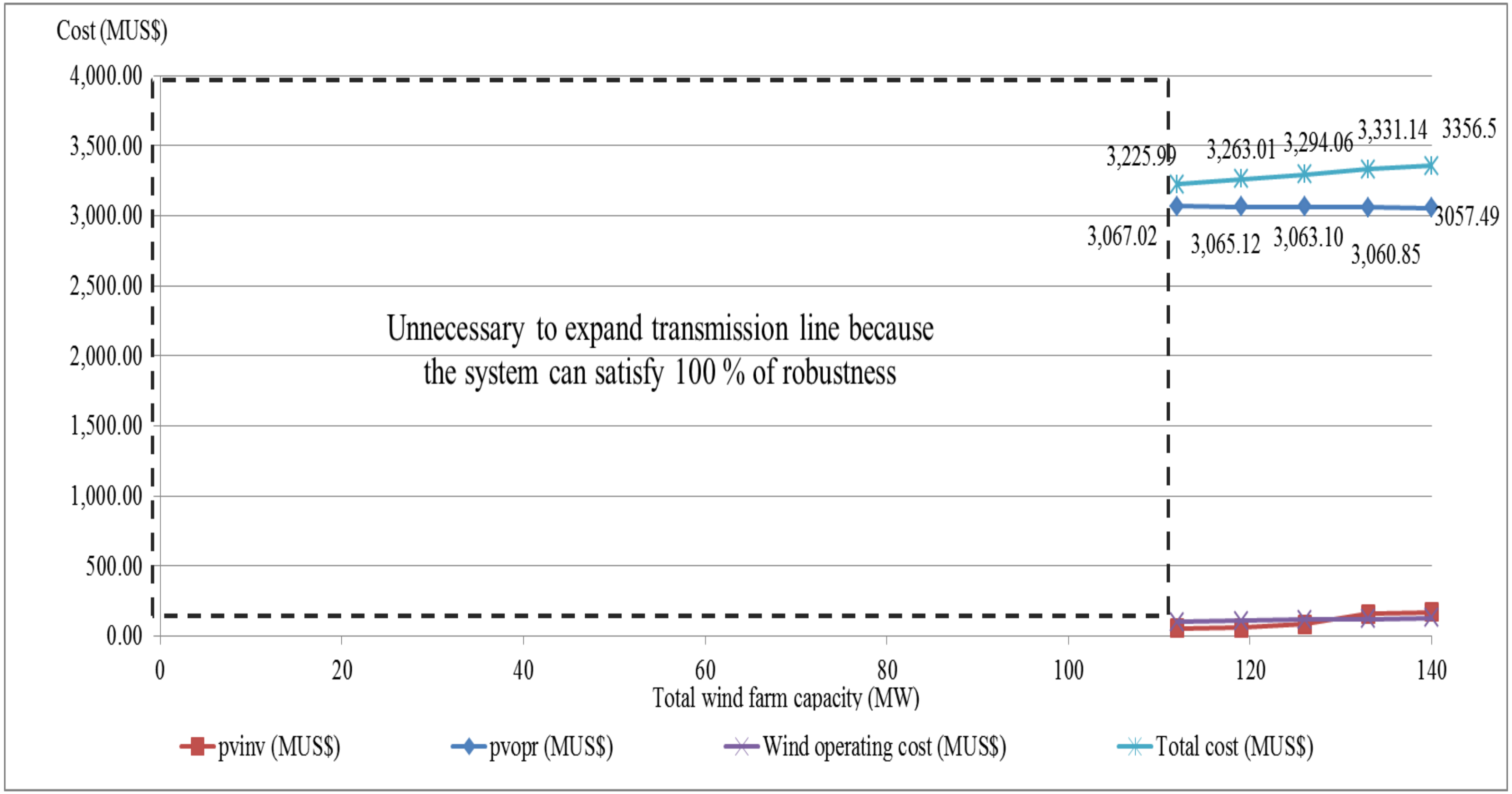

Figure 6.2 Graph of wind farms effect on planning cost for IEEE-24 buses system

For the environment viewpoint, the greenhouse gas (GHG) emissions from electricity generation technologies accumulated by the reference [96] are studied in order to identify the CO_2 reduction due to using renewable energy sources. In this case, the natural gas which is the most used fuel for electricity generation in Thailand is assumed to be the fuel for conventional generators. The comparison of CO_2 emissions from wind farms and conventional generators is shown in Table 6.42. The relation of total CO_2 emission and wind capacity is plotted as illustrated in Figure 6.3.

Table 6.42 Comparison of CO_2 emissions by wind farms and conventional generators for IEEE-24 buses system

Total wind source capacity (MW)	Total wind energy (MWh/year)	CO_2 emission from wind farms (ton CO_2eq/year) [1]	Total natural gas energy (MWh/year)	CO_2 emission from conventional generators (ton CO_2eq/year) [2]
0	Unnecessary to expand transmission line because the system can satisfy 100% of robustness			
7				
14				
21				
28				
35				
42				
49				
56				
63				
70				
77				
84				
91				
98				
105				
112	572,555.56	6,870.67	15,014,250.00	7,041,683.25
119	608,388.89	7,300.67	14,977,700.00	7,024,541.30
126	644,166.67	7,730.00	14,941,206.66	7,007,425.93
133	679,944.44	8,159.33	14,904,713.34	6,990,310.56
140	715,722.21	8,588.67	14,868,221.14	6,973,195.71

[1] CO_2 emission rate of wind source is 12,000 gCO_2eq/MWhr [96]

[2] CO_2 emission rate of natural gas generator is 469,000 gCO_2eq/MWhr [96]

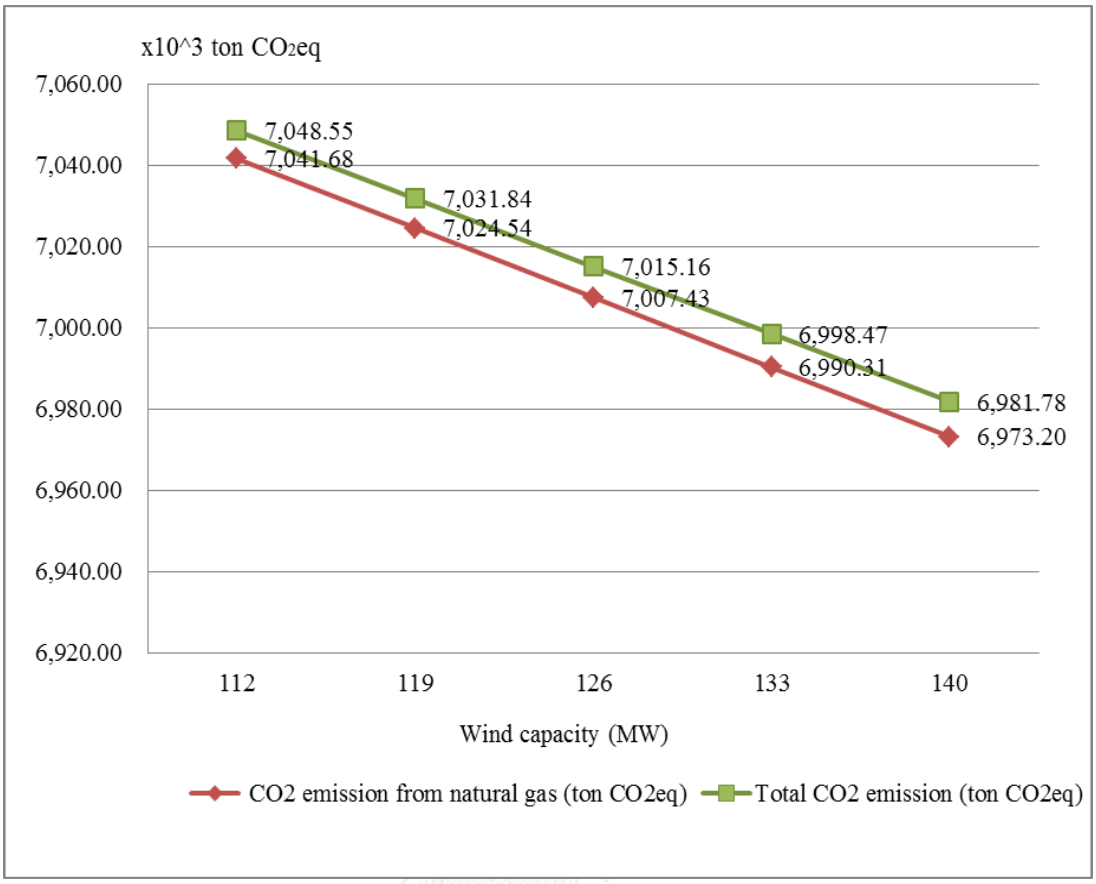

Figure 6.3 The relation between CO_2 emissions and wind capacity for IEEE 24-buses system

In the case of northeastern Thailand system, wind and solar sources are installed as shown in Table 6.12. The capacity of each wind and solar sources is varied from 0% to 100% of their capacities in Table 6.12 with the step length of 20% to study the effect of renewable energy sources on planning. The proposed RTEP method which can provide the 100 percent of robustness is applied in this study.

The result of this study is shown in Table 6.43 which can be plotted as illustrated in Figure 6.4.

Table 6.43 Effect of wind and solar sources on planning cost for northeastern Thailand system

Renewable energy sources percent	Total wind capacity (MW)	Total solar capacity (MW)	pv_{inv} (MUS$)	pv_{opr} (MUS$)	Wind operating cost (MUS$) [1]	Solar operating cost (MUS$) [2]	Total cost (MUS$)
0	0.00	0.00	182.36	4,536.81	0.00	0.00	4,719.17
20	37.88	74.12	212.89	4,527.72	24.09	65.61	4,830.31
40	75.76	148.25	216.82	4,522.64	48.18	131.21	4,918.86
60	113.64	222.37	241.67	4,515.55	72.27	196.82	5,026.32
80	151.52	296.49	241.67	4,509.07	96.36	262.43	5,109.53
100	189.40	370.61	293.98	4,501.38	120.45	328.04	5,243.85

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[1] Calculated based on Thailand feed in tariff rates of wind energy at 0.179 US$/kWhr (year 2015) [95]

[2] Calculated based on Thailand feed in tariff rates of solar energy at 0.167 US$/kWhr (year 2015) [95]

For the environment viewpoint, the CO_2 emissions of wind and solar sources are compared with the emission by conventional generators using natural gas which is the most used fuel for electricity generation in Thailand. The comparison is shown in Table 6.44. The relation of total CO_2 emission and renewable energy sources capacity is plotted as illustrated in Figure 6.5.

