Transmission Network Expansion Planning Considering Wind Farms

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ABSTRACT

Recently, electrical energy consumption has been increasing significantly as a consequence of industry advancement and lifestyle quality improvement. To fulfill future energy demand, the generation capacity has to be expanded. Previously, power generation was essentially based on conventional units. But, because of some issues related to the environment and economy, the permeation of renewable energy (RE) resources in the electrical power system have been notably increased bringing significant challenges to transmission expansion planning (TEP) issue due to intermittent and unmanageable nature of the renewable resources. TEP is a mixed-integer non-linear optimization problem. Where its essential aim is to determine the optimum lines to be constructed in order to transmit the power and supply the current and the predicted load in a reliable and economical way over the planning horizon.

This thesis proposes a methodology for solving the TEP problem with consideration of wind farms integration into the power system. Where a hybrid heuristic optimization approach (a mixture of backward and forward approach) is utilized to find the optimum branches to be built for several scenarios of wind energy generation to show the impact of the RE resources on the TEP. Moreover, both conditions normal and N-1 contingency are considered to ensure the robustness of the system against the contingencies and check if it is able to withstand at least one contingency criterion.

The proposed approach was applied to the 24-Bus IEEE Reliability Test System where the optimal solutions of the different cases were obtained and the results confirmed that penetration of wind farm does modify the optimal plan.

Keywords: Transmission expansion planning, renewable energy resources, wind farms, forecasted load, uncertainty, IEEE-RTS, contingency N-1, optimization techniques, hybrid approach.

ÖZ

Son zamanlarda, elektrik enerjisi tüketimi, sektördeki ilerlemenin ve yaşam tarzı kalitesinin iyileşmesinin bir sonucu olarak önemli ölçüde artmaktadır. Gelecekteki enerji talebini karşılamak için, üretim kapasitesinin arttırılması gerekmektedir. Önceden, elektrik üretimi temel olarak geleneksel birimlere dayanıyordu. Ancak, çevre ve ekonomi ile ilgili bazı meseleler nedeniyle, elektrik enerjisi sistemindeki yenilenebilir enerji (RE) kaynaklarının geçirgenliği büyük ölçüde artmıştır. Bununla birlikte, yenilenebilir kaynakların aralıklı ve yönetilemez doğası, iletim genişletme planlaması (TEP) sorununa önemli zorluklar getirmiştir. TEP, karışık tamsayılı doğrusal olmayan bir optimizasyon problemidir. Temel amacının, gücü ulaştırmak ve mevcut ufuktaki öngörülen yükü planlama ufku üzerinden güvenilir ve ekonomik bir şekilde sağlamak için yapılacak optimum hatların belirlenmesidir.

Bu tez, rüzgar santrallerinin enerji sistemine entegrasyonu ile ilgili olarak TEP problemini çözmek için bir metodoloji önermektedir. RE kaynaklarının TEP üzerindeki etkisini göstermek için rüzgar enerjisi üretiminin birkaç senaryosunda kurulacak optimum dalları bulmak için hibrit bir sezgisel optimizasyon yaklaşımının (geri ve ileri yaklaşımın bir karışımı) kullanılması durumunda. Ayrıca, normal ve N-1 koşullarının her ikisinin de koşullu koşullara karşı sistemin sağlamlığını sağladığı ve en az bir acil durum kriterine dayanıp dayanamadığını kontrol ettiği düşünülmektedir.

Önerilen yaklaşım, farklı vakaların en uygun çözümlerinin elde edildiği 24-Bus IEEE Güvenilirlik Test Sistemine uygulandı ve sonuçlar rüzgar çiftliği nüfuzunun en uygun planı değiştirdiğini doğruladı.

Anahtar Kelimeler: İletim genişleme planlaması, yenilenebilir enerji kaynakları, rüzgar çiftlikleri, öngörülen yük, belirsizlik, IEEE-RTS, beklenmedik durum N-1, optimizasyon teknikleri, hibrid yaklaşım.

DEDICATION

“To My Beloved Family And Dear Friends Who Believed In Me”.

ACKNOWLEDGMENT

I have finally reached the end of this new journey. I would like to thank my supervisor, Assoc.Prof.Dr.Reza Sirjani, whose door was always opened for my questions and for his guidance and kindness.

I would like also to thank my family for their support and motivation. For their efforts to help me overcome my fears and face my obstacles. Finally, I would like to thank my friends for standing by my side and helping me to relax and rest my mind every once in a while.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

DCLF	Direct Current Load Flow
IEEE	Institute Of Electrical And Electronics Engineers
MCS	Monte-Carlo Simulation
MINLP	Mixed-Integer Nonlinear Programming
MOF	Min Objective Function
N	Normal Condition
N-1	A Single Contingency Condition Caused by an Outage of one Line
Pu	Per Unit
RE	Renewable Energy
RPS	Renewable Portfolio Standard
RTS	Reliability Test System
TCB	Total Cost of the Optimum Lines Chosen by the Backward Method
TCF	Total Cost of the Optimum Lines Chosen by the Forward Method
TEP	Transmission Expansion Planning

Chapter 1

INTRODUCTION

1.1 Background

The electrical power system is made up of generation, transmission, and distribution system. The main role of the power system is to generate and transfer power to the intended customer in an authentic and reasonable manner. Over the past years, the lifestyle quality improvement and rapid industrial sector development led to a significant increment in electrical energy usage, and as a way to fulfill the increasing demands on energy the generation capacity has to be expanded. Moreover, due to some issues that are related to the environment and economy; the permeation of renewable energy (RE) resources in the electrical power system has been notably increased. As a consequence of growing demands on energy and integration of (RE) to the system the transmission network needs to be modified, where new lines must be incorporated into the network to transmit the electrical energy from power plants to the target destination in a timely and convenient manner.

Transmission expansion planning (TEP) remedy the issue of extending a current transmission network to serve the predicted demands subject to many of the financial and technical requirements. The TEP signifies the place, time and the number of the new lines that ought to be introduced in the network. But, the variable and discontinuous nature of renewable sources will influence the TEP process. Thus, the incorporation of RE resources with conventional ones should be dealt with strictly whilst upgrading the system [1].

TEP might be analyzed from different aspects such as a planning horizon, problem modeling, problem-solving methods. The objective functions could be investment cost reduction [6,23,24,27], reliability and security improvement [14,20,25], uncertainties consideration [1,3,5,7,9,10,12,13,14,18,19], improving computational performance [8], etc. The proposed objectives are often contradictory and they are not always met simultaneously. In this manner, the TEP issue turns into a multi-objective optimization problem which cannot be fathomed adequately by traditional techniques. In contrast, numerous mathematical [13,23], heuristic and metaheuristic approaches [3,7,18,20,24,25,26,27] were used to figure out the multi-objective optimization problem while considering some constraints. From these suggested strategies, the most essential strategy is meta (heuristic) algorithms since they consume less time, require a minimum extent of efforts and their optimal solution is usually accurate, unlike the classical approaches which may stick to a local minimum solution instead of global one [2].

DC and AC models are the main mathematical formulas that are normally applied to modeling network expansion problems. Despite the fact that the AC model is the more realistic, TEP problem formulation is often based on a DC model. Since the reactive power and the voltage boundaries are usually ignored in the DC model its computational effort is less [3].

1.2 Objectives of The Research

The motivation behind this study can be represented in the following points:

- To develop an optimization technique for addressing the problem of TEP of minimizing the investment cost of newlines construction.
- To integrate RE resources in the network and analyze the effect of high renewable energy penetration in the results of TEP.

1.3 Problem Statement

The problem of expanding network planning is the problem that looks for the optimum way for expanding an existing grid to satisfy loads adequately at present i.e. short-term expansion planning and at a predicted future i.e. long-term expansion planning at normal or contingency conditions. The Short-term planning essentially includes expansion of transmission lines in an existing overloaded area; While long-term planning includes adding new generating units and transmission lines to the grid to satisfy future demand.

Under the continuing trend of integration of RE in the power system, ever-increase difficulties are coming up. The implementation of TEP under the uncertainty that result from the incorporation of RE resources in a power system is investigated from two main aspects: The first one is the process of selecting which line to be chosen for construction among a group of candidate lines, where the nominee line might be any line connected to any two buses and the TEP will eventually choose some of these lines for construction according to its optimum criteria. This process is considered as a basic work for TEP. Therefore, the main motivation of this study is to introduce an automatic method for selecting the optimal lines that should be constructed among the candidate set.

In addition to the issue of selecting the lines to be built, there is another essential matter caused by permeation of RE resources in the network. Conventional generation power is known, controllable, and dispatchable, whereas the energy of renewable resources is intermittent, uncontrollable and non-dispatchable. For instance, wind and solar generation depend on the wind speed and the intensity of sunlight respectively. In fact, different scenarios of renewable generation may occur during the actual implementation according to the weather conditions. Therefore, the transmission system must be capable to take in different scenarios and implement it in a robust manner. This uncertainty of the RE resources affects TEP issue especially when the permeation of RE resource is at a high-level.

As a result, TEP has more than one objective to be improved concurrently. Therefore, in order to use the optimization techniques; the objective functions have to be changed to an individual function through multiplying each one of them by a significant factor. To conclude, although there are many studies about TEP problem, research work on the TEP with consideration of RE penetration needs to be improved. Thus, it is valuable to proceed research about TEP from the aspect of the methodology of selecting which lines to build among the candidate set additionally to the aspect of the TEP problem which takes into consideration the renewable energy resources effects.

1.4 Contributions

The contributions of this dissertation can be sectioned into two major parts:

- Firstly, the optimization model technique (Hybrid search approach) will be applied to obtain the best set of lines which must added to the transmission grid to fulfill the future forecasted loads and to accommodate the RE resources permeation into the system while ensuring that there will not be any violation in any constraint of the problem.

- Secondly, the N-1 contingency condition is taken into account during the expansion planning since it is important to fortify the robustness of the system against transmission line contingencies. For instance, transmission line outage does not surpass the emergency load ratings in any of the transmission lines.

1.5 Thesis Outline

This dissertation separable includes five chapters. Following this preliminary chapter is chapter 2 which presents the literature review and the background information about an existing research of TEP with consideration of renewable resource integration into the electrical grid in addition to a brief introduction of the various algorithms used for solving the problem of TEP.

Chapter 3 is an overview of the optimization technique terminologies and it includes a sample of a small-scale network that was used to illustrate the methodology of the hybrid search approach which will be utilized for the case studies.

Chapter 4 consists of the formulation of the TEP problem where the objective function and the problem restrictions are defined here. Furthermore, it includes the explanation for DC load flow and the process of hybrid approach (forward and backward) algorithms.

Chapter 5 includes the case study of IEEE-RTS of 24 nodes to test the TEP procedures along with the result interpretation for not only normal condition but also contingency condition and an analysis of the effect of RE resources permeation on the expansion plan.

Chapter 6 represents the conclusions of the research and some suggestions for the future research work.

Chapter 2

LITERATURE REVIEW

Recently, because of the fast-growing of electricity consumption, new power plants are needed to incorporate into the networks. In order to decrease greenhouse gas (GHG) emission, the permeation of RE resources into the electrical system has been significantly increased. As a consequence, new lines should be constructed beside the current transmission network. TEP is a plan that specifies the number and the location of the transmission lines which are needed to transfer the power to satisfy the expected demand.

2.1 Electric Power Systems Structure

The typical power system below (Figure 2.1) depicts a power system comprising of generators, interfaces, and loads. As the generators are usually installed far from the end users, transmission lines system is needed as an interconnection between the generation stations and substations close by the load users. A way to minimize the losses in the grid is through stepping up the voltages at the generation side by using a step-up transformer. Since transformers operate at constant power (P) when the voltage (V) is higher value then the current (I) has a lower value as can be inferred from the equation below:

$$P = V \times I \qquad (2.1)$$

Therefore, lower current leads to lower ohmic loss when resistance (R) is fixed as shown in the following equation:

$$P_{loss} = I^2 R \qquad (2.2)$$

A step-down transformer is used to step down the voltage at the side of the end receiver. The transmission lines connect the generators and the loads could be made up of various voltages. For instance, 20, 63,132, 230, 400 kV and higher. We can classify these voltages to:

- Generated voltage: Usually as high as 33 kV or such alike.
- Transmission voltage: 230 kV and above.
- Substation voltage: Usually termed according to the higher voltage level of its transformers. For example, a 400-kV substation might consist of four 400 kV:230 kV transformers.
- Sub-transmission voltage: 63, 132 kV, and so.
- Distribution voltage: It might be divided into a medium distribution voltage (20kV) and low distribution voltage (400 V) [6].

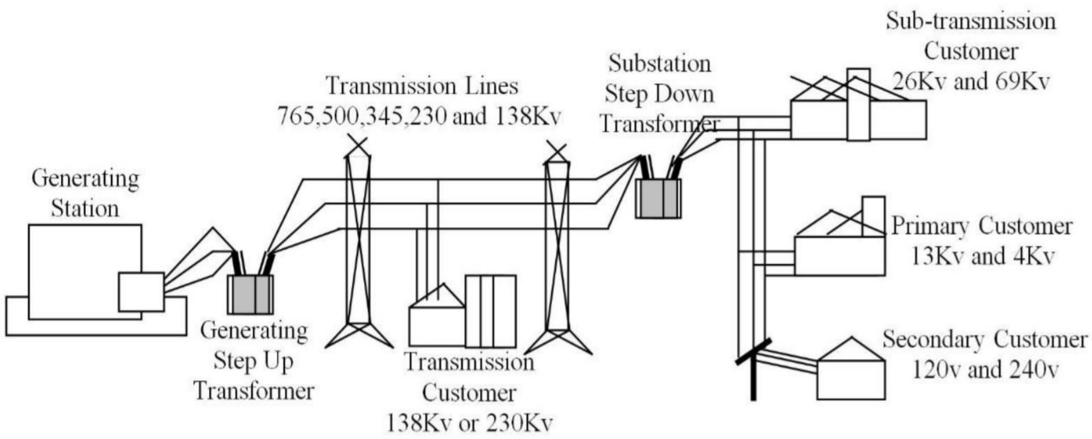


Figure 2.1: A Typical Power System [5]

2.2 Classification of TEP Problem

TEP problem might be analyzed from different points of view, such as: the planning objectives, problem modeling, time horizon, solving methods, etc.

2.2.1 TEP from the View of Planning Objectives

TEP planning had been executed with several objectives, such as: cost reduction, future load and renewable sources uncertainty consideration, reliability and security improvement, improving computational performance, etc.

Reducing the cost of investment and transmission line losses are the most TEP objectives that have been accomplished. In 2012 Sruthi Hariharan applied an optimization model for finding the lines that should be constructed with a minimum cost and analyzed the effect of renewable resources on the transmission grid during the planning time [1]. Moreover, in 2017 Phillipe, V.G., & João T.S. have used PSO method to minimize the cost of the new line construction of TEP problem and minimize the penalty of Power Not Supplied (PNS) which were caused by solar energy penetration to the distributed generation system [3]. In [4,20,25] an extensive transmission expansion planning was proposed to obtain optimal planning cost, increase system reliability and decrease transmission losses. While in [5,7,9,10,12,13,14,18,19,29] reducing the cost of the new lines constructing and the expense of generation operation with considering the uncertainties of the forecasted load and RE generation have been the objectives of the planning. In [6,23,24,27] only the total cost minimization of the power system was the TEP objective. Furthermore, in [11,15,16,17,21] the prime purpose of the planning was to present a tool for transmission planning under generation uncertainty. Another TEP objective has been presented. For example, in [8], the issue of improving computational performance for

TEP problem has been addressed. The review studies of TEP according to the planning objectives can be summed up in Table 2.1 below.