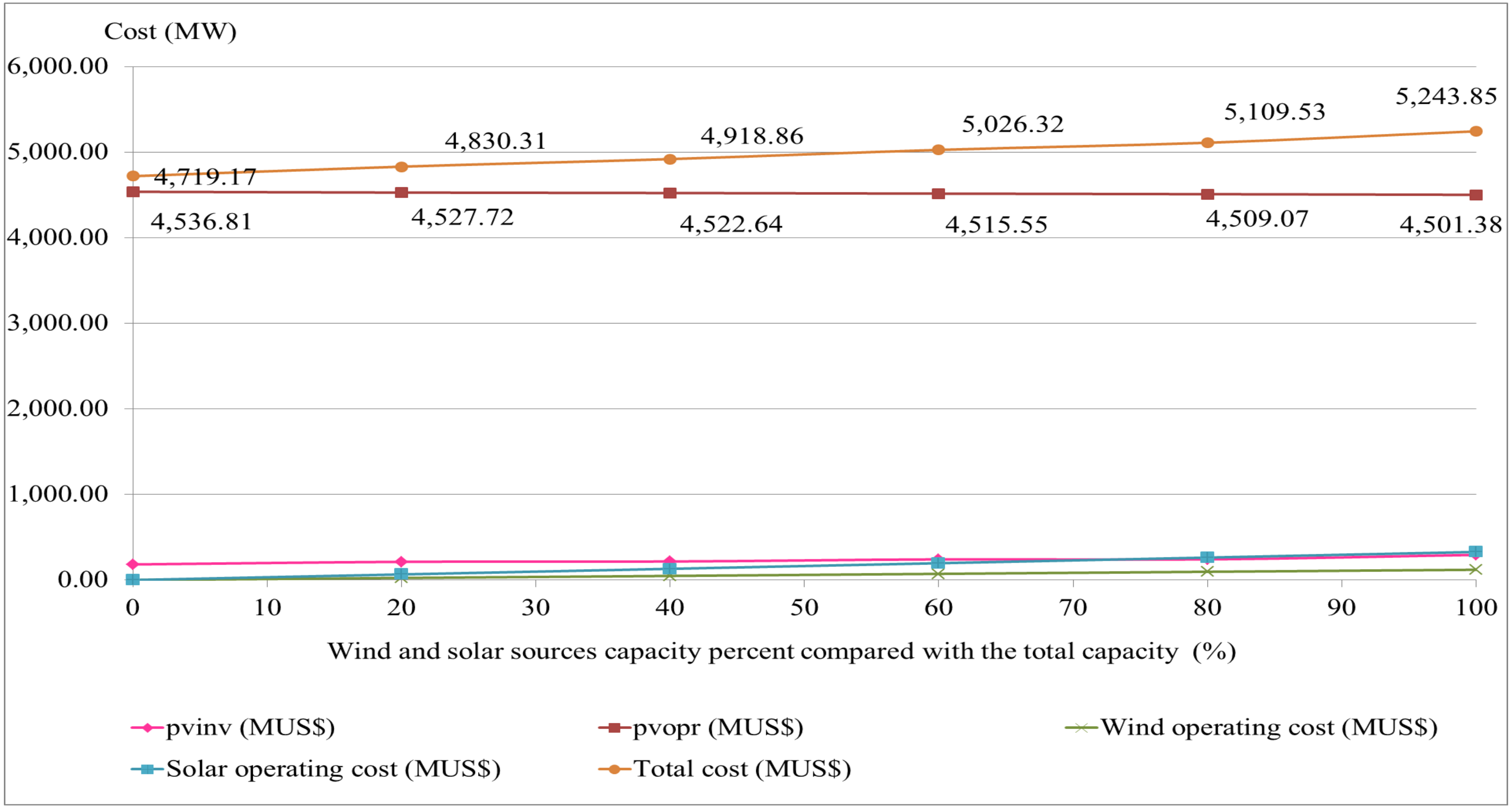

Figure 6.4 Graph of wind and solar sources effect on planning cost for northeastern Thailand system

Table 6.44 Comparison of CO_2 emissions by wind sources, solar sources and natural gas generator for northeastern Thailand system

Renewable energy sources percent	Total wind source capacity (MW)	Total solar source capacity (MW)	Total wind energy (MWhr)	Total solar energy (MWhr)	Summation of wind and solar energies (MWhr)	CO_2 emission from wind source (ton CO2eq) [1]	CO_2 emission from solar source (ton CO2eq) [2]	CO_2 emission from natural gas (ton CO2eq) [3]
0	0	0	0	0	0	0	23,021,269.35	10,796,975.33
20	37.88	74.12	6,144.95	17,863.46	73.74	821.719	22,996,780.77	10,785,490.18
40	75.76	148.25	30,724.73	89,317.31	368.70	4,108.596	22,898,826.46	10,739,549.61
60	113.64	222.37	76,811.83	223,293.29	921.74	10,271.491	22,715,162.13	10,653,411.04
80	151.52	296.49	128,019.72	372,155.48	1,536.24	17,119.152	22,511,090.65	10,557,701.52
100	189.40	370.61	160,024.64	465,194.35	1,920.30	21,398.940	22,383,545.98	10,497,883.06

[1] CO_2 emission rate of wind source is 12,000 $gCO_2eq/MWhr$ [96]

[2] CO_2 emission rate of solar source is 46,000 $gCO_2eq/MWhr$ [96]

[3] CO_2 emission rate of natural gas generator is 469,000 $gCO_2eq/MWhr$ [96]

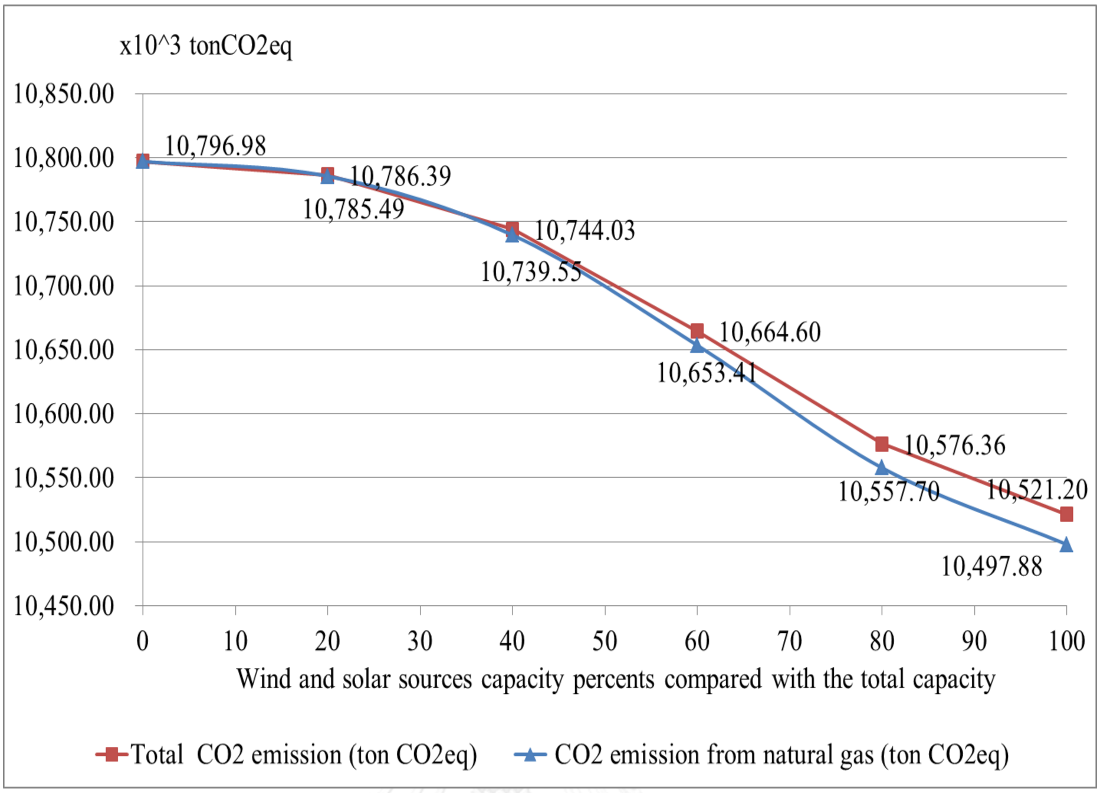

Figure 6.5 The relation between CO_2 emissions and renewable energy sources capacity for northeastern Thailand system

Discussion

For IEEE 24-buses system, in Table 6.41, when the capacity of each wind farm increases from 0 to 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 to 20 MW, it will cause the system robustness to be below 100%. Therefore, transmission lines are needed to be expanded in order to keep the system robustness at 100%. From Figure 6.2, it can be concluded that, more installation of wind farms causes the increasing of investment cost while the operating cost decreases insignificantly. Moreover, the increasing of wind operating cost is higher than the decreasing of conventional generators operating cost; therefore, when the wind farms are increasingly installed in the system, the total cost will be increased. From these results, it can be said that more installation of intermittent renewable energy sources such as wind farms causes more total cost of an expansion plan.

From Table 6.42 and Figure 6.3, the CO_2 emissions from wind farms and conventional generators using natural gas are compared. It can be noticed that when the wind farms are increasingly installed in the system, the CO_2 emission from conventional generators are decreased. This results in the decreasing of total CO_2 emission as well. It should be noted that even if the intermittent of wind farms cause the increasing of the total cost of expansion plan, it can decrease the CO_2 emission. Therefore, if the decreasing of CO_2 can be evaluated as the cost, the suitable expansion plan which is the break-even point of the cost of expansion plan and the cost of CO_2 decreasing can be determined.

For northeastern Thailand system, same as the case of IEEE-24 buses system, when the wind and solar sources are increasingly installed in the system, the total cost of expansion plan will be increased as shown in Table 6.43 and Figure 6.4. For CO_2 emission point of view as shown in Table 6.44 and Figure 6.5, when the wind and solar sources are increasingly installed in the system, the total CO_2 emission will be decreased same as the case of IEEE-24 buses system.

CHAPTER 7

CONCLUSION

In this chapter, the summary of this dissertation, the advantage and disadvantage of the proposed method and the suggestion to improve the RTEP method are presented.

7.1 Dissertation Summary

This dissertation proposes a method for solving a robust transmission expansion planning (RTEP) problem considering intermittent renewable energy generation and loads. The objective function of the planning consists of investment and operating costs. The problem can be divided into two problems consisting of main problem and subproblem. The objective function of the main problem is minimizing the investment cost of transmission line and the operating cost of conventional generators whereas the objective function of subproblem is to avoid the violation of system operation by the minimum of generation dispatch and curtailments of renewable energy generation and loads. In order to obtain the result that can be applied in realistic situation, AC model is used to formulate the transmission expansion planning problem. The solving method used in this dissertation is adaptive tabu search (ATS) which has the mechanism to avoid the local optimum trap.

Generally, only peak loads scenario is considered in TEP problem which is based on the assumption that if the system can operate without any violations or load curtailments for the peak loads, it will operate without any violations or load curtailments for any loads values as well. In other words, the system has 100 percent of robustness. However, in the case of intermittent renewable energy sources are installed in the system, the uncertain generation from renewable energy sources can lead system robustness lower than 100 percent. In other words, the system cannot support some values of renewable energy generation or loads. This occurrence should not appear. Therefore, the considered scenario for TEP problem when considering intermittent renewable energy sources is needed to be revised in order to keep the system robustness equally or close to 100 percent. In this dissertation, three scenarios consisting of: 1) zero capacity of renewable energy source and peak loads 2) half capacity of renewable energy source and peak loads 3) full capacity of renewable energy source and peak loads are tested in order to identify the suitable scenario for TEP. However, the results from these three scenarios are dissatisfied. Consequently, robust transmission expansion planning (RTEP) is applied to solve the problem. The planning results from the three methods to select scenarios for RTEP are compared. In the first method, the minimum and maximum values of both renewable energy generation and loads are selected as the considered scenarios for planning. For the second method, the TOAT is used to generate the considered scenarios based on the minimum and maximum values of both renewable energy generation and loads. For the last method which is proposed by this dissertation, the considered scenarios for planning are selected by the proposed scenario selection indicator (SSI). This indicator is calculated based on the maximum curtailments of renewable energy generation and loads of each hour in a target year. In addition, the proposed method for solving RTEP is applied to solve multistage planning by the consecutively single stage planning. Finally, the effect of renewable energy source on cost of planning is studied.

7.2 Advantage and Disadvantage

The first advantage of the proposed method is the capability for finding the global optimum when solving TEP based on AC model. This is resulted from the mechanism of local optimum avoidance in ATS. The evidence is shown in the single stage TEP when neglecting operating cost. The obtained result from the proposed method is the same as the result which is guaranteed as the global optimum in previous research work.

For solving RTEP with intermittent renewable energy generation and loads, the second advantage is the robustness of an expansion plan. The system robustness can be guaranteed at 100 percent when the proposed method is applied while the system robustness from the other methods cannot be guaranteed at 100 percent.

The disadvantage can be separated into three aspects. The first aspect is the computation time. The proposed TEP and RTEP methods are solved based on ATS in order to obtain the high solution quality. However, ATS which is one of the metaheuristic methods consumes the large computation time. The second one is system reliability aspect. Even if system robustness is considered in the proposed planning, it cannot express in the term of system reliability. This is because the robustness is interpreted in the manner of renewable energy generation and load variations while the reliability is interpreted in the term of system components, e.g. generator and transmission line outages, etc. The last one is the computation of multistage planning. Consecutively single stage planning is applied to solve multistage planning in this dissertation. By this method, the optimal result of each stage will be obtained. However, the obtained results from each stage may not be the optimal result for all stages.

7.3 Additional Works

There are many topics of transmission expansion planning which have not been considered in previous research works. Examples of them are written below.

a) Some additional constraints have to be considered in some occasions. For example, N-1 security, transient stability, short circuit current limit, etc. The transient stability constraint is usually considered when transferring a large amount of power in the power purchasing project, while the short circuit current constraint is usually considered in the transmission planning for the urban area.

b) In long term planning horizon, the forecasted values of renewable energy generation and loads are uncertain. Therefore, the uncertainties of the forecasted values of renewable energy generation and loads should be taken into account in the planning.

c) The coordination of transmission expansion planning, generation expansion planning and renewable energy generation expansion planning is necessary. The process of power system planning will be much more efficient when the generation expansion planning and renewable energy generation expansion planning are coordinated with the transmission expansion planning. When the transmission constraints are considered in the generation expansion planning and renewable energy generation expansion, a good quality of both generation and renewable energy generation plans will be obtained. With the good quality of both generation and renewable energy generation plans, the good optimum transmission plan can be obtained as well.

d) The worthiness of renewable energy source when it is installed in the system. As mentioned in the Section 6.5, the higher incoming of renewable energy sources results to the higher cost of transmission expansion. It seems that renewable energy sources only lead trouble to the system. However, there are many advantages from renewable energy source, e.g. reduction of CO_2 emission, delay of generation expansion and reactive power procurement, etc. These advantages should be appraised to the cost and taken into account.

e) For the robustness point of view, the system robustness tends to increase the investment cost. Therefore, the formulation providing system decision maker an opportunity to compromise between the investment cost and system robustness should be studied.

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APPENDIX

APPENDIX

DATA OF TEST SYSTEMS

In this chapter, the detailed data of the IEEE-24 buses system, the northeastern Thailand system and Thailand solar radiation and wind speed are presented. The active, reactive, and apparent powers are expressed in MW, MVAr and MVA, respectively. The columns P^D and Q^D refer to the peak values of active and reactive power demands, respectively. $P_g^{\max}$ and $P_g^{\min}$ represent the maximum and minimum limits of the active power generation, respectively. $Q_g^{\max}$ and $Q_g^{\min}$ refer to the maximum and minimum limits of the reactive power generation, respectively.

The branch parameters, i.e. r_{ij}, rx_{ij} and b_{ij} are expressed in per unit based on 100 MVA. The n_{ij}^0 is number of existing transmission lines or existing transformers of the path ij. The costs c_{ij} and c_g are expressed in million US$ and US$/KWh, respectively.

A.1 IEEE-24 Buses System

The IEEE-24 buses system used in this dissertation is obtained from research work [44]. The system consists of 24 buses, 33 transmission lines and 5 transformers. There are 41 transmission line candidates. Bus, transmission line and transformer data of the existing IEEE-24 bus system are listed in Table A.1, Table A.2 and Table A.3. The transmission line candidate data are listed in Table A.4. The capacitors and reactors can be installed to compensate the reactive power at every bus. The maximum sizes of both devices are 200 MVAr. Weekly, daily and hourly load data are listed in Table A.5, Table A.6 and Table A.7, respectively. Moreover, the original bus data of the IEEE-24 bus system [94] tested in Section 6.5 are listed in Table A.8.

Table A.1 Bus data of IEEE-24 buses system

Bus	Type	P_d	Q_d	P_g^{max}	P_g^{min}	Q_g^{max}	Q_g^{min}	c_g
1	SL	324	66	576	0	240	–150	0.05
2	PV	291	60	576	0	240	–150	0.05
3	PQ	540	111	–	–	–	–	–
4	PQ	222	45	–	–	–	–	–
5	PQ	213	42	–	–	–	–	–
6	PV	408	84	0	0	0	–300	0
7	PV	375	75	900	0	540	0	0.08
8	PQ	513	105	–	–	–	–	–
9	PQ	525	108	–	–	–	–	–
10	PQ	585	120	–	–	–	–	–
11	PQ	–	–	–	–	–	–	–
12	PQ	–	–	–	–	–	–	–
13	PV	795	162	1,773	0	720	0	0.08
14	PV	582	117	0	0	600	–150	0
15	PV	951	192	645	0	330	–150	0.08
16	PV	300	60	465	0	240	–150	0.03
17	PQ	–	–	–	–	–	–	–
18	PV	999	204	1,200	0	600	–150	0.02
19	PQ	543	111	–	–	–	–	–
20	PQ	384	78	–	–	–	–	–
21	PV	–	–	1,200	0	600	–150	0.02
22	PV	–	–	900	0	288	–180	0.01
23	PV	–	–	1,980	0	930	–375	0.03
24	PQ	–	–	–	–	–	–	–

Table A.2 Transmission line data of IEEE-24 buses system

From bus	To bus	r_{ij}	rx_{ij}	b_{ij}	S_{ij_lim}	n_{ij}^0
1	2	0.0026	0.0139	0.4611	200	1
1	3	0.0546	0.2112	0.0572	220	1
1	5	0.0218	0.0845	0.0229	220	1
2	4	0.0328	0.1267	0.0343	220	1
2	6	0.0497	0.192	0.052	220	1
3	9	0.0308	0.119	0.0322	220	1
4	9	0.0268	0.1037	0.0281	220	1
5	10	0.0228	0.0883	0.0239	220	1
6	10	0.0139	0.0605	2.459	200	1
7	8	0.0159	0.0614	0.0166	220	1
8	9	0.0427	0.1651	0.0447	220	1
8	10	0.0427	0.1651	0.0447	220	1
11	13	0.0061	0.0476	0.0999	625	1
11	14	0.0054	0.0418	0.0879	625	1
12	13	0.0061	0.0476	0.0999	625	1
12	23	0.0124	0.0966	0.203	625	1
13	23	0.0111	0.0865	0.1818	625	1
14	16	0.005	0.0389	0.0818	625	1
15	16	0.0022	0.0173	0.0364	625	1
15	21	0.0063	0.049	0.103	625	2
15	24	0.0067	0.0519	0.1091	625	1
16	17	0.0033	0.0259	0.0545	625	1
16	19	0.003	0.0231	0.0485	625	1
17	18	0.0018	0.0144	0.0303	625	1
17	22	0.0135	0.1053	0.2212	625	1
18	21	0.0033	0.0259	0.0545	625	2
19	20	0.0051	0.0396	0.0833	625	2
20	23	0.0028	0.0216	0.0455	625	2
21	22	0.0087	0.0678	0.1424	625	1

Table A.3 Transformer data of IEEE-24 buses system

From bus	To bus	r_{ij}	rx_{ij}	b_{ij}	S_{ij_lim}	n_{ij}^0
3	24	0.0023	0.0839	0	600	1
9	11	0.0023	0.0839	0	600	1
9	12	0.0023	0.0839	0	600	1
10	11	0.0023	0.0839	0	600	1
10	12	0.0023	0.0839	0	600	1