Table 2.1: Typical Planning Objectives

	Objectives			
References	**Investment cost reduction**	**Uncertainties consideration**	**Reliability and Security improvement**	**Improving computational performance**
[1]	✓	✓		
[3]	✓	✓		
[4]	✓		✓	
[5]	✓	✓	✓	
[6]	✓			
[7]	✓	✓		
[8]				✓
[9]	✓	✓		
[10]	✓	✓		
[11]		✓		
[12]	✓	✓		
[13]	✓	✓		
[14]	✓	✓		
[15]		✓	✓	
[16]		✓		
[17]		✓		
[18]	✓	✓		
[19]	✓	✓		
[20]	✓		✓	
[21]		✓		
[23]	✓			
[24]	✓			
[25]	✓		✓	
[26]	✓			
[27]	✓			

[29]	✓	✓		
[30]	✓	✓		

2.2.2 TEP from the View of Modeling

In general, two main models usually have been used for modeling the TEP problem which are the AC and DC models. In DC model, voltage magnitude is thought of as 1 pu at all nodes. Furthermore, only the active power parts of the complex power are considered; Whereas in AC model both components (active/reactive power) are considered. AC model is the most precise and the most computationally complex too. In contrast, DC model is simple and computationally less complex [5]. The merits and demerits of these models can be sum up as detailed below:

2.2.2.1 DC Model Merits

DC model could be shown as linear system constraints, and hence this feature brings many advantages for the DC model which might be outlined as follow:

i. DC power flow is easy to compute, and it is mathematically less complex to solve.
ii. A globally optimum solution can be guaranteed.
iii. It has no convergence problem.

2.2.2.1 DC Model Demerits

Regardless of the above-mentioned advantages, the DC model has some disadvantages which can be summed up below:

i. In DC modeling, reactive power and amplitude of the voltage are neglected. Consequently, the active power in lines and the bus voltage angle only are considered.

ii. In some cases, consideration of the power losses in a DC model is quite difficult. According to the assumption that considers the loss in the transmission line is limited, it is possible to ignore the loss in short term planning. Nevertheless, this supposition might not be acceptable for long term planning.

iii. In order to implement the plan achieved by the DC model practically, we need to reinforce the resulted plan by using the AC model.

2.2.2.3 Advantages of the AC Model

In contrast, the advantages of AC model can be defined in the following points:

i. Reactive power is considered.

ii. The ability of full consideration of the power loss.

iii. The possibility of including the Flexible AC Transmission System (FACTS) equipment and other components in the AC model.

iv. The possibility of carrying out the reliability and voltage stability analysis and other studies.

2.2.2.4 Disadvantages of the AC Model

The disadvantages of AC model may be briefly summarized in the following points:

i. It needs a great effort to solve as it considers a complex and non-linear problem.

ii. It fails to manage the problem of disconnection in the initial stage of TEP before connecting the new generators and loads to the grid.

iii. It has convergence problem and it takes time to be solved.

Although AC model is considered the ultimate suitable model to transact with TEP problems, only few research works have used it due to its complexity. In [3], the author chose an AC-OPF model to determine the PNS for the yearly maximum demands along the planning horizon and integrate the new equipment planned to be included. In 2012, Srinivasulu and Subramanian used AC load flow utilizing the Newton Raphson Method for making an inclusive study for Transmission Expansion Planning [4]. Moreover, in [12,27], AC model was proposed for modeling the TEP problem. In contrast, most planning research used DCLF equations as trying to avoid convergence difficulties and the problem of computing time increasing which usually happen in case of using ACLF for a large-scale power system [1,5,6,11,13,20,24]. Other different models have been presented in TEP studies. For example, in [23], the transmission network was modeled as a transportation model.

Transportation model can be gained by relaxing the equation of real power flow of a DC model while ignoring the line flow calculation equations which is counted in AC and DC models. That is to say, only the constraint of the line limit is considered for power flow analysis. So, the ideal expansion solution that is obtained by the transportation model might not be feasible for a DC or AC model.

In [26], a DC model was used to formulate the problem and Gauss-Seidel (GS) load flow has been utilized to define the line flow and voltage magnitude in all lines and buses respectively. Where the result of GS used as data for the genetic algorithm to find how many lines must be constructed in order to accommodate the forecasted load.

2.2.3 TEP from the Point of View of Planning Horizon

From the perspective of the planning horizon, TEP problem is categorized into two categories: static and dynamic planning. In the former, the time sphere is neglected, i.e. the optimum solution is determined for just a year. That is to say, it is considered that by the first year of the planning time, the selected lines must be incorporated into the network. Yet, in the latter, determining the yearly built lines with in the planning time is the must. This is what makes it very complex, large, time-consuming, and need computational effort to obtain the optimal solution compared with the static planning. However, it offers finer and inexpensive planning [5].

2.2.4 TEP from the Perspective of Solving Methods

Several methods have been presented to achieve the different objectives of the TEP problem. These methods are categorized as: mathematical, heuristic and metaheuristic methods.

2.2.4.1 Mathematical Optimization Methods

Mathematical optimization techniques present the problem in a mathematical formulation where the mathematical formulation consists of an objective function which should be decreased or increased while guaranteeing that the model's constraint equations are not violated. Generally, the problem is designed as a non-linear optimization problem (NLP) when the restrictions and /or the evaluation function are nonlinear. In contrast, the problem designs as linear programming (LP) is when the evaluation function and restrictions both are linear functions. Depending on the nature of the variables other designs might also be identified. For instance, the problem is signified by integer programming (IP) when the variants are integers. In some cases, where the variants are a mix of real and integer, this is referred to as the mixed integer linear programming (MILP), it also one of LP types [6].

Different mathematical optimization techniques were proposed to figure out the TEP problem. For example, in [23], the problem is sectioned to two subproblems master and slave, and Benders decomposition (BD) method was proposed to solve it where the master subproblem is answered through a branch-and-bound algorithm and the slave subproblem is solved using a particular linear program. In [13], Benders decomposition approach was presented for solving the master problem that minimizes the expansion plan cost and the slave problem that minimizing the ultimate load and RE generation curtailment. Generally, mathematical methods suffer from a complexity in converting the power system equations into the optimization model especially in the large-scale power systems. In spite, Suitable convergence could be fortified. Yet, the globally best solution set is guaranteed just for a few types like LP [6].

2.2.4.2 Heuristic and Metaheuristic Methods

Heuristic and metaheuristic techniques are the algorithms that imitate some of nature's behavior. They were suggested in the early 1970s. Unlike mathematical methods, heuristic and metaheuristic techniques are simple, easily to apply, and they convert power system equations to the optimization model is not required where only the output responses of the power system analysis are needed to feed an optimization algorithm for solving the problem. The main point of using the meta (heuristic) techniques is to accelerate the process of getting a satisfying solution although the acquired solution might not be the optimal one. In other words, meta (heuristic) techniques could grant a computationally less effort solution compared to mathematical methods. Yet, the potential of obtaining a local optimal solution rather than a global one is on a higher level than the mathematical techniques too.

The distinction between heuristic and metaheuristic techniques is that, the heuristic methods was created to solve a specific issue and most likely nothing else. While meta-heuristics methods are independent methods and it might be applied for solving a vast extent of issues. TEP problem were solved using various meta (heuristic) algorithms. However, the Genetic algorithm (GA), Particle swarm optimization (PSO), Tabu search (TS) and the Artificial bee colony algorithm (ABC) were the most widely used.

- **Genetic Algorithm (GA)**

GA is a technique that is utilized to solve optimization problems according to natural choice conception. Initially, the population is generated randomly and in order to establish the future generation from the existing population there are three fundamental operations:

i. Selection: identifying the individuals to be parents.
ii. Crossover: combining a couple of parents to produce children for the upcoming generation.
iii. Mutation: its arbitrary changes applying to individual parents. Usually, it is in the range (0.001- 0.05).

In [18], GA has proposed to reduce the cost of (TNEP) problem under uncertainty without losing robustness. The proposed algorithm verified on standard IEEE 24-bus systems. In [24], a genetic algorithm was presented to optimize the cost of static transmission planning problem under a deregulated environment (non-irregular uncertainties) and the presented methodology was investigated on Graver's six- bus network. In [25], the author has developed one of the multi-objective genetic algorithm techniques for solving TEP problem where two objective functions had been optimized which are: minimizing the expenses of the added lines to be constructed and decreasing the predicted power that will not imparted to the system. The developed method had executed on the IEEE- RTS of 24 nodes successfully. In [26] GA has been applied to determine the optimum set of the transmission lines that should construct per corridor while satisfying several financial and technical requirements, and the method was tested on IEEE 14 – bus test network.

- **Particle Swarm Optimization (PSO)**

PSO is a technique that was presented by Kennedy and Eberhart. It's based on bird or fish developed behavior. Initially, the population of random solutions among the potential solutions (particles) has to be generated, and to gain an optimal solution an updating of generation is needed. There are three "best" values that are tracked by the PSO:

i. Pbest: the best solution accomplished by each particle.
ii. Ibest: best value gotten by any particle neighbors.
iii. Gbest: (global best) is the best value among all the population.

The idea of this method lays in changing the particle's acceleration towards its pbest and lbest locations at each step. In [3] PSO was used to solve a multiyear (TEP) problem while keeping in mind the uncertainties of the forecasted load and solar energy generation where the suggested method was applied to IEEE – RTS of 24 bus. In [27] PSO has been applied for solving TEP problem for a realistic power system (Western of Romanian Power System) for 10 years' time period and provided good results.

- **Tabu Search (TS)**

Tabu search is an algorithm invented in 1986 by Fred Glover where the "Tabu " word means things that can't be searched or touched. TS algorithm can sum up in the next steps:

i. Generating an initial solution.
ii. Movement selection from one possible solution to an improved solution.
iii. Solution updating, where the next solution is selected from the neighbor's list.

The procedure is reiterated until any stopping criterion achieved.

In [7] TS algorithm was used to minimize: TEP investment cost, annual loss cost of the transmission lines and annual generators operation cost while considering the leakage of renewable energy (REL). The introduced algorithm was executed to a modified IEEE-RTS of 79 nodes and the result has shown the efficiency of the algorithm.

- **Artificial bee colony algorithm (ABC)**

ABC is a technique that mimics the bee's behavior for foraging honey and was presented in 2005 by Dr. Karaboga. ABC algorithm comprises of three sorts of artificial bees:

i. Employed bees (EBs): fifty percent of the colony and its numbers equivalent to the food sources number.
ii. Onlooker bees (OBs): fifty percent of the colony.
iii. Scout bees (SBs): only one.

That is to say, the colony is divided into two parts: one part includes the employed artificial bees. While the other half contain the onlooker bees where the scout bees are the employed bee whose their sources of food have been exhausted. In optimization problems, possible solutions correspond to food source positions, and the robustness of the solution corresponds to the food source nectar amount. The conception that considers the solution with the highest fitness function (source that has the highest amount of nectar) as the best one, applies to maximization problem. In minimization problem, the reverse of the evaluation function value is thought of as an evaluation function value. In [20] the algorithm was applied on various test systems and the result confirmed that ABC is a good alternative to many optimization techniques for solving the complex TEP problem with less mathematical computations. In brief, the assessment of TEP depends on the optimization algorithms as presented in the following Table (2.2).

Table 2.2: Typical Optimization Techniques

Algorithm	Optimization Algorithm Type	References
Benders Decomposition (BD)	Mathematical method	[13,23]
Genetic Algorithm (GA)	Meta-heuristic method	[18,24,25,26]
Particle Swarm Optimization (PSO)	Meta-heuristic method	[3,27]
Tabu Search (TS)	Meta-heuristic method	[7]
Artificial Bee Colony (ABC)	Meta-heuristic method	[20]

2.3 Challenges in the Transmission Expansion Planning

The essential issues in TEP consist of: load prediction, Generation prerequisites, and network expansion [6].

2.3.1 Load Prediction

The first key element in the TEP plan is the power usage forecast for the trial time, and that what called the load forecasting. There are many parameters that affect future forecasted load which can be summarized in:

i. Time aspect:
   - Day hours (day or night).
   - Year seasons (summer, autumn, spring, and fall).

ii. Climate conditions: Weather temperature and humidity.

iii. User class: (residential, commercial, industrial, etc.).

However, Future load forecasting usually done by increases the existing load by a fixed percentage rating annually through the planning horizon.

2.3.2 Generation Prerequisites

The next step after predicting the load is to define the generation prerequisites to meet up with the load. Typically, the rate of increase of the generation is equal to the load increasing rate. Nevertheless, the generation increasing rate assumed to be (5-10%) more than the demand load as a try to cater for any surge in load growth. This consideration applies only to conventional generators, but in case of RE generation, the increasing rate of the generation need to be dealt with in different ways.

2.3.3 Inclusion of a Renewable Resource

Recently, TEP problem with the consideration of the RE resource that is incorporated to the power grid has been one of the research interesting topics. Where the increase of RE resource permeation in the power grid has been very fast due to the economic and environmental purposes, such as reducing CO_2 emission level, reduce the operational costs because of the zero-fuel profit of the RE resources, and so on. Therefore, to ensure the growing permeation of RE resources, several countries have a compulsory renewable portfolio standard (RPS) that seeks to meet a precise percent of load by RE resources. For instance, in California, the proposed RPS permeation rate is about 33% by 2020 [1]. As a result of increased RE resource penetration, the transmission network might need to be modified in order to transfer the RE to the consumers.

2.3.4 Network Expansion

After the load forecasting and the generation requirements (which consider as inputs available to the planner) have been defined, the focus will be on the issue of expanding the network for transferring the power to fulfill the predicted load in an economic and reliability way.

2.3.5 Contingency Condition

A contingency is an unpredicted failure of any system component like a generator, transmission line and others due to several reasons like the adverse weather, equipment faults, human intervention...etc. This failure of any system element might cause a system limits violation. Therefore, it is important to ensure the robustness of the system against the contingencies. In this thesis, the N-1 contingency condition is considered, where the system should be able to at least withstand one contingency criterion, i.e., an outage of any transmission line in the grid must not lead to any exceed on other transmission lines capacity limits.

2.3.6 Islanding Condition

A case that an isolated bus (substation) seems is indicated to an island, and it has to be averted. It usually happens in the contingency conditions. However, It can be discovered by verifying the difference of the voltage angles over the line which will be a huge digit because of the violation of the balance between load and generation in the islanded circuit which leads to abnormal frequencies and voltages.

2.4 Dealing with Uncertainty in TEP Study

TEP problem is classified according to how it handles the uncertainties as in the following sections:

2.4.1 Deterministic Problem

In this case, there is no obvious consideration of uncertain variables. Where the problem formulated to analyzes one or two scenarios. This scenario, for example, could be the maximum demand load, N-1 contingency or outage of a generating unit and so forth. The drawbacks of this approach are that the future expansion solution gets optimal only if it happens as predicted. Furthermore, the solution may prompt an inappropriate or costly planning decision. In addition to that, the solution is considered an optimal one for a limited period of time and usually it does not work out in long term expansion planning.

2.4.2 Probabilistic Problem

In this approach, as trying to overcome the drawbacks of deterministic approach, the problem formulated to analyzes a set of potential scenarios that contain the uncertainty varies to represent uncertainty which may occur hereafter. The only shortcoming of this approach is that it needs a great effort to find a solution for the problem.

2.4.3 Under Uncertainty Problem

This approach is used in case of having uncertainties that cannot be represented by using probability theory. Uncertainties are divided to two sections: random and non-random uncertainties. In random uncertainties, the parameters are possible to be represented from historical data based on the natural repeated phenomena concept, and there is an ability to reproduce them as many times as needed under the same conditions. The uncertainties of the forecasted load and the RE generation are included in this group. In other hands, the parameters of non- random uncertainties are not possible to be represented from the past experiments and observations. Generators closure, transmission expansion costs, and the like are classified in this group [6].

Many strategies were suggested to model uncertainties in the TEP problem. Mathematical model and Monte-Carlo Simulation (MCS) model. Among the mathematical model, stochastic optimization formulation and the scenario-based analysis are the most frequently used [21].

In [1], a stochastic model was proposed to TEP to model the interrupted nature of renewable resources. While in [3], four scenarios: 0%, 10%, 15% and 20% of the solar energy penetration in the distributed generation system was applied at the maximum forecasted load in each year. In [4], Zhi Wu proposed a method for applying one of the most powerful stochastic approaches, namely, dual dynamic programming (SDDP) in a two-stage stochastic TEP problem.

Another approach has been introduced to deal with uncertainties in TNEP problem such as Taguchi's orthogonal array testing (TOAT). In [7,11], TOAT was utilized to attain the minimum set of scenarios which depict the loads and RE resources uncertainties, where the principle of the TOAT is selecting the high-prospect scenarios that is pointed by the unpredictable loads and RE resources. As a result of considering only the highest prospect scenarios, the scenarios number decreases, therefore, the calculation time reduce substantially.