Table A.4 Transmission line candidate data of IEEE-24 buses system

From bus	To bus	r_{ij}	rx_{ij}	b_{ij}	S_{ij_lim}	c_{ij}	n_{ij}^0
1	2	0.0026	0.0139	0.4611	200	3	1
1	3	0.0546	0.2112	0.0572	220	55	1
1	5	0.0218	0.0845	0.0229	220	22	1
1	8	0.0348	0.1344	0	220	35	1
2	4	0.0328	0.1267	0.0343	220	33	1
2	6	0.0497	0.192	0.052	220	50	1
2	8	0.0328	0.1267	0	220	33	1
3	9	0.0308	0.119	0.0322	220	31	1
4	9	0.0268	0.1037	0.0281	220	27	1
5	10	0.0228	0.0883	0.0239	220	23	1
6	7	0.0497	0.192	0	220	50	1
6	10	0.0139	0.0605	2.459	200	16	1
7	8	0.0159	0.0614	0.0166	220	16	1
8	9	0.0427	0.1651	0.0447	220	43	1
8	10	0.0427	0.1651	0.0447	220	43	1
11	13	0.0061	0.0476	0.0999	625	66	1
11	14	0.0054	0.0418	0.0879	625	58	1
12	13	0.0061	0.0476	0.0999	625	66	1
12	23	0.0124	0.0966	0.203	625	134	1

From bus	To bus	r_{ij}	rx_{ij}	b_{ij}	S_{ij_lim}	c_{ij}	n_{ij}^0
13	14	0.0057	0.0447	0	625	62	1
13	23	0.0111	0.0865	0.1818	625	120	1
14	16	0.005	0.0389	0.0818	625	54	1
14	23	0.008	0.062	0	625	86	1
15	16	0.0022	0.0173	0.0364	625	24	1
15	21	0.0063	0.049	0.103	625	68	1
15	24	0.0067	0.0519	0.1091	625	72	1
16	17	0.0033	0.0259	0.0545	625	36	1
16	19	0.003	0.0231	0.0485	625	32	1
16	23	0.0105	0.0822	0	625	114	1
17	18	0.0018	0.0144	0.0303	625	20	1
17	22	0.0135	0.1053	0.2212	625	146	1
18	21	0.0033	0.0259	0.0545	625	36	1
19	20	0.0051	0.0396	0.0833	625	55	1
19	23	0.0078	0.0606	0	625	84	1
20	23	0.0028	0.0216	0.0455	625	30	1
21	22	0.0087	0.0678	0.1424	625	94	1
3	24	0.0023	0.0839	0	600	50	1
9	11	0.0023	0.0839	0	600	50	1
9	12	0.0023	0.0839	0	600	50	1
10	11	0.0023	0.0839	0	600	50	1
10	12	0.0023	0.0839	0	600	50	1

Table A.5 Weekly load data of IEEE 24-buses system in percent of annual peak

Week	Load (%)	Week	Load (%)	Week	Load (%)	Week	Load (%)
1	86.2	14	75	27	75.5	40	72.4
2	90	15	72.1	28	81.6	41	74.3
3	87.8	16	80	29	80.1	42	74.4
4	83.4	17	75.4	30	88	43	80
5	88	18	83.7	31	72.2	44	88.1
6	84.1	19	87	32	77.6	45	88.5
7	83.2	20	88	33	80	46	90.9
8	80.6	21	85.6	34	72.9	47	94
9	74	22	81.1	35	72.6	48	89
10	73.7	23	90	36	70.5	49	94.2
11	71.5	24	88.7	37	78	50	97
12	72.7	25	89.6	38	69.5	51	100
13	70.4	26	86.1	39	72.4	52	95.2

Table A.6 Daily load data of IEEE 24-buses system in percent of annual peak

Day	Load (%)
Monday	93
Tuesday	100
Wednesday	98
Thursday	96
Friday	94
Saturday	77
Sunday	75

Table A.7 Hourly load data of IEEE 24-buses system in percent of annual peak

Hour	Winter week 1-8 & 44-52		Summer week 18-30		Spring & Fall week 9-17 & 31-43	
	Week day	Week end	Week day	Week end	Week day	Week end
12-l am	67	78	64	74	63	75
1-2	63	72	60	70	62	73
2-3	60	68	58	66	60	69
3-4	59	66	56	65	58	66
4-5	59	64	56	64	59	65
5-6	60	65	58	62	65	65
6-7	74	66	64	62	72	68
7-8	86	70	76	66	85	74
8-9	95	80	87	81	95	83
9-10	96	88	95	86	99	89
10-11	96	90	99	91	100	92
11-Noon	95	91	100	93	99	94
Noon-l pm	95	90	99	93	93	91
1-2	95	88	100	92	92	90
2-3	93	87	100	91	90	90
3-4	94	87	97	91	88	86
4-5	99	91	96	92	90	85
5-6	100	100	96	94	92	88
6-7	100	99	93	95	96	92
7-8	96	97	92	95	98	100
8-9	91	94	92	100	96	97
9-10	83	92	93	93	90	95
10-11	73	87	87	88	80	90
11-12	63	81	72	80	70	85

Table A.8 Original bus data of IEEE-24 buses system

Bus	Type	P_d	Q_d	$P_g^{\max}$	$P_g^{\min}$	$Q_g^{\max}$	$Q_g^{\min}$	c_g
1	SL	108	22	192	62.4	80	-50	0.05
2	PV	97	20	192	62.4	80	-50	0.05
3	PQ	180	37	–	–	–	–	–
4	PQ	74	15	–	–	–	–	–
5	PQ	71	14	–	–	–	–	–
6	PV	136	28	–	–	–	–	–
7	PV	125	25	300	75	180	0	0.08
8	PQ	171	35	–	–	–	–	–
9	PQ	175	36	–	–	–	–	–
10	PQ	195	40	–	–	–	–	–
11	PQ	–	–	–	–	–	–	–
12	PQ	–	–	–	–	–	–	–
13	PV	265	54	591	–	240	–	0.08
14	PV	194	39	–	–	–	–	0
15	PV	317	64	215	66.3	110	-50	0.08
16	PV	100	20	155	54.3	80	-50	0.03
17	PQ	–	–	–	–	–	–	–
18	PV	333	68	400	100	200	-50	0.02
19	PQ	181	37	–	–	–	–	–
20	PQ	128	26	–	–	–	–	–
21	PV	–	–	400	100	200	-50	0.02
22	PV	–	–	300	60	96	-60	0.01
23	PV	–	–	660	248.6	310	-125	0.03
24	PQ	–	–	–	–	–	–	–

A.2 Northeastern Thailand System

The system consists of 75 buses, 129 transmission lines and 24 transformers. There are 218 transmission line candidates and 20 transformer candidates. Bus, transmission line and transformer data of the northeastern Thailand system are listed in Table A.9, Table A.10 and Table A.11, respectively. The transmission line candidate and transformer candidate data are listed in Table A.12 and Table A.13, respectively. The capacitors and reactors can be installed to compensate the reactive power at every bus. The maximum sizes of both devices are 200 MVAr. The hourly load curve of the system in the year 2012 is illustrated in Figure A.1.

Table A.9 Bus data of northeastern Thailand system

Bus	Type	P_d	Q_d	$P_g^{\max}$	$P_g^{\min}$	$Q_g^{\max}$	$Q_g^{\min}$	c_g
1	PQ	79.56	44.07	–	–	–	–	–
2	PV	28.08	17.42	920	0	446.4	–288.0	0.04
3	PQ	–	–	–	–	–	–	–
4	PV	118.17	65.39	35	0	18	–9.0	0.03
5	PQ	47.84	26.52	–	–	–	–	–
6	PQ	98.93	54.73	–	–	–	–	–
7	PQ	4.55	2.47	–	–	–	–	–
8	PQ	41.86	23.14	–	–	–	–	–
9	PQ	25.35	14.04	–	–	–	–	–
10	PQ	81.51	45.11	–	–	–	–	–
11	PQ	138.97	76.83	–	–	–	–	–
12	PQ	–	–	880	0	542.9	–542.9	0.05
13	PV	0.78	0.52	50	0	23.3	–9.6	0.04
14	PV	54.99	30.42	60	0	28.4	–14.2	0.04
15	PV	1.56	0.91	165	0	72	–36.0	0.02
16	PQ	68.51	37.96	–	–	–	–	–
17	PQ	47.06	26	–	–	–	–	–
18	PQ	209.3	115.83	–	–	–	–	–
19	PQ	–	–	–	–	–	–	–

Bus	Type	P_d	Q_d	$P_g^{\max}$	$P_g^{\min}$	$Q_g^{\max}$	$Q_g^{\min}$	c_g
20	PQ	72.41	40.04	–	–	–	–	–
21	PQ	–	–	880	0	542.9	–542.9	0.05
22	PQ	117.52	65	–	–	–	–	–
23	SL	0.78	0.52	2,300	0	1,240.5	1,094.1	0.04
24	PQ	86.06	47.58	–	–	–	–	–
25	PQ	118.04	65.26	–	–	–	–	–
26	PQ	34.32	18.98	–	–	–	–	–
27	PQ	63.44	35.1	–	–	–	–	–
28	PQ	147.55	81.64	–	–	–	–	–
29	PQ	–	–	–	–	–	–	–
30	PQ	82.55	45.63	–	–	–	–	–
31	PQ	495.95	274.43	–	–	–	–	–
32	PQ	–	–	–	–	–	–	–
33	PV	–	–	72	0	39.7	–19.2	0.05
34	PV	1.56	0.91	114	0	59.5	–28.8	0.04
35	PV	0.78	0.52	8	0	4.3	0	0.05
36	PQ	7.93	4.42	–	–	–	–	–
37	PQ	54.73	30.29	–	–	–	–	–
38	PQ	44.2	24.44	–	–	–	–	–
39	PQ	145.86	80.73	–	–	–	–	–
40	PQ	62.14	34.32	120	0	74.3	–74.3	0.04
41	PV	1.56	0.91	85	0	38.4	–26.4	0.05
42	PQ	–	–	–	–	–	–	–
43	PQ	23.27	12.87	–	–	–	–	–
44	PQ	117.13	64.74	–	–	–	–	–
45	PQ	107.9	59.67	–	–	–	–	–
46	PQ	31.98	17.68	–	–	–	–	–
47	PQ	46.15	25.48	–	–	–	–	–
48	PQ	–	–	–	–	–	–	–
49	PQ	49.79	27.56	–	–	–	–	–