In [13], R. A. Jabr made a comparison between the result of BD algorithm that was chosen to deal with the TEP problem and which employed the Greedy Randomized Adaptive Search Procedure (GRASP) for handling TEP uncertainties, and the result of a GA which employed TOAT for choosing the scenarios of the expected load and renewable generation, where the result has shown the robust of the former.

In [14], robust linear optimization (RLO) has been proposed as a method for converting the uncertainty problem into a deterministic one. In [15], TEP problem has been investigated under the stochastic and deterministic models, where a multi-stage scenario tree method has been employed to transform stochastic model into deterministic model.

In [18], the uncertainties problem was converted into a deterministic optimization and with using the genetic algorithm, the best solution of TNEP problem was obtained. In [19], a probabilistic method for the static TEP problem was used to present the generation uncertainties of the wind power and the forecasted load then the Benders decomposition algorithm has been proposed to handle the presented TEP problem.

In [16,17,21], a two-stage stochastic approach had been suggested to present the uncertainties of TEP problem, and decomposition algorithms were utilized to deal with the problem, where the outcomes showed the effectiveness of the stochastic approach in comparison to the deterministic approach which concentrates just on the maximum load scenario.

To sum up, from the literature review it is notable that the TEP that includes the uncertainties are more preferred than those with deterministic ones. Generally, the most frequent methods that is used for handling the uncertainties are the Mathematical method and the Monte-Carlo Simulation (MCS) method. The consumed time in the mathematical method is less than MCS, and the uncertainties can be considered through using probabilistic models, scenario-based analysis or stochastic optimization formulation model. Whilst, MCS is easy to be implemented compared with the mathematical ones, and it is considered as a numerical method that depends on the iterations.

In conclusion, the issue of the uncertainties was extensively considered in the TEP problem. Yet, the methodology of solving TEP problem while considering uncertainties need to be developed. In this thesis, a Hybrid Heuristic approaches (backward and the forward approach) will be applied to find a solution for the TEP problem with the evaluation functions of lessening the investment expense of constructing new lines while ensuring the system's reliability in normal and (N-1) conditions. Where we considered a deterministic load scenario with several permeation scenarios of the wind energy in the IEEE- RTS of 24 nodes to investigate its impact on the expansion plan.

Chapter 3

OPTIMIZATION TECHNIQUE

3.1 Terminologies of the Optimization Model

Optimization technique aim is to find the value of the variant that provides the least or the greatest value of the evaluation function with consideration to the restrictions. Any optimization issue contains inputs to the optimization model, decision variants, problem restrictions, and evaluation functions, this is detailed in the following subsections.

3.1.1 Optimization Model Inputs

Optimization model inputs data can be categorized into two types: Static data which is unchangeable data over the time and the time-varying data which can be provided in Table 3.1 below.

Table 3.1: Optimization Model Inputs Types

Static data	**Time-varying data** (at each bus for each hour of the scenario time period)
Bus data: ▪ Bus number. ▪ Bus type. ▪ Generator type. ▪ Generator cost.	Generation capacity (MW).
Branch data: ▪ From bus- To bus. ▪ Admittance. ▪ Active power limit. ▪ Construction cost.	The load demand (MW).

3.1.2 Decision Variables

Decision variables play a big role in the optimization problem where the aim of the optimization model is to obtain the set of the decision variants which optimize the evaluation functions during fulfilling the problem constraints.

As it is known, the first step toward finding a solution for the optimization problem is defining it, where identifying the decision variables from the parameters set that have a direct effect on the evaluation function which is considered a function of the decision Variants is the first step of the problem definition. The next step that follows identifying the decision variables is formulating the problems in optimization form, where decision variables can be binary variables, real variables, or integer variables. The method of solving the optimization problem depends on the type of decision variables that is used in the optimization model.

In the TEP problem the decision variables that used in the optimization model can be summed up as follow:

i. Binary variables: (1) if the line should be chosen for construction and (0) if it is not.
ii. The angle of the bus voltage (θ) in radians.
iii. The real power flows of the branch in per unit (pu).
iv. The real power dispatch of the generator (pu).

3.1.3 Constraints

In the optimization problem, some boundaries are applied to the solution region. The boundaries can be economical, environmental or technical boundaries. These boundaries are called constraints. Generally, the problem constraints could be in the following form:

$$\text{Subject to} \quad a_{ij}\ X_i \leq b_j \ , \quad j = 1,2,\ \dots,\ n \qquad (3.1)$$

Where:

a_{ij} , X_i, b_j and n are the coefficient of the decision variable, the decision variable, the right-hand side and the constraints number respectively.

In cases where the solution of the optimization problem is fulfilled the constraints are identified as feasible solution, while in the other case where it does not satisfy the constraints then it is called infeasible solution. Constraints of an optimization problem determines whether the values of decision variants lead to a feasible solution nor not. That is to say, the constraints divide the solution region into two regions: feasible and infeasible regions.

TEP problem looks for the optimal cost of new lines construction and optimal dispatch of the RE resources generation. There are many constraints that could be assorted into two types: The first type is the compulsory constraints such as generator output power limits, Line flow limits, number of lines in each corridor and so like. Where the second type is the nonobligatory constraints, for instance, reliability and security limits, environmental impact limit, investment limits, and others.

3.1.4 Objective Functions

It is a function of the decision variables that needs either to be increased or decreased without the system constraints violation. Depending on the optimization purposes the optimization problems is sectioned into individual-objective problem and various-objective problem. Where it is possible to convert the various-objective functions into an individual one through multiplying each objective by a certain constant. Generally, the majority of the optimization problems are various-objective problems and which often conflict with each other. The problem of transmission expansion planning with renewable energy resources consideration is a various - objective problem, it usually pursues to enhance various aims. For instance, diminish the construction expense of the added lines, minimize the operational expense of generators, power not supplied lessening and so on.

According to the above descriptions, the optimization model might be summed as the following: Min/Max objective function contingent upon compulsory restrictions and nonobligatory restrictions. A common form of the optimization model can be listed as below:

$$\text{Min/ max} \quad C(x) \tag{3.2}$$

$$S.T. \quad g(x) \leq b \tag{3.3}$$

$$f(x)=a \tag{3.4}$$

Where

C(x) : The evaluation function.

x: The decision variant.

C: Coefficient corresponding to the decision variable.

$g(x) \leq b$: An inequality constraint.

$f(x)= a$: An equality constraint.

The above objective function and the constraints are used for assessing the algorithm under another function named the Evaluation function. The equation of the evaluation function is shown below:

Evaluation Function = The objective function + α (Constraint violations) (3.4)

α: is a large constant selected randomly.

Constraint violations: the absolute values summation of all violations.

3.2 Proposed Hybrid Heuristic Approach (Backward - Forward Methods)

In this research, Hybrid heuristic is utilized for expanding the transmission network to transmit maximum power to the forecasted loads in a reliable, robust and stable way under N/N-1 conditions. Different stages of this approach explained below. At first, the backward and the forward methods will be illustrated since the two are the basic approaches, then the decrease method and the hybrid approach will be discussed. Where a small-scale network which shown in figure 3.1, will be used to illustrate the approach of expansion planning as a launching pad to executing on the proposed case studies that will be used in this thesis.

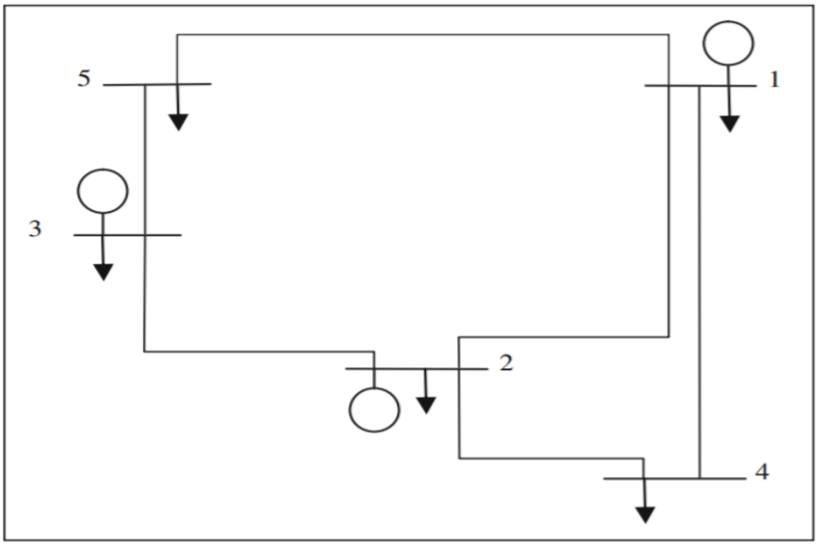


Figure 3.1: A Small-Scale Test System

3.2.1 Forward Method

In the forward heuristic method, the conception is that the nominated lines are inserted one after another, where in the classic TEP, the nominated lines are assumed to have the same properties (impedance and maximum line flow) with the existing ones without denying that the planner has the opportunity to select a new type of line sets to be installed tandem with the existing ones. The evaluation function value is calculated for every step individually, thereafter, the step with the least value is used as the starting point for the next level. This procedure reiterates as long as there is no violation of system constraints. Therefore, a solution with the least objective value (investment cost) and without constraints violations is the best one. Where the total cost of the optimum lines chosen by the forward approach (TCF) must be less than the value of the minimum evaluation function (MOF) that has been defined before. The process of the forward approach for the case study in Fig 3.1 and the set of nominated lines in Fig 3.2 can be explained in figure 3.3 below:

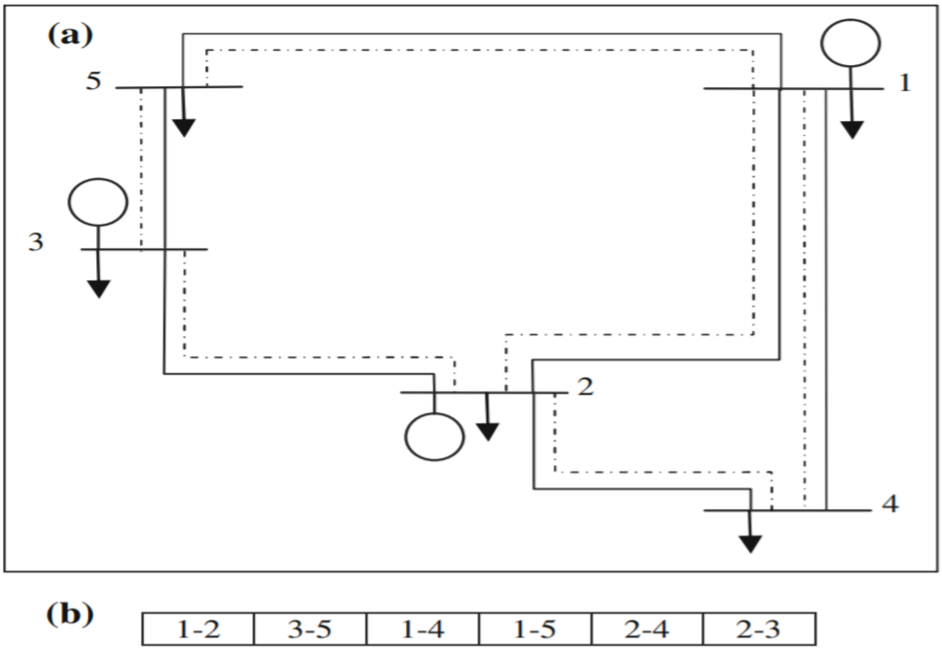


Figure 3.2: Set of the Nominated Lines

Where the nominated lines indicated by the dashed line, (a) is the single line diagram for the nominated lines and (b) is the block representation.

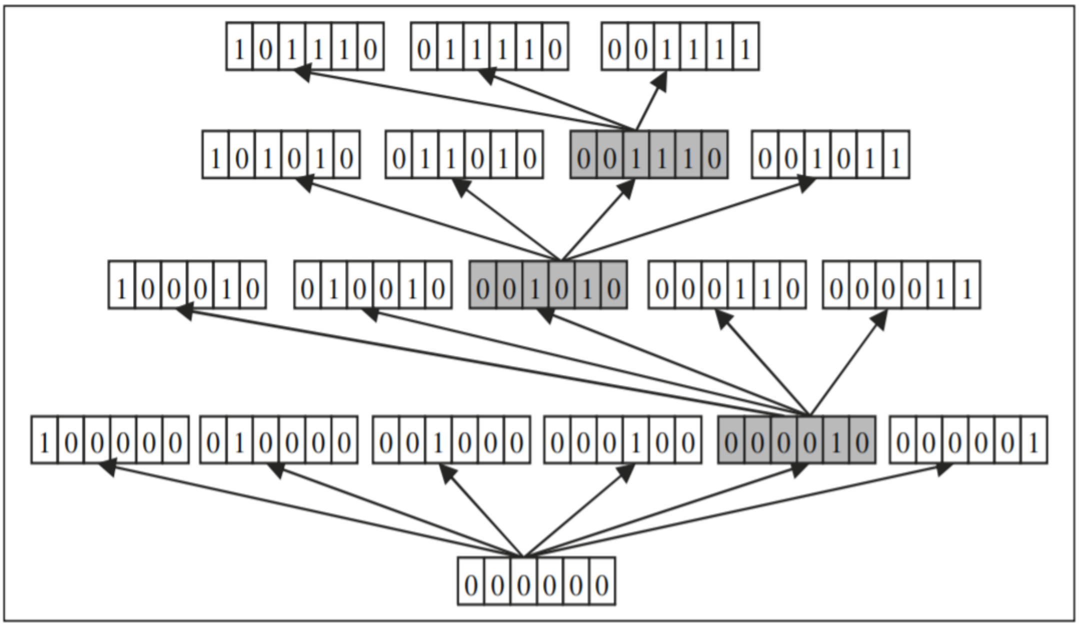


Figure 3.3: Forward Approach Representation

As shown in the above figure, the forward approach starts with no included for any candidate lines (000000), then- nominated lines are added one at a time (100000 - 000001) while the evaluation function is calculated, the point with the least value (000010) uses as the starting point for the next level, the process reiterates until there is no violation of any constraint of the problem.

3.2.2 Backward Method

The backward method is the inverse of the forward method, where initially all the candidate lines are inserted into the grid. Then the nominees remove one after another and the evaluation function value will be calculated for each case. The one (removed candidate) with the least evaluation function value is considered as a commencing stage for the next level. This action reiterates until the point that causes a violation in any constraint of the problem. Therefore, the solution that provides the lowest evaluation function value and with no constraint's violations is the best one. Where the total cost of the optimum lines chosen by the Backward approach (TCB) must be less than the value of the minimum evaluation function (MOF) that has been defined before. The process of the backward approach explained in Fig 3.4 below according to the case study in Fig 3.1 and the set of candidate lines in Fig 3.2.

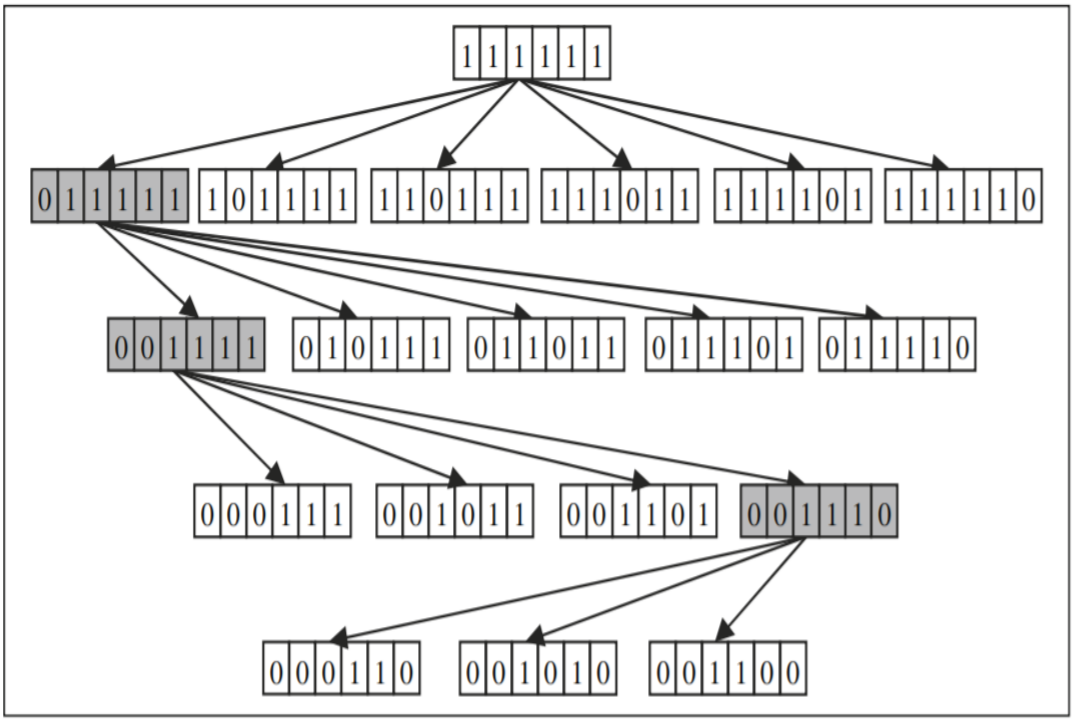


Figure 3.4: Backward Approach Representation

Where the binary number 111111 indicates the case that all candidates are included in the network. Subsequently, starts the process of removing candidates one by one as shown (011111–111110) while calculating the objective function for each case, and the one with the least evaluation function value (here it is 011111) is considered as a starting point for the next level. The algorithm continues until reach to the solution that provides the lowest evaluation function value and with no constraint's violations.