Bus	Type	P_d	Q_d	$P_g^{\max}$	$P_g^{\min}$	$Q_g^{\max}$	$Q_g^{\min}$	c_g
50	PQ	80.34	44.46	–	–	–	–	–
51	PQ	–	–	–	–	–	–	–
52	PQ	–	–	–	–	–	–	–
53	PQ	59.02	32.63	–	–	–	–	–
54	PQ	–	–	–	–	–	–	–
55	PQ	–	–	–	–	–	–	–
56	PQ	28.47	15.73	–	–	–	–	–
57	PQ	120.38	66.56	–	–	–	–	–
58	PQ	52.26	28.99	120	0	74.3	–74.3	0.04
59	PV	67.86	37.57	50	0	22.3	–10.8	0.05
60	PQ	55.51	30.68	–	–	–	–	–
61	PQ	36.01	19.89	–	–	–	–	–
62	PQ	–	–	–	–	–	–	–
63	PQ	–	–	–	–	–	–	–
64	PQ	–	–	–	–	–	–	–
65	PQ	27.95	15.47	–	–	–	–	–
66	PV	1.56	0.91	290	0	156	–76.8	0.04
67	PV	0.78	0.52	35	0	15.5	–10.8	0.04
68	PQ	49.4	27.3	–	–	–	–	–
69	PQ	192.01	106.21	–	–	–	–	–
70	PQ	–	–	–	–	–	–	–
71	PQ	94.12	52	–	–	–	–	–
72	PQ	127.14	70.33	–	–	–	–	–
73	PQ	–	–	–	–	–	–	–
74	PQ	62.79	34.71	–	–	–	–	–
75	PQ	–	–	–	–	–	–	–

Table A.10 Transmission line data of northeastern Thailand system

From bus	To bus	r_{ij}	rx_{ij}	b_{ij}	S_{ij_lim}	n_{ij}^{0}
1	10	0.0662	0.1404	0.0171	96.4	1
1	45	0.058	0.255	0.0383	162.9	1
1	61	0.0008	0.0033	0.0005	162.9	1
1	61	0.0008	0.0033	0.0005	162.9	1
2	21	0.0015	0.0154	0.0628	858.9	1
2	21	0.0015	0.0154	0.0628	858.9	1
3	4	0.0019	0.0124	0.0032	325.9	1
3	4	0.0019	0.0124	0.0032	325.9	1
4	18	0.0298	0.0836	0.0117	119.5	1
4	18	0.0298	0.0836	0.0117	119.5	1
4	67	0.0623	0.0782	0.0083	67.1	1
4	71	0.0991	0.2813	0.0387	119.5	1
4	71	0.0991	0.2813	0.0387	119.5	1
4	72	0.0832	0.2339	0.0328	325.9	1
4	72	0.0832	0.2339	0.0328	325.9	1
5	26	0.2398	0.3017	0.0323	67.1	1
5	68	0.0409	0.1799	0.027	162.9	1
5	74	0.0495	0.139	0.0195	119.5	1
5	74	0.0495	0.139	0.0195	119.5	1
6	11	0.0376	0.1653	0.0248	162.9	1
7	38	0.0412	0.1212	0.0154	119.5	1
8	18	0.0399	0.1119	0.0157	119.5	1
8	22	0.0975	0.2742	0.0385	119.5	1
9	43	0.0101	0.03	0.0038	119.5	1
9	44	0.1106	0.326	0.0417	119.5	1
10	30	0.1579	0.3359	0.0411	96.4	1
10	31	0.1389	0.3914	0.0551	119.5	1

From bus	To bus	r_{ij}	rx_{ij}	b_{ij}	S_{ij_lim}	n_{ij}^0
10	31	0.1389	0.3914	0.0551	119.5	1
10	49	0.0489	0.1372	0.0192	119.5	1
11	46	0.0549	0.1616	0.0206	119.5	1
12	21	0.0097	0.0702	0.1546	429.4	1
12	21	0.0097	0.0702	0.1546	429.4	1
12	32	0.0101	0.0729	0.1605	429.4	1
12	32	0.0101	0.0729	0.1605	429.4	1
13	14	0.0515	0.1523	0.0192	119.5	1
14	18	0.0872	0.2582	0.0326	119.5	1
15	70	0.0225	0.1637	0.3661	429.4	1
15	70	0.0225	0.1637	0.3661	429.4	1
16	20	0.0753	0.2113	0.0297	119.5	1
16	20	0.0753	0.2113	0.0297	119.5	1
16	25	0.1166	0.1464	0.0156	67.1	1
16	50	0.0382	0.1071	0.015	119.5	1
16	50	0.0382	0.1071	0.015	119.5	1
16	53	0.0775	0.3415	0.0513	162.9	1
16	60	0.0263	0.1158	0.0173	162.9	1
17	69	0.0352	0.1547	0.0232	162.9	1
18	20	0.0071	0.0198	0.0028	119.5	1
18	20	0.0071	0.0198	0.0028	119.5	1
18	22	0.1365	0.3845	0.0541	119.5	1
18	25	0.2222	0.2794	0.0299	67.1	1
18	46	0.189	0.2376	0.0254	67.1	1
18	67	0.141	0.1771	0.0189	67.1	1
19	21	0.0007	0.005	0.011	429.4	1
19	21	0.0007	0.005	0.011	429.4	1
21	52	0.0092	0.0663	0.1459	429.4	1

From bus	To bus	r_{ij}	rx_{ij}	b_{ij}	S_{ij_lim}	n_{ij}^0
21	52	0.0092	0.0663	0.1459	429.4	1
22	30	0.0612	0.1719	0.0241	119.5	1
22	31	0.0501	0.1407	0.0197	119.5	1
23	32	0.0065	0.0468	0.1028	1503.1	1
23	32	0.0065	0.0468	0.1028	1503.1	1
24	37	0.0787	0.2318	0.0296	119.5	1
25	50	0.0986	0.1232	0.0133	67.1	1
26	27	0.0055	0.0243	0.0036	162.9	1
26	65	0.0292	0.1282	0.0192	162.9	1
27	65	0.0226	0.0994	0.0149	162.9	1
28	54	0.1878	0.2095	0.0286	67.1	1
28	65	0.038	0.167	0.025	162.9	1
28	65	0.038	0.167	0.025	162.9	1
29	55	0.0086	0.062	0.137	429.4	1
29	63	0.0019	0.0136	0.0299	429.4	1
30	31	0.0074	0.0324	0.0048	162.9	1
30	31	0.0074	0.0324	0.0048	162.9	1
30	46	0.2861	0.3603	0.0386	67.1	1
31	58	0.0303	0.0872	0.0117	117.5	1
31	58	0.0303	0.0872	0.0117	117.5	1
33	34	0.0456	0.1349	0.017	119.5	1
33	43	0.0862	0.2549	0.0321	119.5	1
34	48	0.074	0.208	0.0292	119.5	1
34	48	0.074	0.208	0.0292	119.5	1
34	48	0.1892	0.2378	0.0254	67.1	1
36	53	0.0164	0.0721	0.0108	162.9	1
36	60	0.033	0.1452	0.0217	162.9	1
37	71	0.0522	0.1534	0.0196	119.5	1

From bus	To bus	r_{ij}	rx_{ij}	b_{ij}	S_{ij_lim}	n_{ij}^0
37	72	0.0388	0.1707	0.0256	162.9	1
38	44	0.0557	0.1656	0.0207	119.5	1
38	72	0.039	0.1159	0.0145	119.5	1
39	48	0.0261	0.0732	0.0103	119.5	1
39	48	0.0261	0.0732	0.0103	119.5	1
39	64	0.0283	0.0355	0.0038	67.1	1
39	71	0.0475	0.1332	0.0187	119.5	1
39	71	0.116	0.1456	0.0156	67.1	1
39	72	0.0527	0.148	0.0208	119.5	1
40	58	0.0448	0.129	0.0173	117.5	1
41	69	0.0717	0.2013	0.0283	119.5	1
41	69	0.0717	0.2013	0.0283	119.5	1
42	59	0.0608	0.1789	0.0228	119.5	1
42	73	0.0709	0.2087	0.0266	119.5	1
44	53	0.0746	0.1608	0.019	96.4	1
44	53	0.0521	0.1535	0.0195	119.5	1
44	72	0.1454	0.3139	0.0372	96.4	1
45	50	0.0576	0.2532	0.038	162.9	1
45	50	0.0576	0.2532	0.038	162.9	1
47	50	0.0253	0.111	0.0166	162.9	1
48	64	0.0467	0.0586	0.0063	67.1	1
50	74	0.0701	0.197	0.0276	119.5	1
50	74	0.0701	0.197	0.0276	119.5	1
51	52	0.002	0.0144	0.0316	429.4	1
51	52	0.002	0.0144	0.0316	429.4	1
51	75	0.0034	0.036	0.1469	858.9	1
51	75	0.0034	0.036	0.1469	858.9	1
52	62	0.0144	0.1038	0.2301	398.4	1

From bus	To bus	r_{ij}	rx_{ij}	b_{ij}	S_{ij_lim}	n_{ij}^{0}
52	62	0.0144	0.1038	0.2301	398.4	1
53	54	0.0056	0.0348	0.0102	325.9	1
53	54	0.0056	0.0348	0.0102	325.9	1
53	65	0.278	0.2484	0.0246	48.2	1
55	63	0.0075	0.0543	0.12	429.4	1
56	61	0.0272	0.1196	0.0179	162.9	1
57	69	0.0608	0.1707	0.024	119.5	1
57	69	0.0608	0.1707	0.024	119.5	1
57	74	0.0897	0.2517	0.0354	119.5	1
57	74	0.0897	0.2517	0.0354	119.5	1
59	68	0.164	0.1905	0.0239	67.1	1
59	68	0.164	0.1905	0.0239	67.1	1
63	66	0.0084	0.0605	0.1337	429.4	1
63	66	0.0084	0.0605	0.1337	429.4	1
68	69	0.0302	0.0846	0.0119	119.5	1
68	69	0.0302	0.0846	0.0119	119.5	1
68	74	0.0965	0.285	0.0362	119.5	1
71	72	0.0111	0.0321	0.0043	117.5	1