In simple terms, from Fig 3.4 we can say the optimum answer is the one that added (3, 4 , 5) (000110, 001010 and 001100) candidate lines to the grid.

It is worth to mention that the backward method starts within the feasible zone and it remains in the feasible zone during the solution process, where after the planner adjusts the grid initially at a feasible region with no constraint's violation, the candidate lines with the highest cost will be removed first. By contrast, the forward method begins from beyond the feasible zone, where the most effective nominees are chosen first to be included. Accordingly, the backward approach usually ends with less costly lines comparatively with the forward approach. Furthermore, the execution time normally is higher in the backward approach as the candidate's number is usually higher than the required or the justified ones. The following Figure 3.5 explains the moving manner for both methods (forward and backward) toward the optimal solution.

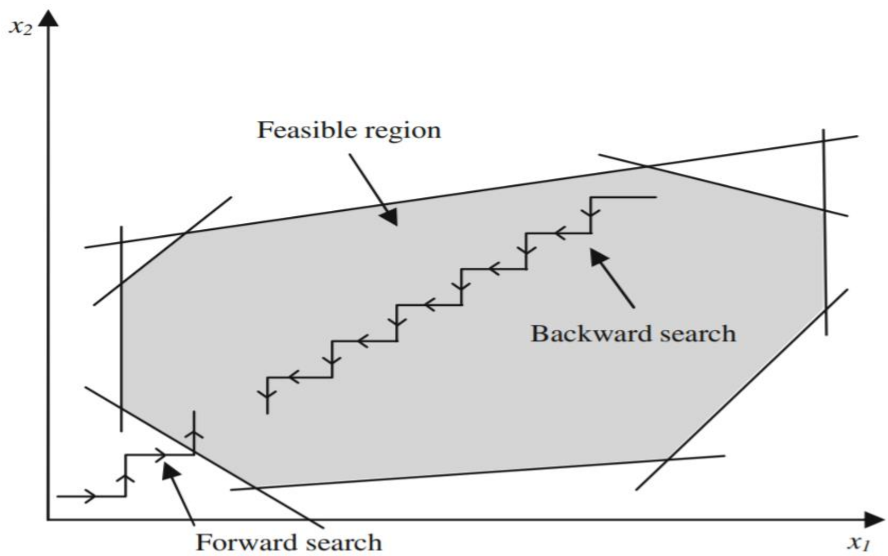


Figure 3.5: Forward and Backward Methods Movement Toward the Optimal Solution

3.2.3 Decrease Method

Once the right way is procured, there might be some choices for constructing different types or capacities of transmission lines in that corridor. In both methods (backward - forward) the solution procedures continue with the largest capability option for the all nominee. In contrast to this, decrease method uses a lower capacity option for each corridor and checks their ability to perform the work. For more explanation, Fig 3.6 below shows the process of the backward approach, where digit (2) denotes the larger capability for all the nominees, while number (1) in the decrease level shown in the same figure denotes the smaller capability option for the all nominees.

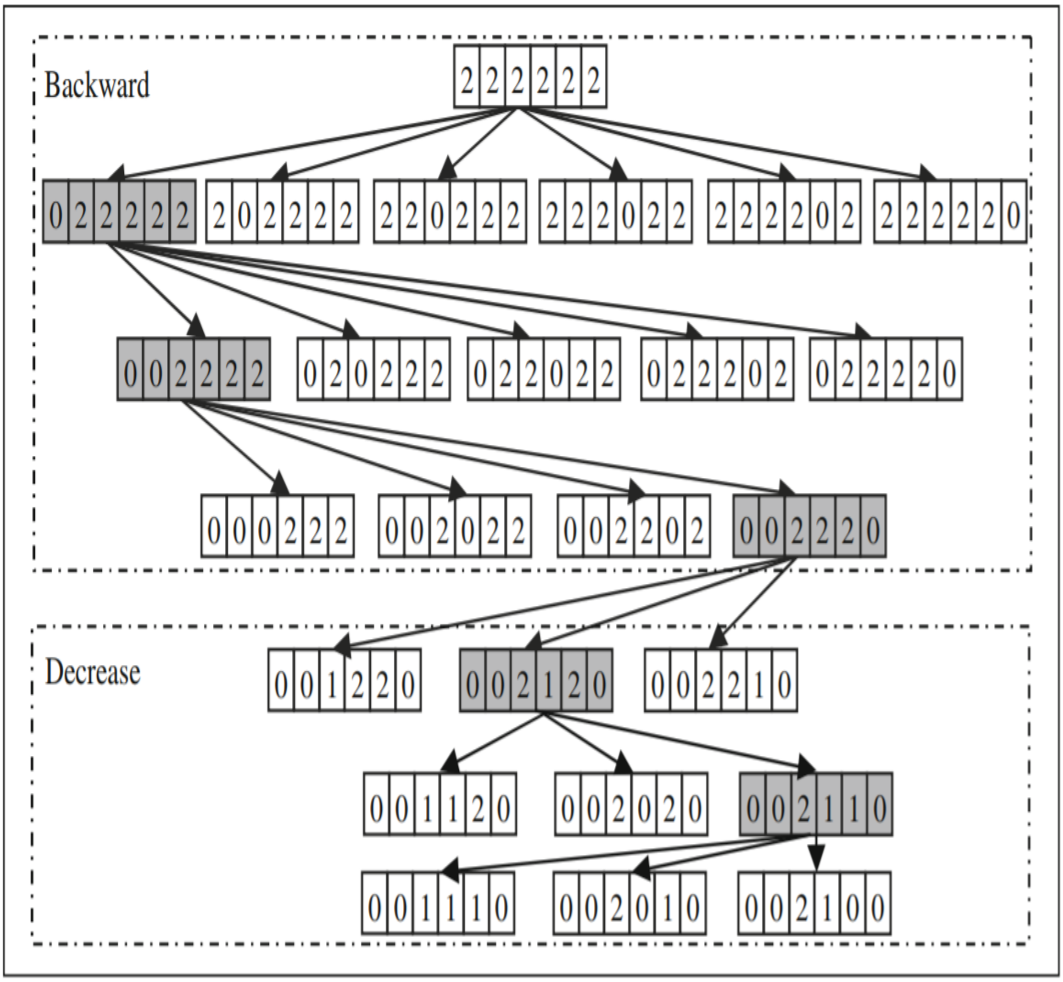


Figure 3.6: Backward -Decrease Approach

We can notice that the backward approach ended with (002220) as the best solution, then the decrease approach applied and ended up with (002110) which indicates that the higher capacity can be picked for candidate 3 while the lower capacity can be chosen for the 4^{th} and the 5^{th} nominees. Any further movement will lead to some constraint's violations.

3.2.4 Hybrid Approach

Generally, we can directly employ the hybrid approach in the normal condition, where we can call the backward approach thereafter the forward approach and the optimal set is the one chosen by both approaches. But in case of considering the two conditions normal and N-1, the backward technique faces a problem, especially in the large-scale systems. So, as trying to overcome the difficulties, the principle working of the hybrid method can be explained using Figure 3.7 as shown below:

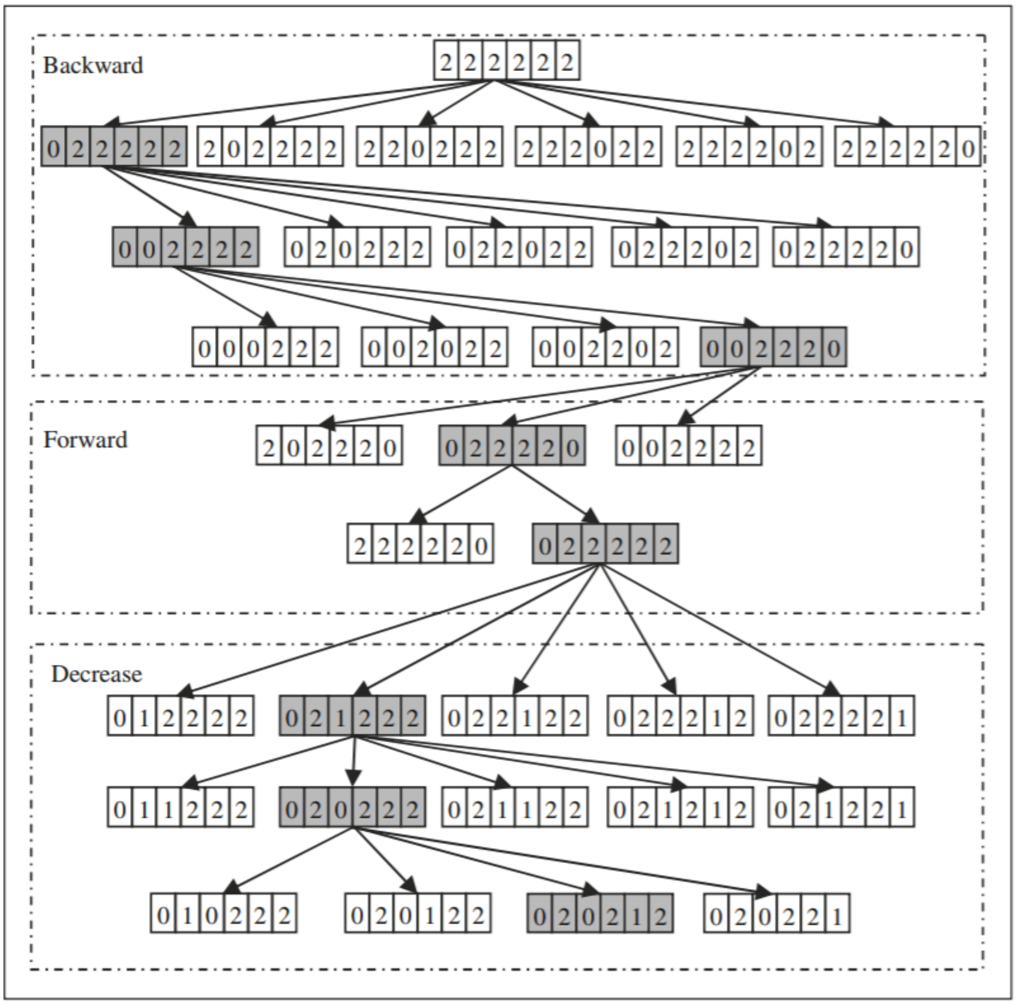


Figure 3.7: Hybrid Approach (Backward, Forward, and Decrease technique)

Initially the backward approach applies for the normal condition (no contingency), and as is shown it ends up with (002220) as the final choice. Therefore, the forward approach starts from 002220 in the presence of all N-1 contingency and the fitness function is measured whenever a candidate line is added as a way to figure out a solution that provides the least evaluation function where there are no violations of the system constraints. As a consequence, the last answer was (022222) for the two conditions; the normal and N-1 which incorporates the 2^{nd}, 3^{rd}, 4^{th}, 5^{th},and the 6^{th} nominees in the network. Where the total cost of the optimum lines chosen by the Hybrid approach (the sum of the TCB and TCF) must be less than the value of the minimum evaluation function (MOF) that Previously identified. Then the decrease approach was aiming to attain the last solution (020212) as mentioned in the process explained before.

To conclude, in the huge network system, the candidate lines number are going to be greater (as the candidate lines can be a collection of all possible lines that connecting between any two buses), thus the solution optimality is not fully warranted yet the solving time and precision are entirely agreeable.

Chapter 4

METHODOLOGY

4.1 Problem Formulation

The TEP problem that takes renewable energy sources into consideration is usually classified as a reduction issue, and as a way to formulate it, the objectives of the study have to be formed as an optimization function and the constraints that have to be fulfilled must be identified too. In this study, the optimization problem aims are to lessen the construction cost of the new lines which will be inserted in the network along the planning time. While the constraints are related to the load-generation balance, the capacity limits of the branches, and generators.

4.1.1 Objective Function

As mentioned earlier, the aim of this thesis is reducing the expense of the new line's construction. The objectives are formulated by the succeeding equations:

- **Cost for new lines construction [4]**

The total cost of constructing the new lines are equal to:

$$\sum_{i-j \in CS} C_{ij} n_{ij} \tag{4.1}$$

$$C_{ij} = C_{Inv}\,(x_{ij}) \times L_{ij} \tag{4.2}$$

Where

C_{ij}: The price of the added branch that connect i-j buses .

n_{ij}: The added branches number between i-j buses.

CS: The set of candidate branches.

$C_{Inv}(x_{ij})$: The investment price per (Km) of line i - j of type x.

x_{ij} : The type of added transmission line between i-j nodes.

L_{ij} : The length of line i-j in (Km).

4.1.2 Constraints

The above objective function is restricted with the following restrictions:

- **Power flow Balance in all node [28] :**

$$P_{ci} + P_{ri} = P_{di} + P_i \tag{4.3}$$

Where

P_{ci}: The real power of the conventional generation.

P_{ri}: The real power of renewable generation.

P_{di}: The load active power at i^{th} bus.

P_i: The real power injection at i^{th} bus.

- **Line flow limit [4] :**

$$\left| P_{ij} \right| \leq (n_{ij}^0 + n_{ij}) P_{ij}^{max} \tag{4.4}$$

Where

P_{ij}: The i-j line power flow.

n_{ij}^0: The number of incorporated lines .

n_{ij}: The number of the existed lines in the initial network.

P_{ij}^{max}: Maximum power flow in the line i-j.

- **Power Generation Limit [28] :**

$$P_{ci}^{min} \leq P_{ci} \leq P_{ci}^{max} \tag{4.5}$$

$$P_{ri}^{min} \leq P_{ri} \leq P_{ri}^{max} \tag{4.6}$$

Where

$P_{ci}^{min}, P_{ci}^{max}$ are the lowest and highest limits of the active power of conventional generation respectively. While $P_{ri}^{min}, P_{ri}^{max}$ is the lowest and highest limits of the real power of renewable generation.

- **Right of way [6] :**

$$0 \leq n_{ij} \leq n_{ij}^{max} \tag{4.7}$$

Where

n_{ij}: The number of the inserted lines between i-j buses (must be an integer number).

n_{ij}^{max} :The highest number allowed for adding lines between i-j buses.

4.2 Load Flow

Load flow is used to analyze the system implementation (the voltage phase angle and the magnitude in all nodal, injection power in each bus, and the power flow in every transmission line…, etc.) in the steady state. Whereas, checking the system stability and testing whether expansion planning is a necessity or not (i.e. the need for inserting new components to the existing system to satisfy the increased demand) is essential. These analyses require two main steps as pointed below:

- Formulate equations of the problem.
- Find a suitable mathematical technique to solve the equations.

Generally, during the solution of the equations, two out of four quantities that are related to the bus (voltage magnitude, voltage phase angle, active and reactive powers) are identified according to the bus type as shown in Table 4.1 below, while the remaining two are unknown and should be obtained. Basically, there are two types of buses: load bus and generator bus. One of the generator buses takes as slack or reference bus with constant voltage magnitude usually is "1" and phase angle normally equal "0".

Table 4.1: Known and Unknown Parameters According to the Bus Classification

Bus type	**Known parameters** (at each bus)	**Unknow parameters** (at each bus)
Load bus	Active and reactive power components (P_D and Q_D).	The voltage magnitude and voltage phase angle.
Generator bus	The voltage magnitude and active power generation (P_G).	The voltage phase angle and the reactive power generation (Q_G).
Slack bus	The voltage magnitude and voltage phase angle.	The active and reactive powers (P_G and Q_G).

There are several methods to get the load flow analysis such as the AC and DC load flow, decoupled load flow and so on. In this research, the ordinary Gause Seidel (DC load flow) will be used and discussed in the following section.

4.2.1 Direct Current Load Flow (DCLF) Presumptions

The DCLF is obtained after applying the following assumptions:

- **Line resistance and conductance assumption**

In DC load flow, the conductance of the transmission line (G_{ij}) assumed to be zero and only the susceptance (B_{ij}) is used to represents the admittance of the line (Y_{ij}). These assumptions are resulting from neglecting of the line's resistance (R_{ij}) which is considered too small in comparison with the reactance of the line (X_{ij}). Neglecting the resistance of the lines does not only has an effect on the power loss but also has a great effect on saving computation time and speed.

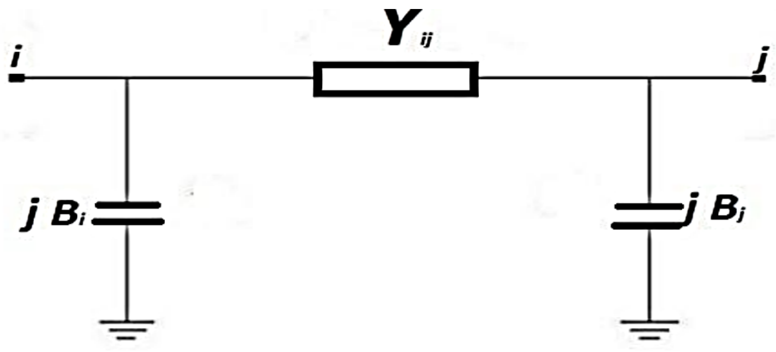


Figure 4.1: A Long Transmission Line Represented by a Nominal- Pi Equivalent Circuit

From figure 4.1 above the admittance of the transmission line can be calculated as below:

$$Y_{ij} = G_{ij} + jB_{ij} = Z_{ij}^{-1} \tag{4.8}$$

$$G_{ij} = \frac{R_{ij}}{{R_{ij}}^2 + {X_{ij}}^2} \tag{4.9}$$

$$B_{ij} = \frac{-X_{ij}}{{R_{ij}}^2 + {X_{ij}}^2} \tag{4.10}$$

Where Y_{ij}, B_{ij}, Z_{ij} and X_{ij} are the admittance, susceptance, impedance and the reactance of the transmission line respectively. While R_{ij} and the G_{ij} are the line resistance and conductance which is neglected in DCLF ($R_{ij} = G_{ij} = 0$), thereafter Y bus matrix of the transmission lines can be calculated quite easily.

In the symmetrical Y bus matrix, the elements of the main/leading diagonal (Y_{ii}) is calculated through the summing of admittances for each line that are linked to the bus (i). While the elements of the off- main diagonal (Y_{ij}) consist of the negative totality of the admittances between i - j buses.

- **Power flow assumption**

As we mention before, only the real power is considered in DCLF, where the active power injection at each bus is expressed as follow:

$$P_i = V_i \sum_{j=1}^{N} B_{ij} \sin(\theta_i - \theta_j) \quad (4.11)$$

Where

$\theta_i - \theta_j$: The phase angle difference between i - j buses.

- **Line flow equation**

$$f_{ij} = \frac{1}{x_{ij}} (\theta_{ij}) \quad (4.12)$$

where,

f_{ij} : real power line flow between bus i – j.

x_{ij} : The reactance of line i – j.

θ_i : Phase angle at bus i.

θ_{ij} : $\theta_i - \theta_j$.

- **Voltage magnitude assumption**

$$|V_i| = 1 \quad (4.13)$$

Where at each bus the voltage magnitude assumed to be 1 pu.

Thus, according to the above assumption, the injected active power and the voltage angles at each bus are the variables of the DCLF [1,6].

4.2.2 Algorithm of DCLF

The steps for DCLF procedures can be listed as the following:

Step 1: Reading the inputs of the system (branches, buses, and the generators data).

Step 2: Calculating Y_{bus} matrix of the network.

Step 3: Computing node power of all buses (P).

Step 4: Defining non-slack buses from the bus-data matrix.

Step 5: Building network susceptance matrix (B) where B_{ij} is the imaginary part of y_{ij}.

Step 6: Calculating and updating voltage angle values at each bus so that ($\theta = B^{-1}*P$), where θ is the phase angles vector.

Step 7: Computing the branches power flow and the overload in each one.

Step 8: Calculating the entire overload in all branches.

Step 9: Showing the bus voltage angles based on both radian and degree where angle (rad) = angle (deg) × (180/π); additionally, also showing the branches power flow and their overload with presenting the total overload of all network.

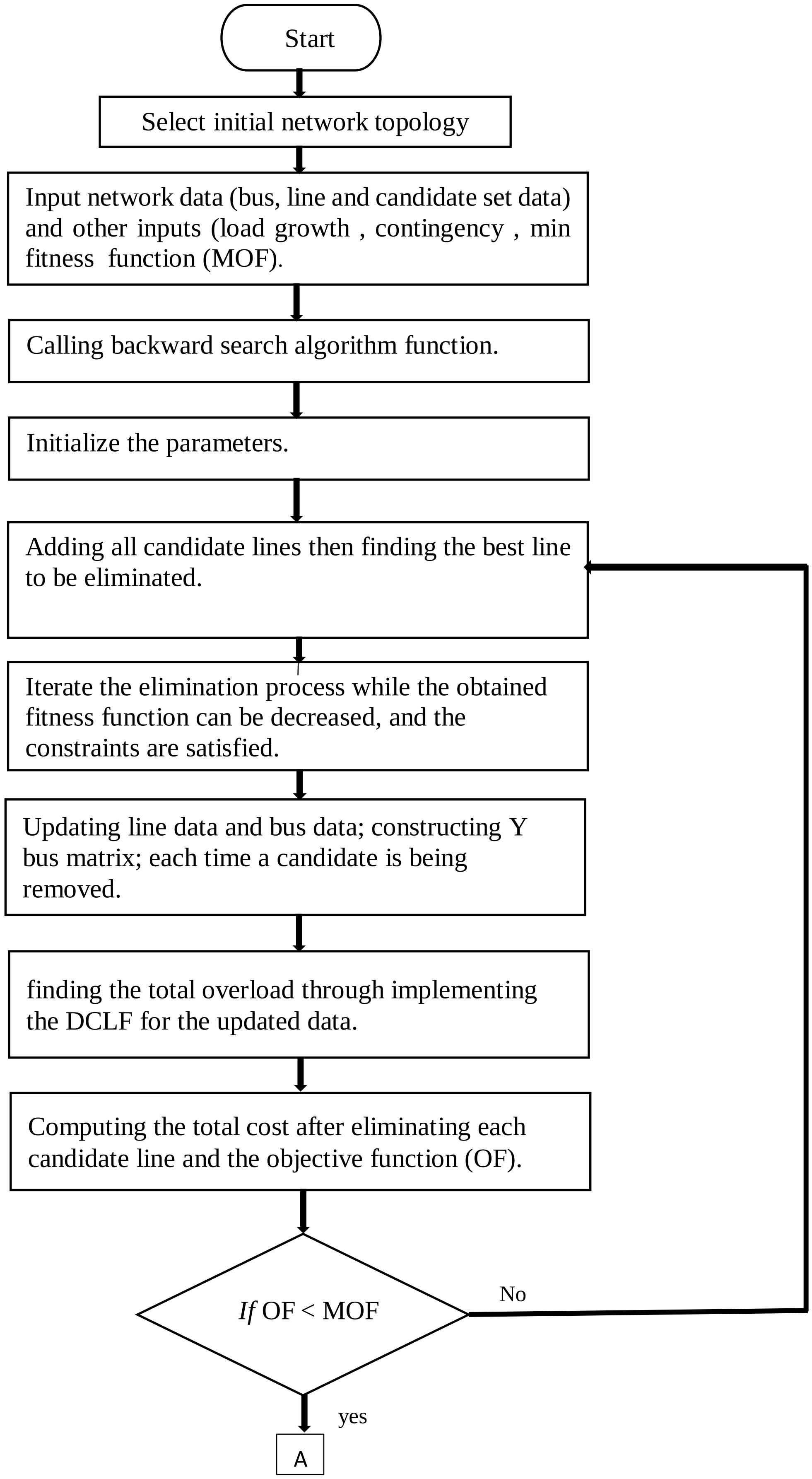
Step 10: End.

4.3 Methodology

In this thesis, a heuristic hybrid approach (backward and forward search) is being used for TEP problem-solving. The algorithm of each one of these algorithms are explained below.

4.3.1 Backward Search Algorithm

The flowchart of the backward search approach for finding the optimum lines that must be added to the grid is shown in Figure 4.2.


Start
Select initial network topology
Input network data (bus, line and candidate set data) and other inputs (load growth , contingency , min fitness function (MOF).
Calling backward search algorithm function.
Initialize the parameters.
Adding all candidate lines then finding the best line to be eliminated.
Iterate the elimination process while the obtained fitness function can be decreased, and the constraints are satisfied.
Updating line data and bus data; constructing Y bus matrix; each time a candidate is being removed.
finding the total overload through implementing the DCLF for the updated data.
Computing the total cost after eliminating each candidate line and the objective function (OF).
If OF < MOF
No
yes
A

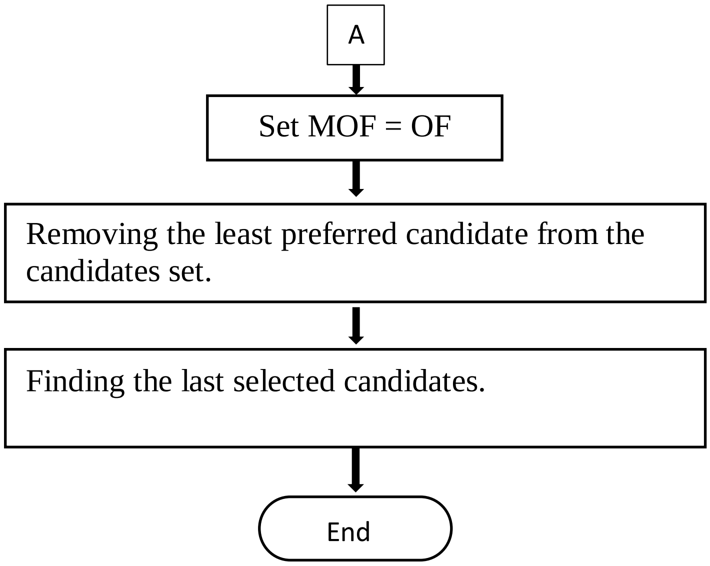
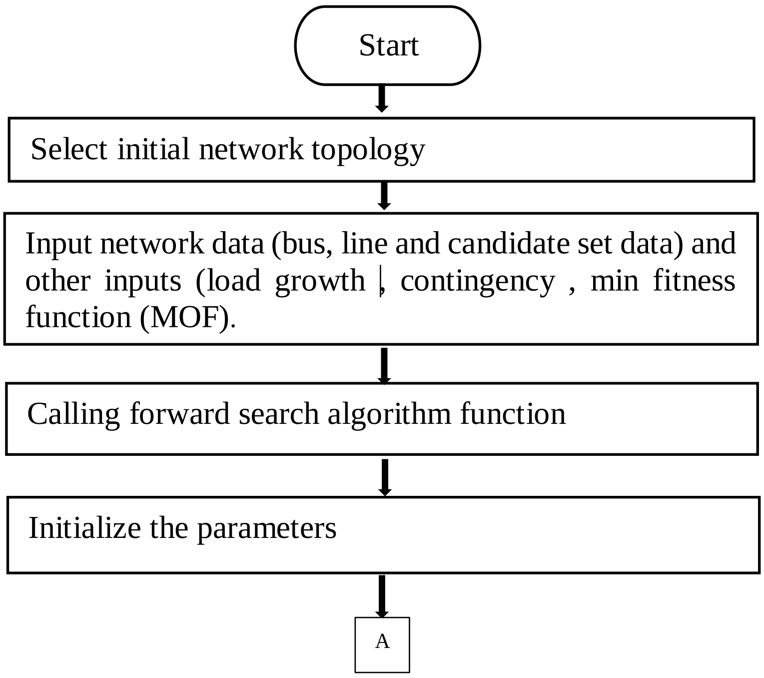


Figure 4.2: Backward Search Algorithm Flow Chart

4.3.2 Forward Search Algorithm

The flowchart of the forward search approach for finding the optimum lines that must be added to the grid is shown below in Figure 4.3.