Table A.11 Transformer data of northeastern Thailand system

From bus	To bus	r_{ij}	rx_{ij}	b_{ij}	S_{ij_lim}	n_{ij}^{0}
2	3	0	0.065	0	200	1
2	3	0	0.0621	0	200	1
11	12	0	0.0692	0	200	1
11	12	0	0.0691	0	200	1
18	19	0	0.0583	0	200	1
18	19	0	0.0583	0	200	1

From bus	To bus	r_{ij}	rx_{ij}	b_{ij}	S_{ij_lim}	n_{ij}^0
18	19	0	0.06	0	200	1
28	29	0	0.065	0	200	1
28	29	0	0.065	0	200	1
31	32	0	0.055	0	300	1
31	32	0	0.055	0	300	1
31	32	0	0.055	0	300	1
35	36	0	0.2338	0	40	1
50	51	0	0.0675	0	200	1
50	51	0	0.0675	0	200	1
50	51	0	0.065	0	200	1
54	55	0	0.0692	0	200	1
54	55	0	0.0692	0	200	1
61	62	0	0.065	0	200	1
61	62	0	0.065	0	200	1
69	70	0	0.072	0	200	1
69	70	0	0.072	0	200	1
74	75	0	0.065	0	200	1
74	75	0	0.065	0	200	1

Table A.12 Transmission line candidate data of northeastern Thailand system

From bus	To bus	r_{ij}	rx_{ij}	b_{ij}	S_{ij_lim}	c_{ij}	n_{ij}^0
1	10	0.0289	0.1272	0.0191	162.9	20.6	1
1	10	0.0289	0.1272	0.0191	162.9	20.6	1
1	45	0.058	0.255	0.0383	162.9	37.6	1
1	45	0.058	0.255	0.0383	162.9	37.6	1
1	56	0.0298	0.1309	0.0196	162.9	21	1
1	56	0.0298	0.1309	0.0196	162.9	21	1

From bus	To bus	r_{ij}	rx_{ij}	b_{ij}	S_{ij_lim}	c_{ij}	n_{ij}^{0}
1	61	0.0008	0.0033	0.0005	162.9	4	1
1	61	0.0008	0.0033	0.0005	162.9	4	1
2	12	0.0129	0.0931	0.2044	429.4	72.9	1
2	12	0.0129	0.0931	0.2044	429.4	72.9	1
2	19	0.0034	0.0244	0.0535	429.4	24	1
2	19	0.0034	0.0244	0.0535	429.4	24	1
2	21	0.0029	0.0211	0.0464	429.4	21.6	1
2	21	0.0029	0.0211	0.0464	429.4	21.6	1
2	51	0.0129	0.093	0.2043	429.4	72.9	1
2	51	0.0129	0.093	0.2043	429.4	72.9	1
2	52	0.0113	0.0812	0.1783	429.4	64.5	1
2	52	0.0113	0.0812	0.1783	429.4	64.5	1
3	4	0.0037	0.0163	0.0024	162.9	5.8	1
3	4	0.0037	0.0163	0.0024	162.9	5.8	1
3	18	0.0213	0.0934	0.014	162.9	16	1
3	18	0.0213	0.0934	0.014	162.9	16	1
3	20	0.0223	0.098	0.0147	162.9	16.7	1
3	20	0.0223	0.098	0.0147	162.9	16.7	1
3	67	0.0117	0.0515	0.0077	162.9	10.5	1
3	67	0.0117	0.0515	0.0077	162.9	10.5	1
4	18	0.0184	0.0811	0.0122	162.9	14.4	1
4	18	0.0184	0.0811	0.0122	162.9	14.4	1
4	20	0.0205	0.0901	0.0135	162.9	15.6	1
4	20	0.0205	0.0901	0.0135	162.9	15.6	1
4	67	0.0151	0.0663	0.0099	162.9	12.4	1
4	67	0.0151	0.0663	0.0099	162.9	12.4	1
4	71	0.0615	0.2705	0.0405	162.9	39.7	1
4	71	0.0615	0.2705	0.0405	162.9	39.7	1

From bus	To bus	r_{ij}	rx_{ij}	b_{ij}	S_{ij_lim}	c_{ij}	n_{ij}^0
4	72	0.0516	0.2269	0.034	162.9	33.9	1
4	72	0.0516	0.2269	0.034	162.9	33.9	1
5	26	0.0583	0.2561	0.0384	162.9	37.8	1
5	26	0.0583	0.2561	0.0384	162.9	37.8	1
5	68	0.0409	0.1799	0.027	162.9	27.6	1
5	68	0.0409	0.1799	0.027	162.9	27.6	1
5	74	0.0307	0.1348	0.0202	162.9	21.6	1
5	74	0.0307	0.1348	0.0202	162.9	21.6	1
6	11	0.0376	0.1653	0.0248	162.9	25.6	1
6	11	0.0376	0.1653	0.0248	162.9	25.6	1
7	38	0.0255	0.1121	0.0168	162.9	18.5	1
7	38	0.0255	0.1121	0.0168	162.9	18.5	1
8	18	0.0247	0.1085	0.0163	162.9	18.1	1
8	18	0.0247	0.1085	0.0163	162.9	18.1	1
8	20	0.0281	0.1234	0.0185	162.9	20	1
8	20	0.0281	0.1234	0.0185	162.9	20	1
8	22	0.0606	0.2662	0.0399	162.9	39.1	1
8	22	0.0606	0.2662	0.0399	162.9	39.1	1
8	46	0.0235	0.1031	0.0155	162.9	17.3	1
8	46	0.0235	0.1031	0.0155	162.9	17.3	1
9	44	0.0688	0.3024	0.0453	162.9	43.9	1
9	44	0.0688	0.3024	0.0453	162.9	43.9	1
10	30	0.0693	0.3047	0.0457	162.9	44.2	1
10	30	0.0693	0.3047	0.0457	162.9	44.2	1
10	31	0.0866	0.3806	0.0571	162.9	54.4	1
10	31	0.0866	0.3806	0.0571	162.9	54.4	1
10	49	0.0303	0.1331	0.02	162.9	21.3	1
10	49	0.0303	0.1331	0.02	162.9	21.3	1

From bus	To bus	r_{ij}	rx_{ij}	b_{ij}	S_{ij_lim}	c_{ij}	n_{ij}^0
10	61	0.0315	0.1385	0.0208	162.9	22.1	1
10	61	0.0315	0.1385	0.0208	162.9	22.1	1
11	46	0.034	0.1496	0.0224	162.9	23.5	1
11	46	0.034	0.1496	0.0224	162.9	23.5	1
12	19	0.0111	0.0803	0.1762	429.4	63.8	1
12	19	0.0111	0.0803	0.1762	429.4	63.8	1
12	21	0.0098	0.0703	0.1545	429.4	56.7	1
12	21	0.0098	0.0703	0.1545	429.4	56.7	1
12	32	0.0101	0.0729	0.1605	429.4	58.7	1
12	32	0.0101	0.0729	0.1605	429.4	58.7	1
13	14	0.0319	0.1403	0.021	162.9	22.3	1
13	14	0.0319	0.1403	0.021	162.9	22.3	1
14	18	0.0541	0.238	0.0357	162.9	35.3	1
14	18	0.0541	0.238	0.0357	162.9	35.3	1
16	20	0.0467	0.2054	0.0308	162.9	31	1
16	20	0.0467	0.2054	0.0308	162.9	31	1
16	25	0.0283	0.1243	0.0186	162.9	20.2	1
16	25	0.0283	0.1243	0.0186	162.9	20.2	1
16	47	0.0272	0.1195	0.0179	162.9	19.5	1
16	47	0.0272	0.1195	0.0179	162.9	19.5	1
16	50	0.0236	0.1039	0.0156	162.9	17.4	1
16	50	0.0236	0.1039	0.0156	162.9	17.4	1
16	53	0.0775	0.3415	0.0513	162.9	49.2	1
16	53	0.0775	0.3415	0.0513	162.9	49.2	1
16	60	0.0263	0.1158	0.0173	162.9	19	1
16	60	0.0263	0.1158	0.0173	162.9	19	1
17	57	0.0354	0.1556	0.0233	162.9	24.3	1
17	57	0.0354	0.1556	0.0233	162.9	24.3	1

From bus	To bus	r_{ij}	rx_{ij}	b_{ij}	S_{ij_lim}	c_{ij}	n_{ij}^0
17	69	0.0352	0.1547	0.0232	162.9	24.2	1
17	69	0.0352	0.1547	0.0232	162.9	24.2	1
18	20	0.0044	0.0192	0.0029	162.9	6.1	1
18	20	0.0044	0.0192	0.0029	162.9	6.1	1
18	22	0.0851	0.3739	0.056	162.9	53.5	1
18	22	0.0851	0.3739	0.056	162.9	53.5	1
18	25	0.054	0.2372	0.0356	162.9	35.2	1
18	25	0.054	0.2372	0.0356	162.9	35.2	1
18	46	0.0459	0.2016	0.0302	162.9	30.5	1
18	46	0.0459	0.2016	0.0302	162.9	30.5	1
18	67	0.0342	0.1503	0.0225	162.9	23.6	1
18	67	0.0342	0.1503	0.0225	162.9	23.6	1
19	21	0.0007	0.005	0.011	429.4	10.2	1
19	21	0.0007	0.005	0.011	429.4	10.2	1
19	51	0.0106	0.0762	0.1672	429.4	60.9	1
19	51	0.0106	0.0762	0.1672	429.4	60.9	1
19	52	0.0089	0.0639	0.1403	429.4	52.1	1
19	52	0.0089	0.0639	0.1403	429.4	52.1	1
20	25	0.0372	0.1636	0.0245	162.9	25.4	1
20	25	0.0372	0.1636	0.0245	162.9	25.4	1
20	67	0.0332	0.1461	0.0219	162.9	23.1	1
20	67	0.0332	0.1461	0.0219	162.9	23.1	1
21	51	0.0113	0.0817	0.1794	429.4	64.8	1
21	51	0.0113	0.0817	0.1794	429.4	64.8	1
21	52	0.0092	0.0663	0.1459	429.4	53.9	1
21	52	0.0092	0.0663	0.1459	429.4	53.9	1
22	30	0.0379	0.1667	0.025	162.9	25.8	1
22	30	0.0379	0.1667	0.025	162.9	25.8	1