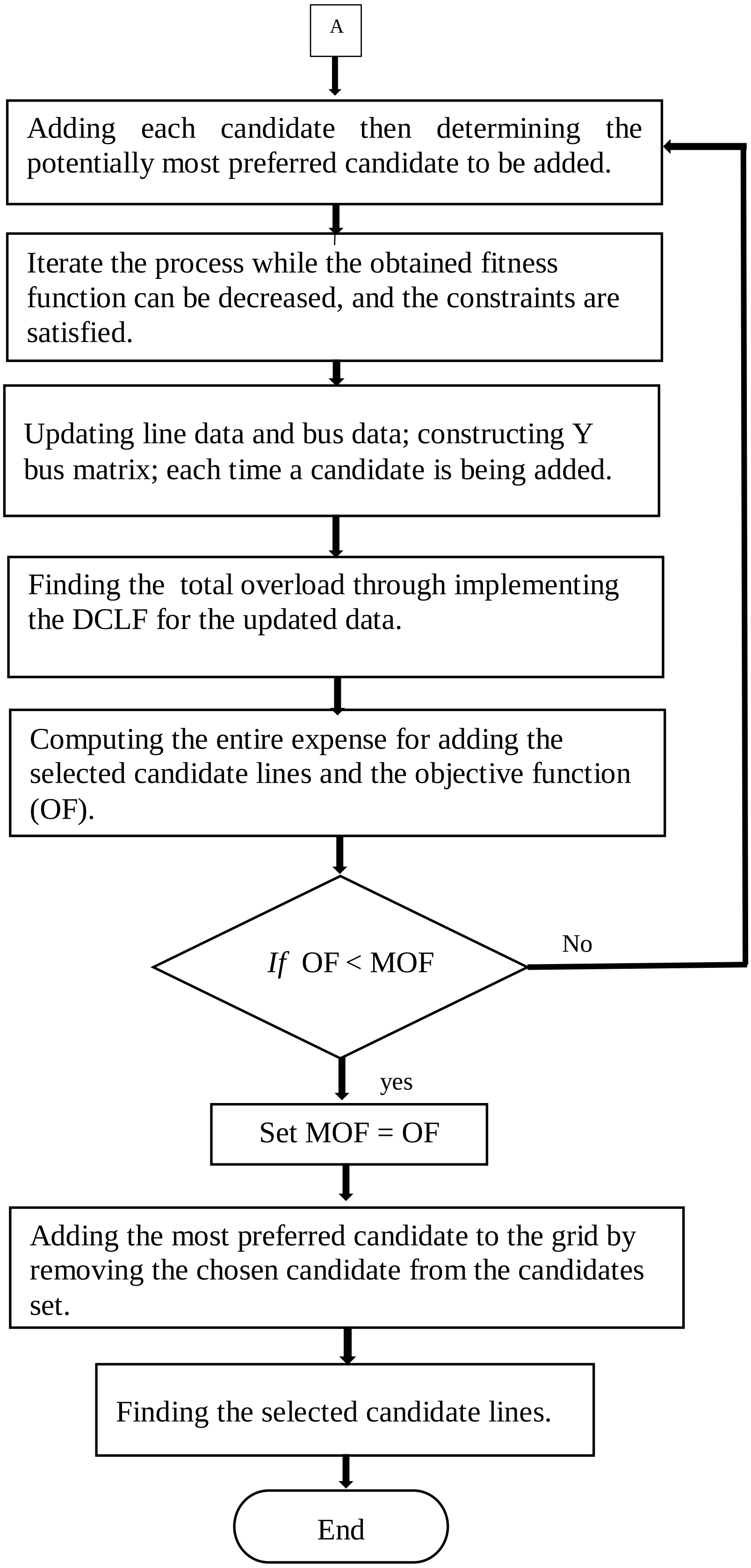
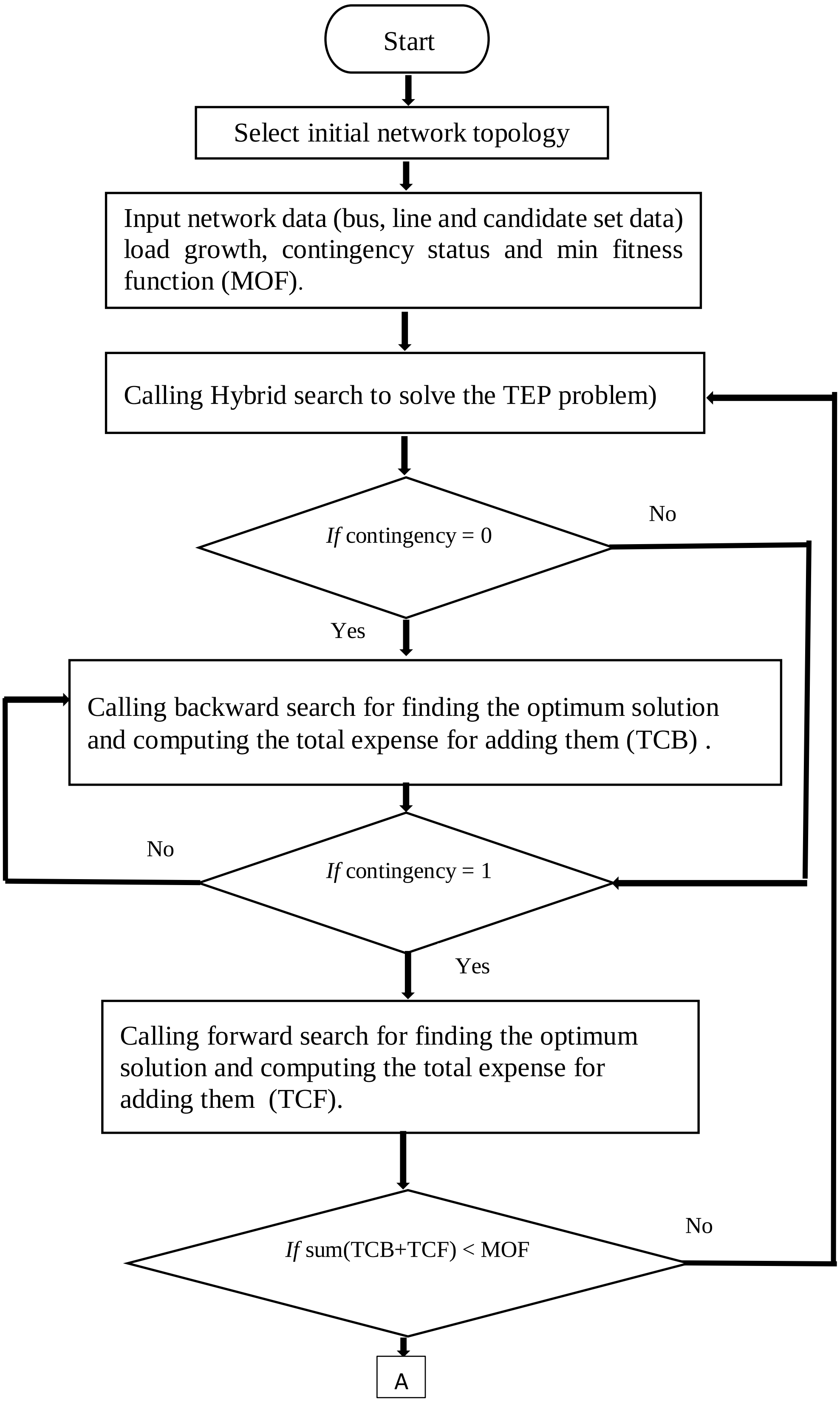


Figure 4.3: Forward Search Algorithm Flow Chart

4.3.3 Hybrid Search Algorithm

The flowchart of the hybrid search approach is shown in Figure 4.4.



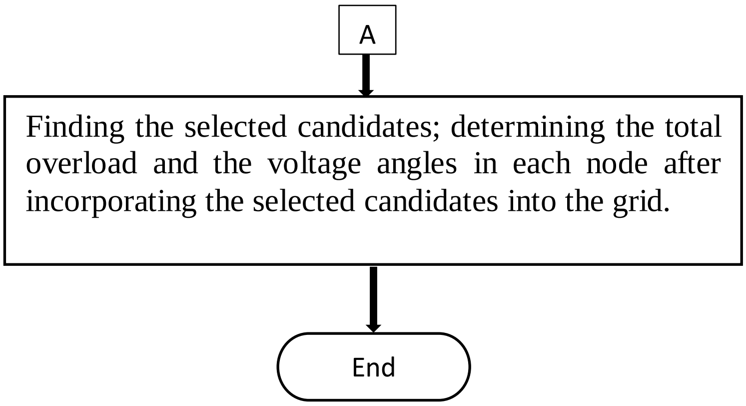


Figure 4.4: Hybrid Search Approach Flow Chart

Chapter 5

RESULTS AND DISCUSSION

The proposed approach was tested on IEEE RTS of 24 nodes to examine the effectiveness of the approach considering both conditions (N and N-1). Furthermore, as the study of the impact of RE resources permeation in the power system is one of the researches aims, the approach was implemented to an updated system of IEEE 24 nodes that contained wind energy resources with neglecting the installation cost of it. Load level is assumed to be the nominal level which represents 100% of the normal system loading.

It is worth mentioning that, DCLF has been used for analyzing the system where the analysis was carried out for the two conditions normal and contingency (N-1). DCLF and the hybrid search approach codes were conducted using MATLAB 2014 on Windows 10 Processor Intel® Core™ i7 @ 2.59 GHz, RAM 8 GB.

5.1 IEEE - RTS of 24 nodes

It includes 24 nodes that are connecting by 38 lines at two different voltages of 138 kV and 230 kV with base 100 MVA. The topology of the grid is shown in Figure 5.1 below.

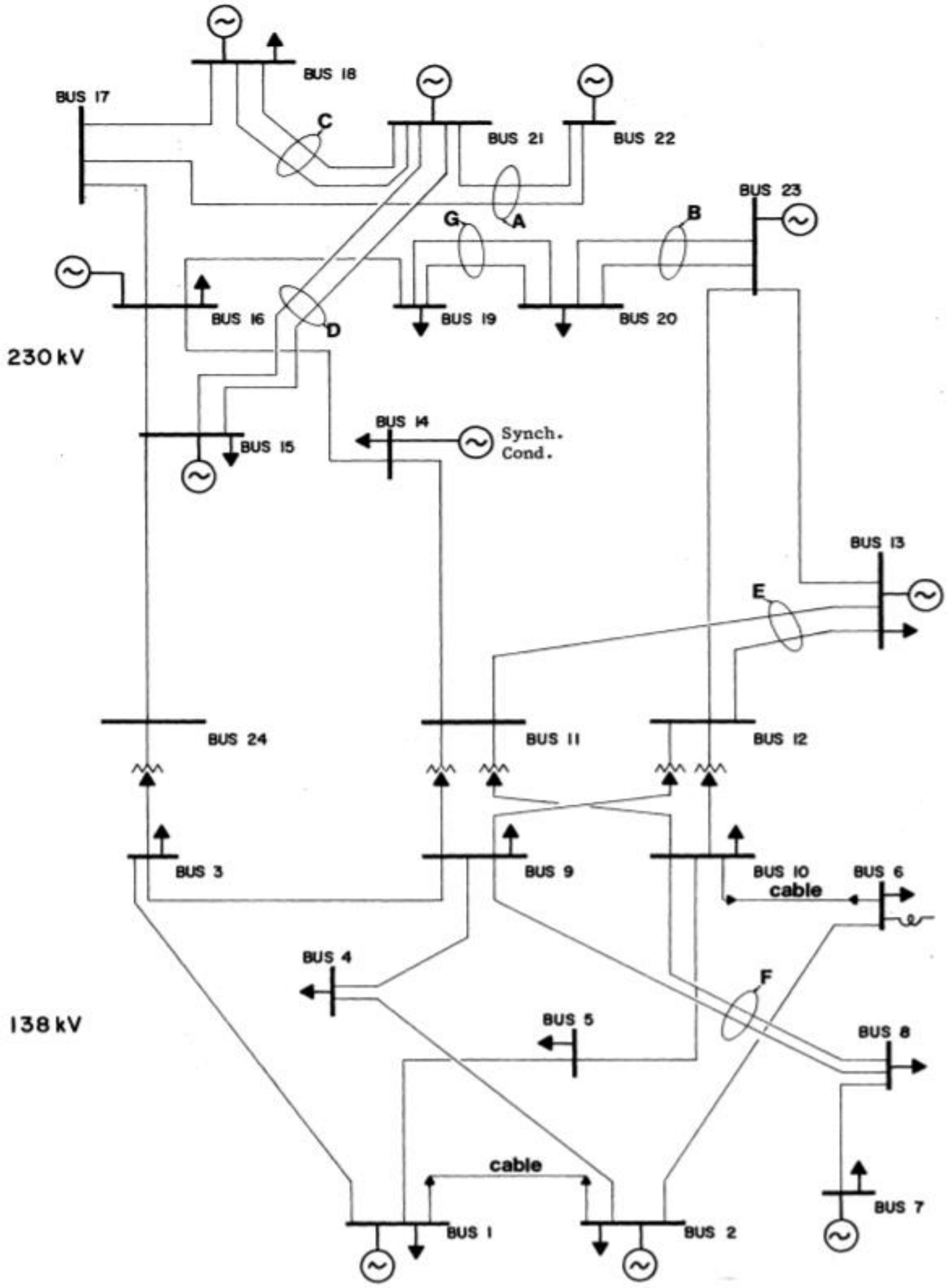


Figure 5.1: IEEE RTS of 24 Bus [30]

Firstly, we should test the capability of the current transmission network for transmitting the power and supplying the present and forecasted loads where the annual load growth rate is assumed as 12% for 5 years of the planning horizon. Hence, a DCLF analysis has been performed with consideration of both (N and N-1) conditions, and the result are shown in the following tables. Table 5.1 below represent the bus voltage angles which were significantly increased in the case of 60% load growth.

Table 5.1: Bus Voltage Angle for the Present and Forecasted Load Scenarios

Bus Number	**Angle (rad.) of the base network (0% Lg)**	**Angle (rad.) of the base network (60% Lg)**
1	-0.0477	-0.62287
2	-0.04913	-0.62303
3	-0.04623	-0.61065
4	-0.10892	-0.63471
5	-0.11057	-0.64304
6	-0.1607	-0.67811
7	0.013407	-0.62456
8	-0.09404	-0.68596
9	-0.08112	-0.52149
10	-0.11357	-0.56382
11	-0.0098	-0.31547
12	-0.00116	-0.25454
13	0	0
14	0.068824	-0.36614
15	0.238982	-0.31344
16	0.217459	-0.29255
17	0.303077	-0.24672
18	0.330196	-0.24056
19	0.187918	-0.26066
20	0.198435	-0.17598
21	0.345907	-0.21783
22	0.452863	-0.10541
23	0.217996	-0.10768

24	0.129981	-0.42703

Table 5.2 represents the line flow in case of the present and predicted load, where results of the branch power flow showed that there was no overload in any line in normal and contingency (N-1) conditions at the present loads of zero load growth. But, there were overloads in several lines for the predicted loads of 60% load growth as shown below in Table 5.3.

Table 5.2: Branch Power Flow for the Present and Forecasted Load Scenarios

Line No	From bus	To bus	Line Power flow (0 Lg) in pu	Line Power flow (60% Lg) in pu
1	1	2	0.102974	0.011105
2	1	3	-0.00698	-0.05785
3	1	5	0.744001	0.238742
4	2	4	0.471908	0.092216
5	2	6	0.581066	0.286889
6	3	9	0.293228	-0.74926
7	3	24	-2.1002	-2.18858
8	4	9	-0.26809	-1.09178
9	5	10	0.034001	-0.89726
10	6	10	-0.77893	-1.88911
11	7	8	1.75	1
12	8	9	-0.07827	-0.99618
13	8	10	0.118272	-0.73982
14	9	11	-0.85005	-2.45551
15	9	12	-0.95309	-3.18172
16	10	11	-1.23681	-2.95998
17	10	12	-1.33985	-3.6862
18	11	13	-0.2059	-6.6276
19	11	14	-1.88096	1.212109

20	12	13	-0.02428	-5.34757
21	12	23	-2.26865	-1.52036
22	13	23	-2.52018	1.244831
23	14	16	-3.82096	-1.89189
24	15	16	1.244088	-1.20798
25	15	21	-2.18215	-1.9513
26	15	21	-2.18215	-1.9513
27	15	24	2.100203	2.188584
28	16	17	-3.30571	-1.76939
29	16	19	1.278833	-1.38048
30	17	18	-1.88324	-0.42746
31	17	22	-1.42247	-1.34193
32	18	21	-0.60662	-0.87773
33	18	21	-0.60662	-0.87773
34	19	20	-0.26558	-2.13824
35	19	20	-0.26558	-2.13824
36	20	23	-0.90558	-3.16224
37	20	23	-0.90558	-3.16224
38	21	22	-1.57753	-1.65807

Table 5.3: Overloaded Lines with 60% Load Increase

Overloaded Lines	**The overloads in line (in per unit)**
6 - 10	0.1391
11 - 13	1.6276
12 - 13	0.3476
Total overload of 60% load growth = 2.1143 pu	

These overloaded branches which exceed their line capacity limit are shown clearly in Figure 5.2.

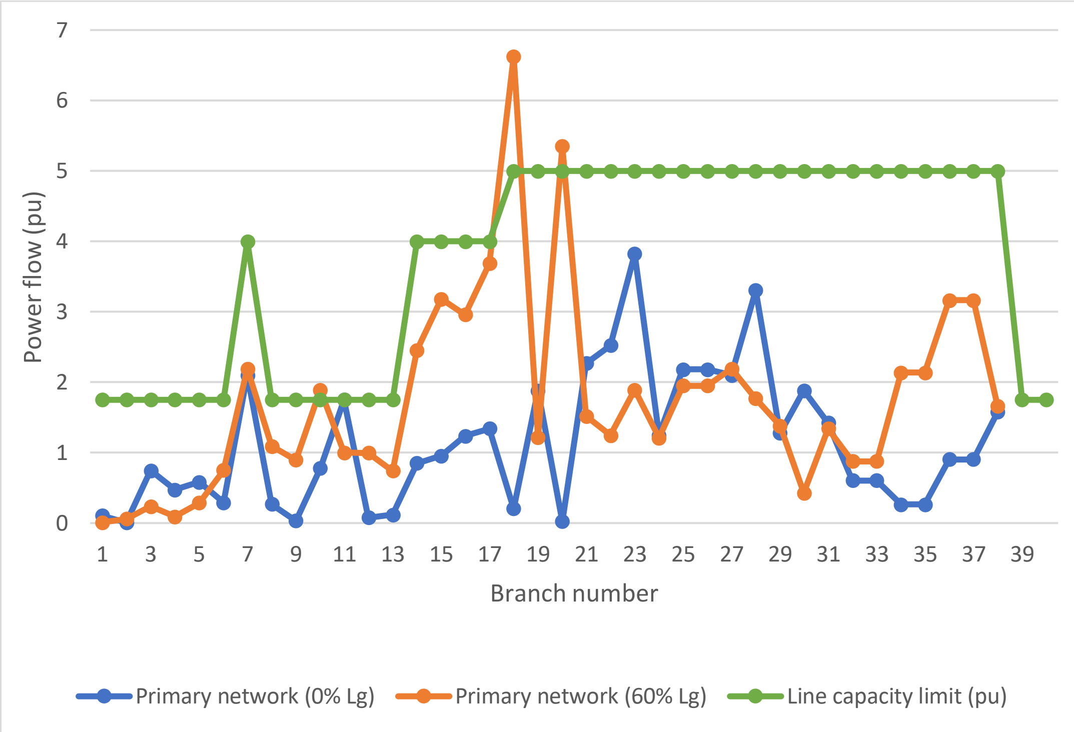


Figure 5.2: Branches Power Flow of the Present and Predicted Load

Hence, the network was demonstrated to be unstable and the forecasted load demand will not be supplied in an appropriate manner. Therefore, an expansion plan must be carried out to supply the forecasted demand properly. Thus, the hybrid heuristic approach will be applied to the RTS of 24 nodes.

The candidate lines set have been selected based on the following assumptions:

i. The candidate lines are supposed to be inserted in 34 existing corridors in addition to seven new corridors.
ii. All the candidate branches have the same line type and the same properties.
iii. The maximum lines number per corridor is three lines.

The bus data, generator data, line characteristics data were taken from [30] and it can be found in Appendix (**A**). Where the line investment cost is 320k per km [6]. It is important to mention that, since only one-line type with one capacity option for that line is used for the whole expansion plan. Thus, there is no meaning behind using the decrease method. Therefore, only the backward and forward approaches will be applied.

Many different cases were considered while solving the TEP problem for investigation the effects of wind energy penetration on the TEP:

- Case 1: The adjusted IEEE - RTS of 24 nodes in the absence of the wind energy.
- Case 2 : The adjusted IEEE - RTS of 24 nodes with 5% presence of wind energy permeation.
- Case 3 : The adjusted IEEE - RTS of 24 nodes with 10% presence of wind energy permeation.
- Case 4 : Case 2 with consideration of the wind energy uncertainty.
- Case 5 : Case 3 with consideration of the wind energy uncertainty.

5.1.1 Case 1 (With the Absence of a Wind Farm)

It is the base case, where the expansion plan is carried out considering only the existing conventional units. The hybrid heuristic approach were applied to the network taking into account N and N-1 contingency conditions. The best lines had been selected to be incorporated into the network are shown in Table 5.4 below.

Table 5.4: Result of the Hybrid Heuristic Algorithm - Case 1

From bus	**To bus**	**Capacity (Branch Per Corridor)**
3	24	1
6	7	1
8	9	1
13	14	3
15	24	1
Total construction cost = 158.58 M$		

After inserting the above branches to the original network, a DCLF has been carried out, and the results of the DCLF for the expanded network could be listed in the following tables, where Table 5.5 represents the bus phase angle for the expanded network.

Table 5.5: Bus Voltage Angle after the Expansion Procedure – Case 1

Bus No	**Angle (rad)**
1	-0.36489
2	-0.36879
3	-0.24699
4	-0.42947
5	-0.40456
6	-0.40140
7	-0.38783
8	-0.38358
9	-0.35635
10	-0.34570
11	-0.12844
12	-0.14930

13	0.00000
14	-0.01944
15	-0.14135
16	-0.09004
17	-0.05486
18	-0.05381
19	-0.09368
20	-0.03946
21	-0.03567
22	0.08055
23	-0.01223
24	-0.19958

It is noticeable that the phase angle after the expansion procedure dramatically decreased as a consequence of stability acquired in the system. This can be presented in the Fig 5.3 below. The power flow in the selected candidate branches and the existing branches has been calculated as shown in Table 5.6 and Table 5.7 below, and from the result, We have verified the robustness of the expanded network, where there was no overload in any line in both N and N-1 conditions.

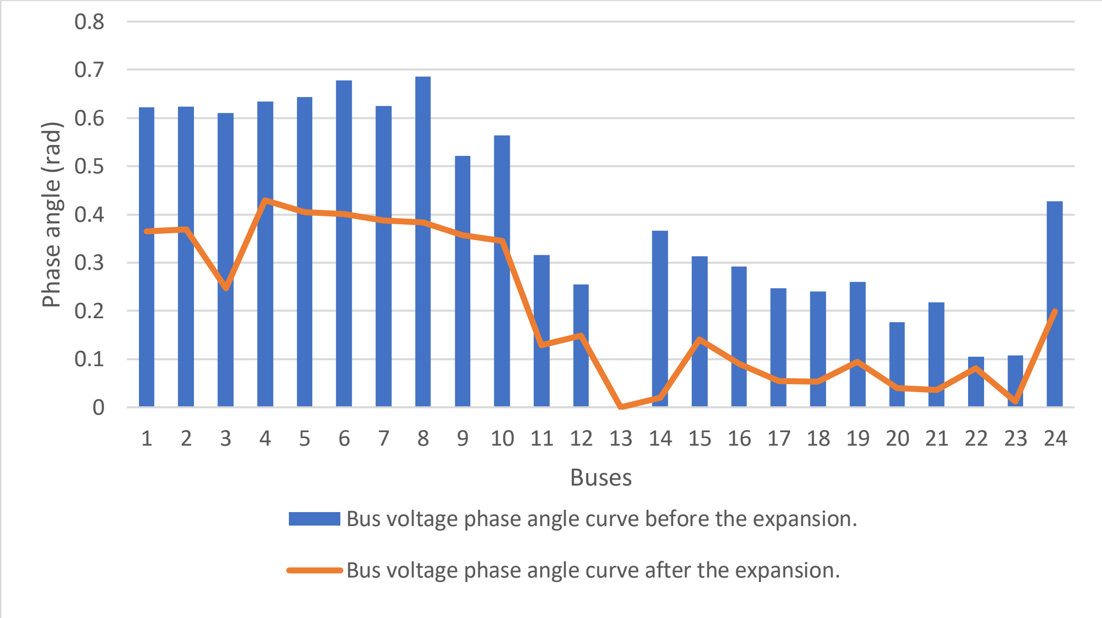


Figure 5.3: Variations of Bus Phase Angle – Case1

Table 5.6: Line Flow in the Selected Candidates – Case 1

From bus	**To bus**	**Line flow (pu)**
3	24	-3.79227
6	7	-1.08557
8	9	-2.43940
13	14	2.50883
13	14	2.50883
13	14	2.50883
15	24	3.23523

Table 5.7: Power Flow in the Existing Branches – Case 1

Line No	**From bus**	**To bus**	**Line flow**
1	1	2	0.28076
2	1	3	-0.55824
3	1	5	0.46948
4	2	4	0.47892
5	2	6	0.16984

6	3	9	0.91903
7	3	24	-0.56500
8	4	9	-0.70508
9	5	10	-0.66652
10	6	10	-0.92059
11	7	8	-0.08557
12	8	9	-0.15883
13	8	10	-0.22333
14	9	11	-2.71645
15	9	12	-2.46784
16	10	11	-2.58953
17	10	12	-2.34092
18	11	13	-2.69836
19	11	14	-2.60762
20	12	13	-3.13657
21	12	23	-1.67218
22	13	23	-0.14141
23	14	16	1.81486
24	15	16	-2.96581
25	15	21	-2.15673
26	15	21	-2.15673
27	15	24	1.12204
28	16	17	-1.35854
29	16	19	0.15759
30	17	18	-0.07267
31	17	22	-1.28588
32	18	21	-0.70033
33	18	21	-0.70033
34	19	20	-1.36920
35	19	20	-1.36920
36	20	23	-2.39320
37	20	23	-2.39320
38	21	22	-1.71412

The branches power flow before and after the expansion is shown in Figure 5.4, Where we can notice that the line flow has considerably decreased after implementing the hybrid approach for the expansion plan and adding the selected candidates to the primary network especially in the lines that were overloaded: 10th, 18th, and 20th lines.

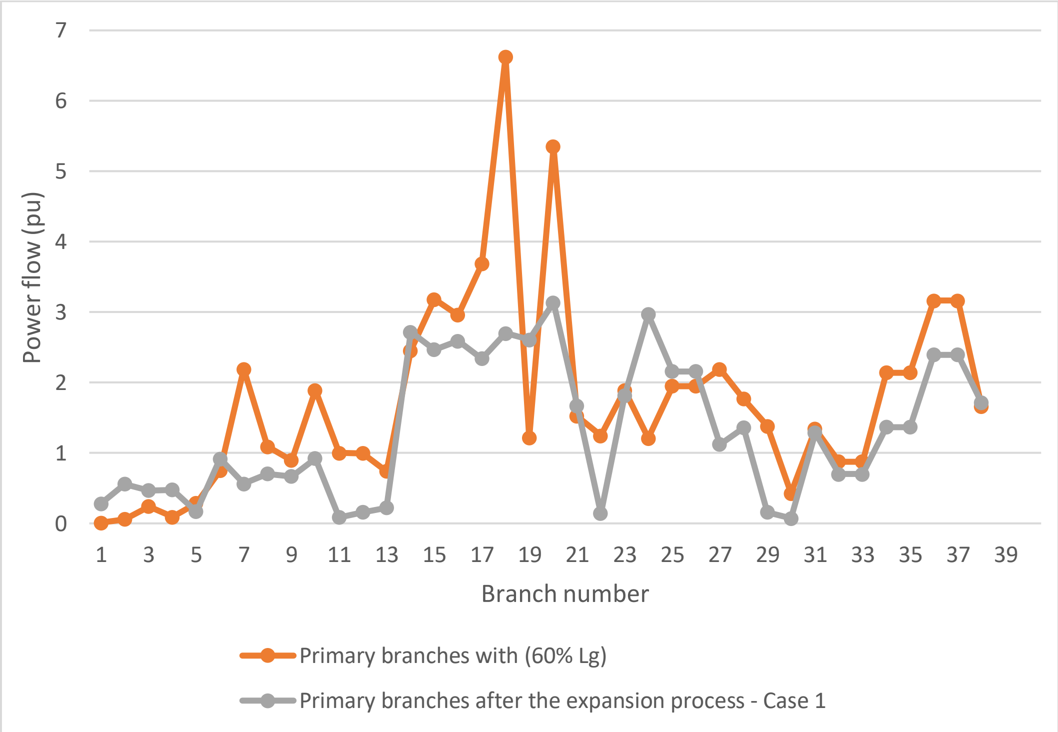


Figure 5.4: Branches Power Flow before and after the Expansion - Case1

5.1.2 Case 2 (With 5% Presence of Wind Energy)

In this case, the IEEE-RTS of 24 nodes is revised by incorporating a wind farm of a maximum of 300 MW which is situated near to node 3 and it is connecting to the network by 175-MW transmission line as seen in Figure 5.5 below.

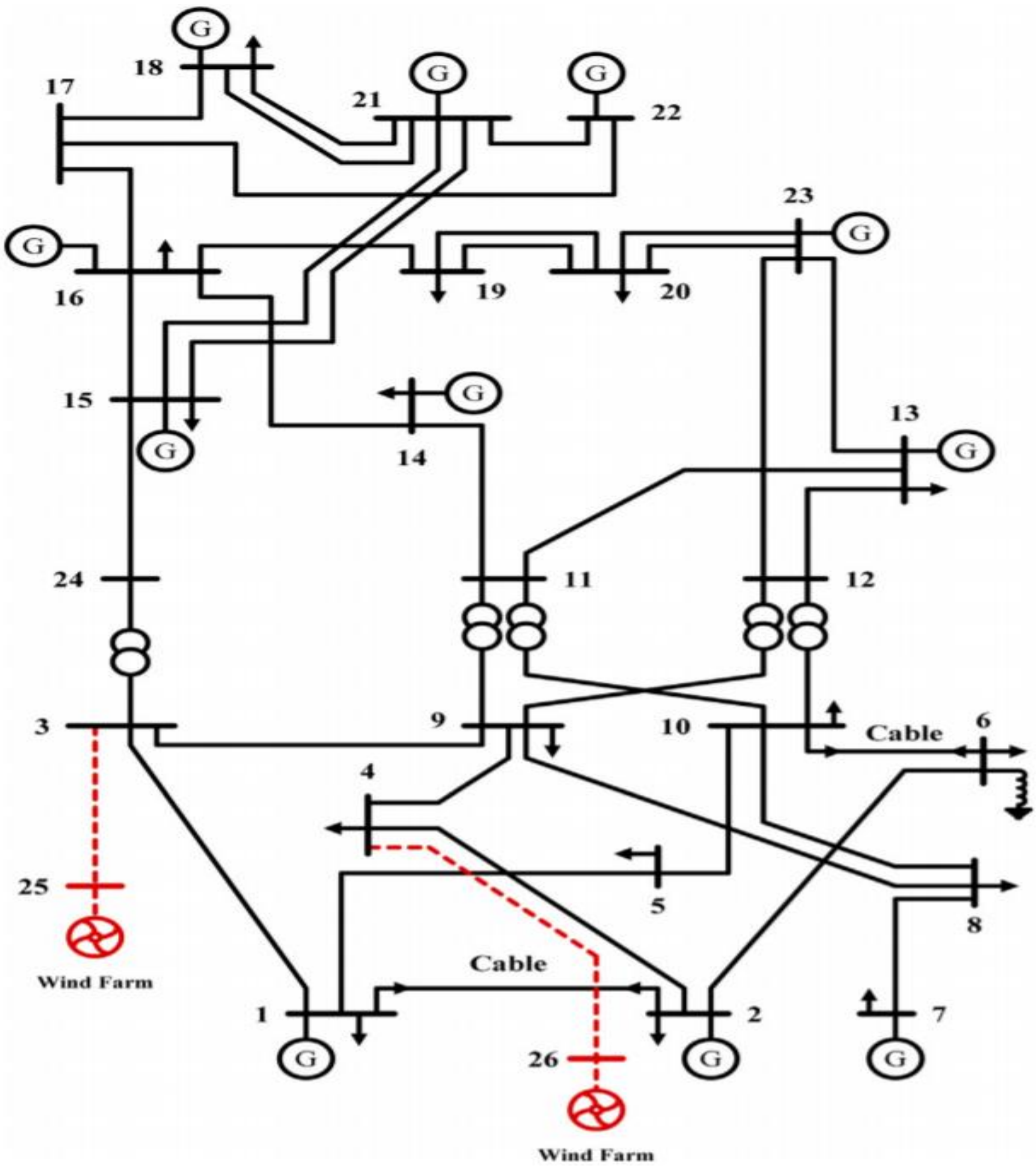


Figure 5.5 : Modified IEEE-RTS of 24-Nodes [30]

According to the future policies of power system generation, the penetration of wind energy in the power system will be increased. Here in Case 2, the wind energy penetration is considered as 5% of the entire generation capacities for the upcoming years [30]. After applied the Hybrid approach to the modified test system with a 60% load increase for the 5 years of planning, the optimum set of lines to be added has been defined and it can be shown below in Table 5.8. This is followed by Table 5.9, 5.10

and 5.11 which include the bus voltage phase angle and the power flow in the selected candidate branches and the existing ones of the modified test system respectively.

Table 5.8 : Result of the Hybrid Heuristic Algorithm - Case 2

From bus	**To bus**	**Capacity (Branch Per Corridor)**
5	10	1
6	7	1
8	9	1
13	14	2
16	23	1
20	23	1
25	3	2
Total construction cost = 162 M$		

Table 5.9: Bus Voltage Angle after the Expansion Procedure – Case 2

Bus No	**Angle (rad)**
1	-0.36767
2	-0.37350
3	-0.30439
4	-0.44240
5	-0.37383
6	-0.42014
7	-0.40673
8	-0.40228
9	-0.37602
10	-0.36809
11	-0.13623
12	-0.15941
13	0.00000

14	-0.02087
15	-0.02172
16	-0.00233
17	0.04403
18	0.05043
19	-0.03658
20	-0.00859
21	0.07339
22	0.18562
23	0.00673
24	-0.12975
25	-0.28724

Table 5.10: Line Flow in the Selected Candidates – Case 2

From bus	**To bus**	**Line flow (pu)**
5	10	-0.99819
6	7	-1.07262
8	9	-2.44250
13	14	2.69341
13	14	2.69341
16	23	-1.34108
16	23	-2.04272
25	3	1.59608

Table 5.11: Power Flow in Branches of the Primary Network – Case 2

Line No	**From bus**	**To bus**	**Line flow (pu)**
1	1	2	0.41881
2	1	3	-0.29962
3	1	5	0.07281

4	2	4	0.54386
5	2	6	0.24295
6	3	9	0.60190
7	3	24	-2.08152
8	4	9	-0.64014
9	5	10	-0.06500
10	6	10	-0.86043
11	7	8	-0.07262
12	8	9	-0.15904
13	8	10	-0.20708
14	9	11	-2.85806
15	9	12	-2.58172
16	10	11	-2.76352
17	10	12	-2.48717
18	11	13	-2.86193
19	11	14	-2.75966
20	12	13	-3.34901
21	12	23	-1.71988
22	13	23	-0.07777
23	14	16	-0.47683
24	15	16	-1.12120
25	15	21	-1.94116
26	15	21	-1.94116
27	15	24	2.08152
28	16	17	-1.78967
29	16	19	1.48273
30	17	18	-0.44497
31	17	22	-1.34470
32	18	21	-0.88649
33	18	21	-0.88649
34	19	20	-0.70664
35	19	20	-0.70664
36	20	23	-0.70928

37	20	23	-0.70928
38	21	22	-1.65530
39	25	3	0.10392

Fig 5.6 below represent the decreasing of the bus phase angle after the expansion process as a sign of system stability. While Figure5.7 illustrate the variation in the power flow for the primary branches before and after the expansion, where the power flow was reduced in most branches after the expansion procedure especially the branches that were overloaded before.