From bus	To bus	r_{ij}	rx_{ij}	b_{ij}	S_{ij_lim}	c_{ij}	n_{ij}^0
22	31	0.031	0.1364	0.0204	162.9	21.8	1
22	31	0.031	0.1364	0.0204	162.9	21.8	1
23	32	0.0065	0.0468	0.1028	429.4	40	1
23	32	0.0065	0.0468	0.1028	429.4	40	1
24	37	0.0488	0.2147	0.0322	162.9	32.2	1
24	37	0.0488	0.2147	0.0322	162.9	32.2	1
25	50	0.0239	0.105	0.0157	162.9	17.6	1
25	50	0.0239	0.105	0.0157	162.9	17.6	1
26	27	0.0055	0.0243	0.0036	162.9	6.8	1
26	27	0.0055	0.0243	0.0036	162.9	6.8	1
26	65	0.0292	0.1282	0.0192	162.9	20.7	1
26	65	0.0292	0.1282	0.0192	162.9	20.7	1
27	65	0.0226	0.0994	0.0149	162.9	16.8	1
27	65	0.0226	0.0994	0.0149	162.9	16.8	1
28	54	0.0456	0.2004	0.03	162.9	30.3	1
28	54	0.0456	0.2004	0.03	162.9	30.3	1
28	65	0.038	0.167	0.025	162.9	25.9	1
28	65	0.038	0.167	0.025	162.9	25.9	1
29	55	0.0086	0.062	0.137	429.4	50.9	1
29	55	0.0086	0.062	0.137	429.4	50.9	1
30	31	0.0074	0.0324	0.0048	162.9	7.9	1
30	31	0.0074	0.0324	0.0048	162.9	7.9	1
30	46	0.0696	0.306	0.0459	162.9	44.4	1
30	46	0.0696	0.306	0.0459	162.9	44.4	1
31	58	0.0187	0.0823	0.0123	162.9	14.6	1
31	58	0.0187	0.0823	0.0123	162.9	14.6	1
36	44	0.0354	0.1557	0.0233	162.9	24.4	1
36	44	0.0354	0.1557	0.0233	162.9	24.4	1

From bus	To bus	r_{ij}	rx_{ij}	b_{ij}	S_{ij_lim}	c_{ij}	n_{ij}^{0}
36	53	0.0164	0.0721	0.0108	162.9	13.2	1
36	53	0.0164	0.0721	0.0108	162.9	13.2	1
36	54	0.0245	0.1078	0.0162	162.9	18	1
36	54	0.0245	0.1078	0.0162	162.9	18	1
36	60	0.033	0.1452	0.0217	162.9	22.9	1
36	60	0.033	0.1452	0.0217	162.9	22.9	1
37	71	0.0323	0.142	0.0213	162.9	22.5	1
37	71	0.0323	0.142	0.0213	162.9	22.5	1
37	72	0.0388	0.1707	0.0256	162.9	26.4	1
37	72	0.0388	0.1707	0.0256	162.9	26.4	1
38	44	0.0345	0.1518	0.0228	162.9	23.8	1
38	44	0.0345	0.1518	0.0228	162.9	23.8	1
38	71	0.0313	0.1374	0.0206	162.9	21.9	1
38	71	0.0313	0.1374	0.0206	162.9	21.9	1
38	72	0.0241	0.1061	0.0159	162.9	17.7	1
38	72	0.0241	0.1061	0.0159	162.9	17.7	1
39	71	0.0294	0.1292	0.0194	162.9	20.8	1
39	71	0.0294	0.1292	0.0194	162.9	20.8	1
39	72	0.0327	0.1436	0.0215	162.9	22.7	1
39	72	0.0327	0.1436	0.0215	162.9	22.7	1
40	58	0.0277	0.1219	0.0183	162.9	19.8	1
40	58	0.0277	0.1219	0.0183	162.9	19.8	1
41	59	0.0064	0.0283	0.0042	162.9	7.4	1
41	59	0.0064	0.0283	0.0042	162.9	7.4	1
41	69	0.0445	0.1954	0.0293	162.9	29.7	1
41	69	0.0445	0.1954	0.0293	162.9	29.7	1
44	53	0.0326	0.1434	0.0215	162.9	22.7	1
44	53	0.0326	0.1434	0.0215	162.9	22.7	1

From bus	To bus	r_{ij}	rx_{ij}	b_{ij}	S_{ij_lim}	c_{ij}	n_{ij}^0
44	54	0.0308	0.1354	0.0203	162.9	21.6	1
44	54	0.0308	0.1354	0.0203	162.9	21.6	1
44	72	0.0638	0.2803	0.042	162.9	41	1
44	72	0.0638	0.2803	0.042	162.9	41	1
45	50	0.0576	0.2532	0.038	162.9	37.4	1
45	50	0.0576	0.2532	0.038	162.9	37.4	1
47	50	0.0253	0.111	0.0166	162.9	18.4	1
47	50	0.0253	0.111	0.0166	162.9	18.4	1
47	60	0.0317	0.1392	0.0209	162.9	22.2	1
47	60	0.0317	0.1392	0.0209	162.9	22.2	1
50	74	0.0435	0.1912	0.0287	162.9	29.1	1
50	74	0.0435	0.1912	0.0287	162.9	29.1	1
51	52	0.002	0.0144	0.0316	429.4	16.9	1
51	52	0.002	0.0144	0.0316	429.4	16.9	1
51	62	0.0145	0.1045	0.2295	429.4	81.1	1
51	62	0.0145	0.1045	0.2295	429.4	81.1	1
51	75	0.0069	0.0493	0.1084	429.4	41.8	1
51	75	0.0069	0.0493	0.1084	429.4	41.8	1
52	62	0.0145	0.1044	0.2293	429.4	81	1
52	62	0.0145	0.1044	0.2293	429.4	81	1
52	75	0.0089	0.0644	0.1414	429.4	52.5	1
52	75	0.0089	0.0644	0.1414	429.4	52.5	1
53	54	0.0111	0.0489	0.0073	162.9	10.1	1
53	54	0.0111	0.0489	0.0073	162.9	10.1	1
53	65	0.044	0.1933	0.029	162.9	29.4	1
53	65	0.044	0.1933	0.029	162.9	29.4	1
56	61	0.0272	0.1196	0.0179	162.9	19.5	1
56	61	0.0272	0.1196	0.0179	162.9	19.5	1

From bus	To bus	r_{ij}	rx_{ij}	b_{ij}	S_{ij_lim}	c_{ij}	n_{ij}^0
57	69	0.0377	0.1657	0.0248	162.9	25.7	1
57	69	0.0377	0.1657	0.0248	162.9	25.7	1
57	74	0.0557	0.2447	0.0367	162.9	36.2	1
57	74	0.0557	0.2447	0.0367	162.9	36.2	1
59	68	0.0398	0.1748	0.0262	162.9	26.9	1
59	68	0.0398	0.1748	0.0262	162.9	26.9	1
62	75	0.0137	0.0984	0.216	429.4	76.7	1
62	75	0.0137	0.0984	0.216	429.4	76.7	1
68	69	0.0187	0.0821	0.0123	162.9	14.5	1
68	69	0.0187	0.0821	0.0123	162.9	14.5	1
68	74	0.0599	0.2635	0.0395	162.9	38.7	1
68	74	0.0599	0.2635	0.0395	162.9	38.7	1
70	75	0.0114	0.082	0.1801	429.4	65.1	1
70	75	0.0114	0.082	0.1801	429.4	65.1	1
71	72	0.0069	0.0302	0.0045	162.9	7.6	1
71	72	0.0069	0.0302	0.0045	162.9	7.6	1

Table A.13 Transformer candidate data of northeastern Thailand system

From bus	To bus	r_{ij}	rx_{ij}	b_{ij}	S_{ij_lim}	c_{ij}	n_{ij}^0
2	3	0	0.055	0	300	18.8	1
2	3	0	0.055	0	300	18.8	1
11	12	0	0.055	0	300	18.8	1
11	12	0	0.055	0	300	18.8	1
18	19	0	0.055	0	300	18.8	1
18	19	0	0.055	0	300	18.8	1
28	29	0	0.055	0	300	18.8	1
28	29	0	0.055	0	300	18.8	1

From bus	To bus	r_{ij}	rx_{ij}	b_{ij}	S_{ij_lim}	c_{ij}	n_{ij}^0
31	32	0	0.055	0	300	18.8	1
31	32	0	0.055	0	300	18.8	1
50	51	0	0.055	0	300	18.8	1
50	51	0	0.055	0	300	18.8	1
54	55	0	0.055	0	300	18.8	1
54	55	0	0.055	0	300	18.8	1
61	62	0	0.055	0	300	18.8	1
61	62	0	0.055	0	300	18.8	1
69	70	0	0.055	0	300	18.8	1
69	70	0	0.055	0	300	18.8	1
74	75	0	0.055	0	300	18.8	1
74	75	0	0.055	0	300	18.8	1

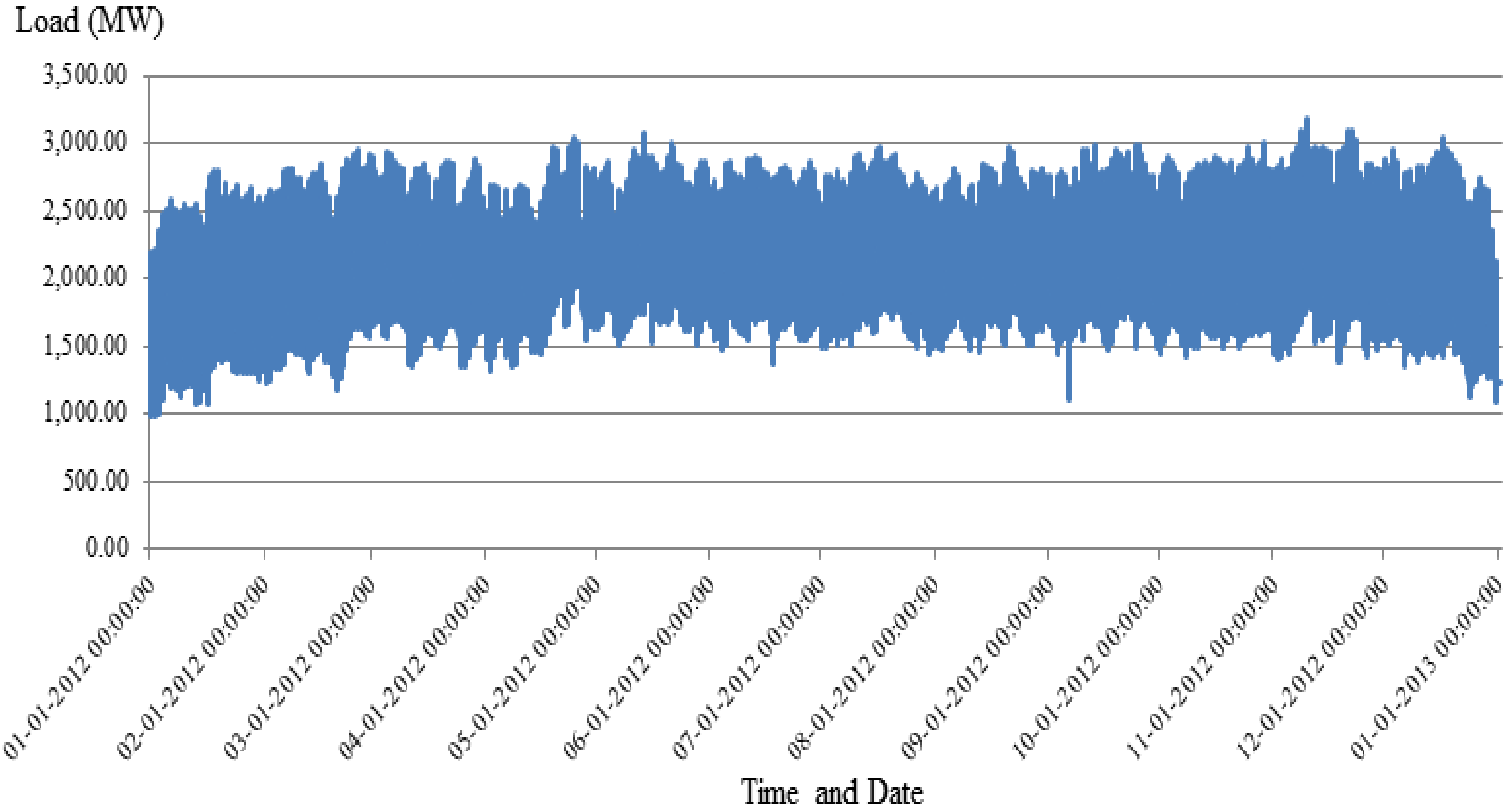

Figure A.1 Hourly load curve of northeastern Thailand system in the year 2012

A.3 Thailand Solar Radiation and Wind Speed

Both solar radiation and wind speed from Nakhon Ratchasima province, Thailand are selected as the representative of the northeastern Thailand solar radiation and wind speed, respectively. For wind speed measurement, the height of wind measurements above ground is 40 meters. These data are obtained from the meteorological department of Thailand. The hourly solar radiation and hourly wind speed are illustrated in Figure A.2 and A.3, respectively.

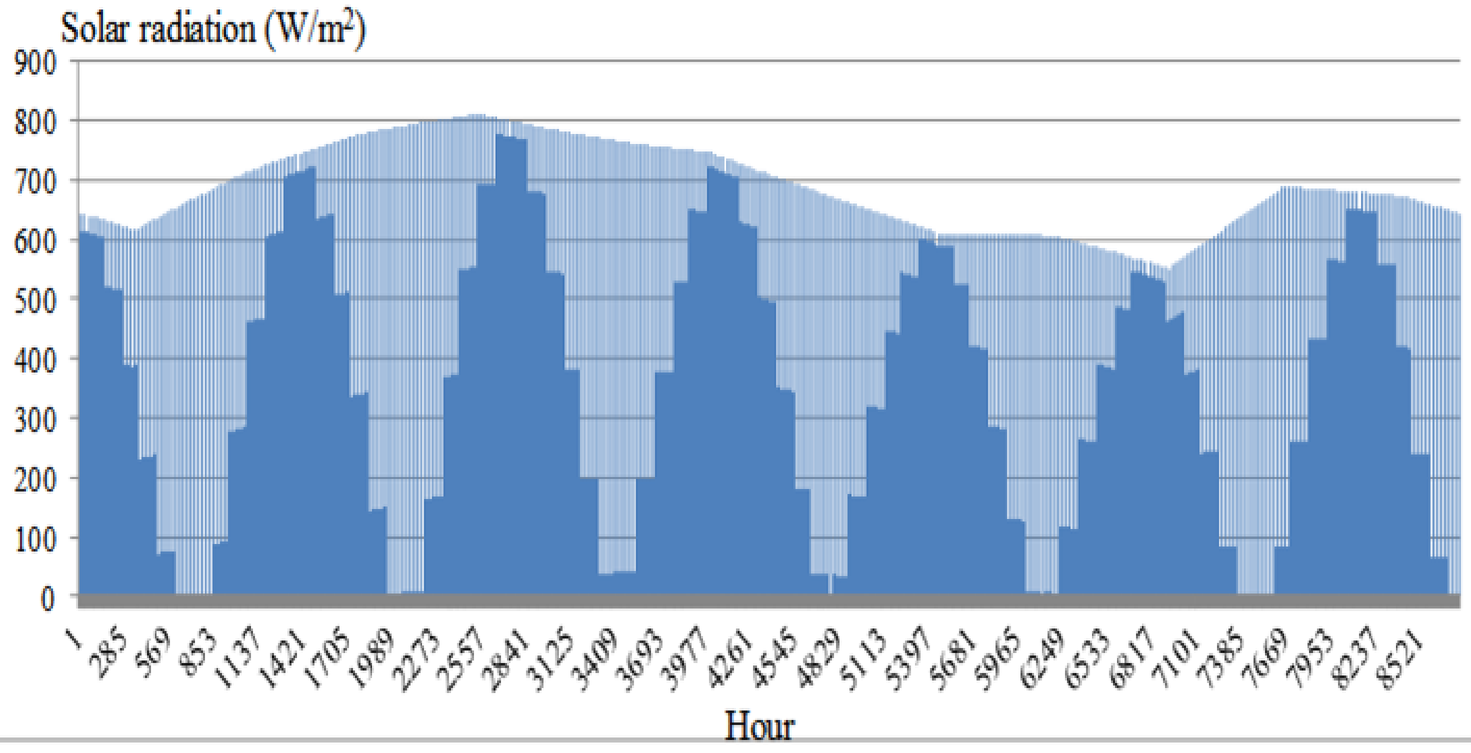

Figure A.2 Hourly solar radiation of Nakhon Ratchasima province, Thailand

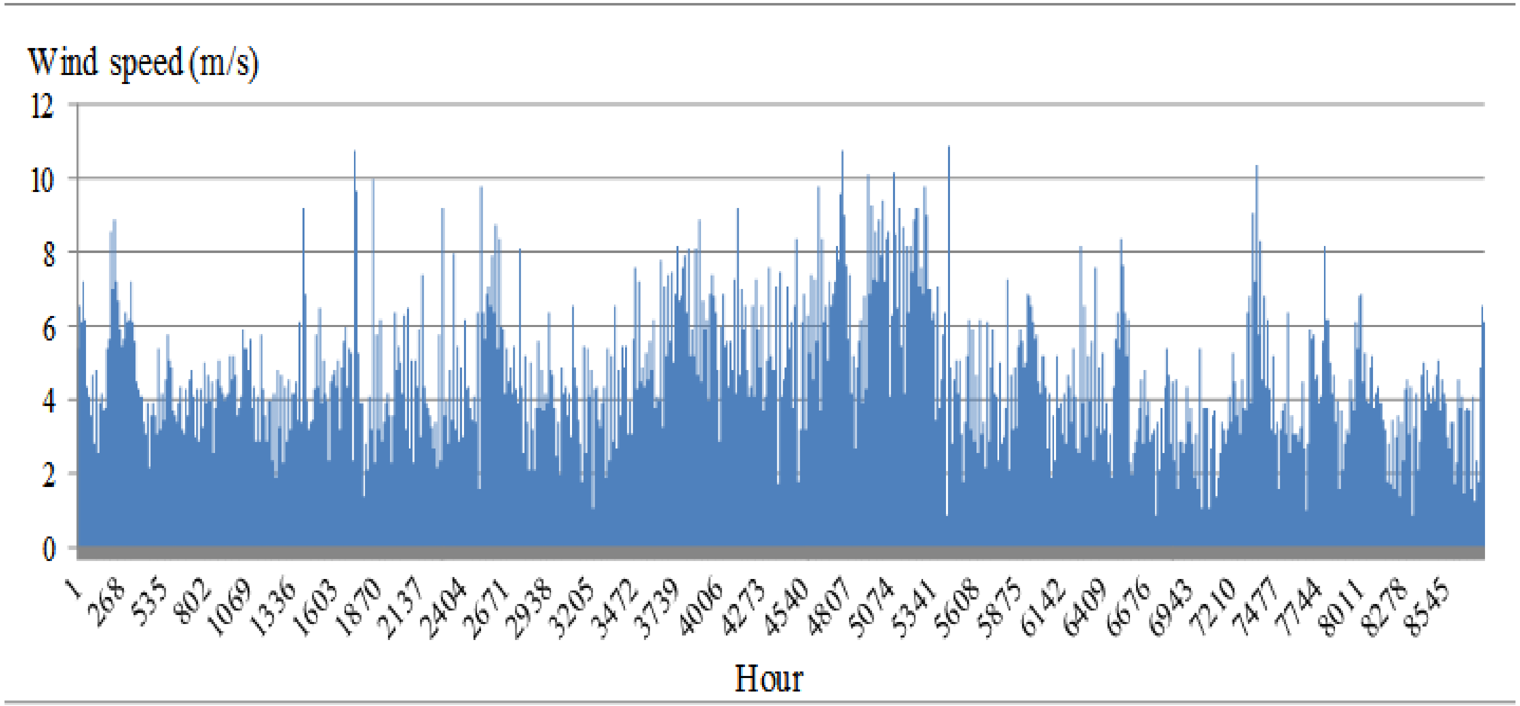

Figure A.3 Hourly wind speed of Nakhon Ratchasima province, Thailand

VITA

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