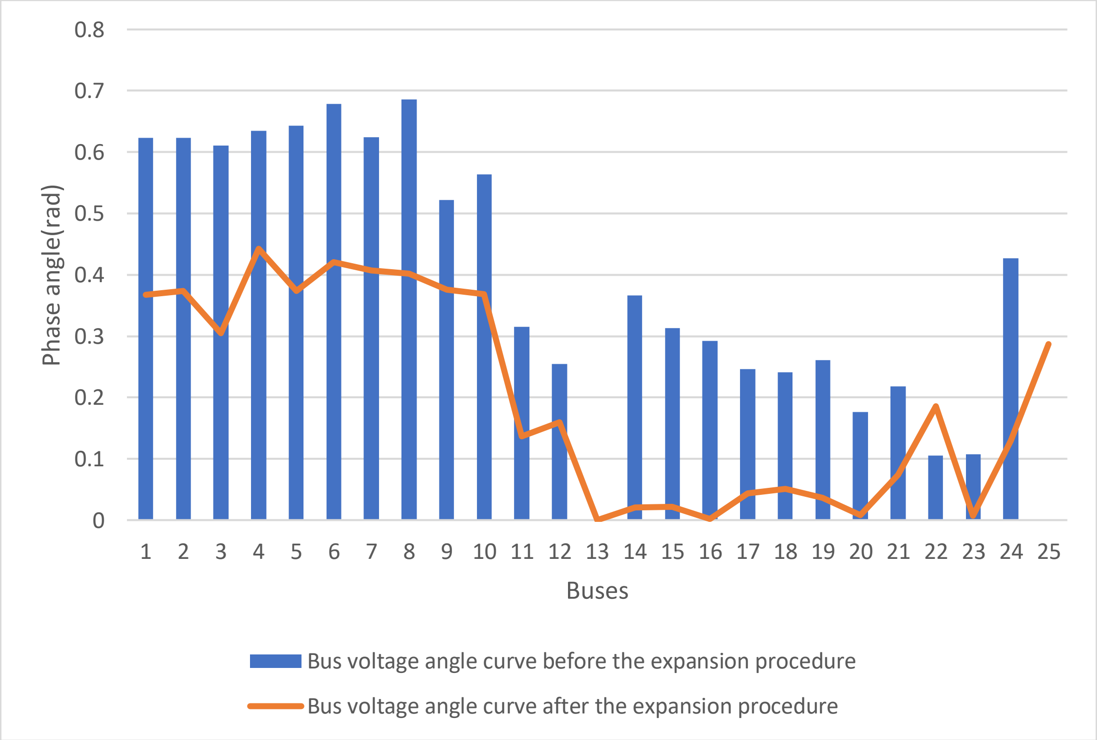


Figure 5.6: Variations of Bus Phase Angle – Case 2

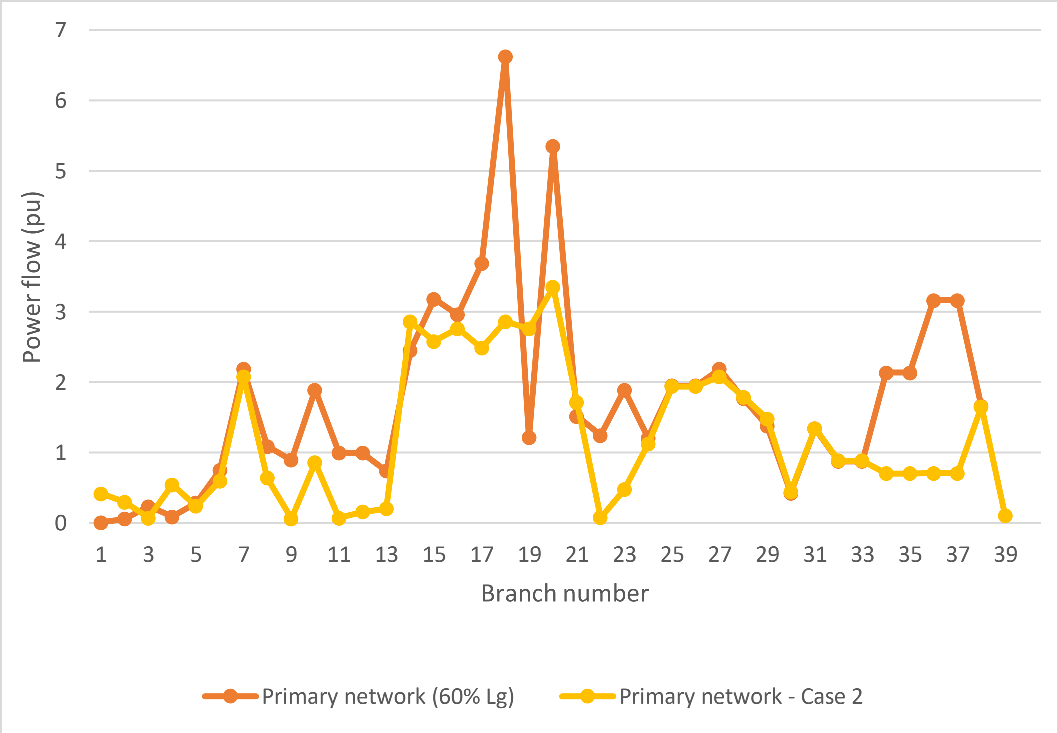


Figure 5.7: Branches Power Flow before and after the Expansion – Case 2

5.1.3 Case 3 (With 10% Presence of Wind Energy)

In this case, the IEEE-RTS of 24 nodes is modified by incorporating two similar wind farms of maximum 300 MW and the energy generated by them is fed to bus 3 and bus 4 , which are the closest nodes to those wind farms as seen in figure 5.3 above. The wind farm is connected to the grid by 175-MW transmission lines and the wind energy penetration considered as 10% of the entire generation capacities for the upcoming years. The Hybrid approach was applied to the modified test system and the result is shown in Table 5.12 below.

Table 5.12 : Result of the Hybrid Heuristic Algorithm - Case 3

From bus	**To bus**	**Capacity (Branch Per Corridor)**
6	7	1
8	9	1
13	14	2

16	23	1
25	3	2
26	4	2
Total construction cost = 155 M$		

The bus voltage phase angle and the power flow in the selected candidate branches and the existing ones for case 3 are listed in Table 5.13, Table 5.14 and Table 5.15 respectively.

Table 5.13: Bus Voltage Angle after the Expansion Procedure – Case 3

Bus No	**Angle (rad)**
1	-0.30298
2	0.29976
3	-0.26001
4	-0.28194
5	-0.35595
6	-0.35299
7	-0.34797
8	-0.33540
9	-0.32086
10	-0.31100
11	-0.11387
12	-0.13301
13	0.00000
14	-0.01252
15	-0.00269
16	0.01408
17	0.06135
18	0.06820

19	-0.03175
20	-0.01369
21	0.09156
22	0.20346
23	0.01828
24	-0.10103
25	-0.25116
26	-0.27741

Table 5.14: Line Flow in the Selected Candidates – Case 3

From bus	**To bus**	**Line flow (pu)**
6	7	-1.20470
8	9	-2.70482
13	14	2.42241
13	14	2.42241
16	23	-1.86270
25	3	1.64640
26	4	1.64642

Table 5.15: Power Flow in Branches of the Existing Network – Case 3

Line no	**From bus**	**To bus**	**Line flow (pu)**
1	1	2	-0.23144
2	1	3	-0.20345
3	1	5	0.62689
4	2	4	-0.14066
5	2	6	0.27722
6	3	9	0.51136
7	3	24	-1.89481
8	4	9	0.37534

9	5	10	-0.50911
10	6	10	-0.69408
11	7	8	-0.20470
12	8	9	-0.08806
13	8	10	-0.14781
14	9	11	-2.46718
15	9	12	-2.23900
16	10	11	-2.34959
17	10	12	-2.12141
18	11	13	-2.39213
19	11	14	-2.42464
20	12	13	-2.79432
21	12	23	-1.56610
22	13	23	-0.21128
23	14	16	-0.68381
24	15	16	-0.96986
25	15	21	-1.92348
26	15	21	-1.92348
27	15	24	1.89481
28	16	17	-1.82505
29	16	19	1.98408
30	17	18	-0.47552
31	17	22	-1.34953
32	18	21	-0.90176
33	18	21	-0.90176
34	19	20	-0.45596
35	19	20	-0.45596
36	20	23	-1.47996
37	20	23	-1.47996
38	21	22	-1.65047
39	25	3	0.05360
40	26	4	0.05358

Figure 5.8 and Figure 5.9 below illustrate the decreasing of the bus phase angle and power flow in the primary branches which indicate the system stability that obtained after the expansion process.

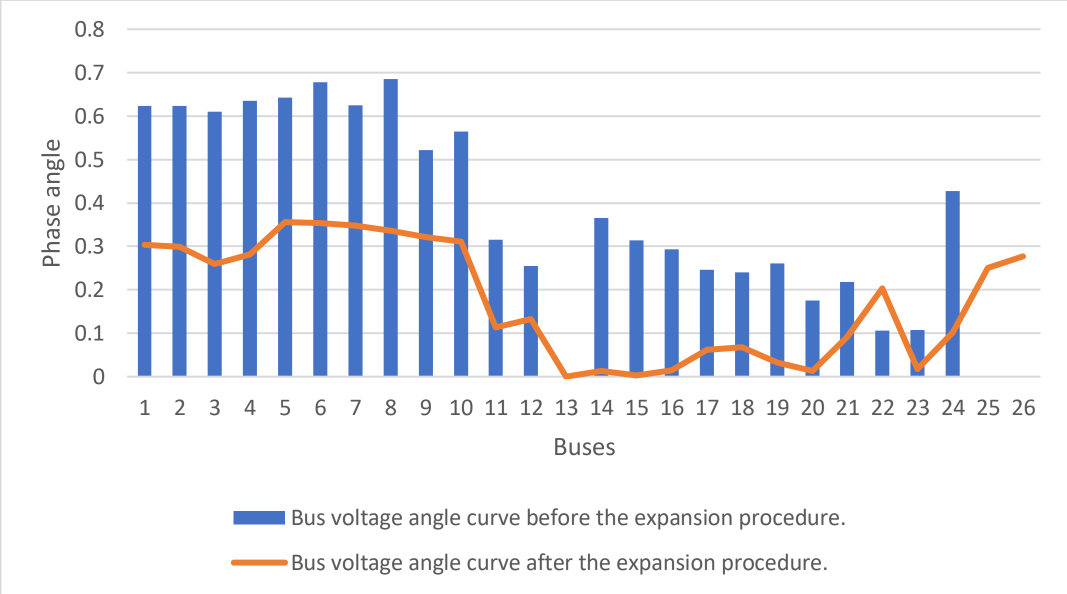


Figure 5.8: Variations of Bus Phase Angle – Case 3

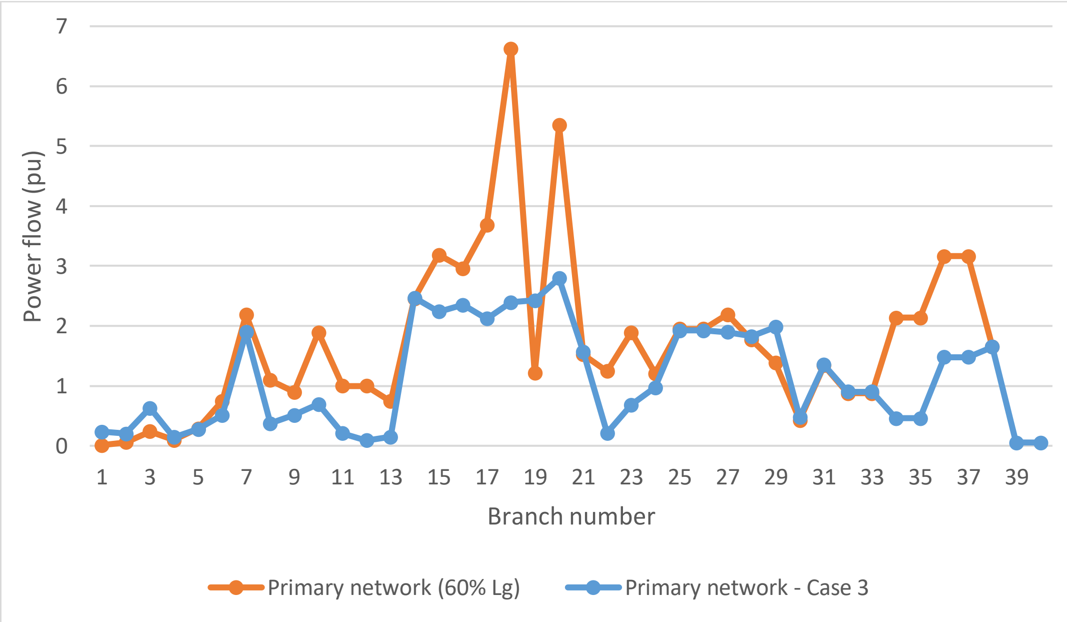


Figure 5.9: Primary Branches Power Flow before and after the Expansion – Case 3

By assessing the results of Table 5.16 below which contains the optimal set of lines that should added to the network for the 3 cases of wind energy permeation into the test system, we can realize that the total number of the inserted branches in Case 2 (with 5% wind energy penetration) and Case 3 (with 10% wind energy penetration) were increased compared to that of Case 1 (with no wind farm). That is to say, incorporating a wind farm to the grid lead to an increase in the number of the inserted lines in the network. Nevertheless, by comparing between the total cost in case 1 and case 3 it is noted that the total cost in case 3 is lower than it in case 1 although the inserted branch numbers in case 3 are higher than it in case 1, that is because the total cost of the expansion plan depends on the total length of the inserted branches, not on their numbers.

Table 5.16: Optimal set of the Inserted Lines for all Cases

Lines		**Cases**		
From	**To**	**Case 1** **No-Wind Farm**	**Case 2** **5% Wind Energy**	**Case 3** **10%Wind Energy**
5	10	0	1	0
3	24	1	0	0
6	7	1	1	1
8	9	1	1	1
13	14	3	2	2
13	23	0	0	0
14	23	0	0	0
15	24	1	0	0
16	23	0	1	1
20	23	0	1	0
25	3	0	2	2
26	4	0	0	2
Total Number		**7**	**9**	**9**
Cost (M$)		**158.6**	**162**	**155.82**

5.1.4 Case 4 (Case 2 with consideration of the wind energy uncertainty)

Practically, wind power output is not considered as a deterministic input variable because it depends on the random wind speed factor, as seen in the following nonlinear equation 5.1 that expresses the relation between the output power and speed of the wind mathematically.

$$P = \frac{\pi}{2} \times r^2 \times v^3 \times \rho \times \eta \qquad (5.1)$$

Where

P : Electric power where 1 W = 1 kg × m² / s³.

r : The radius of the turbine blade (m).

v : Wind speed (m /s).

ρ : Air density (kg/m³).

η : Efficiency factor where the average wind efficiency of turbines is around (35% - 45%) of the theoretical maximum output [31].

The wind farm output power is the summation of the active powers of all turbines of the wind farm. Generally, the majority of the wind turbines start to output power at 4 m/s wind speed (V_{cin}), reach rated power at around 13 m/s (V_r), and stop producing energy at 25 m/s (V_{co}) as shown in Figure 5.10 below [32].

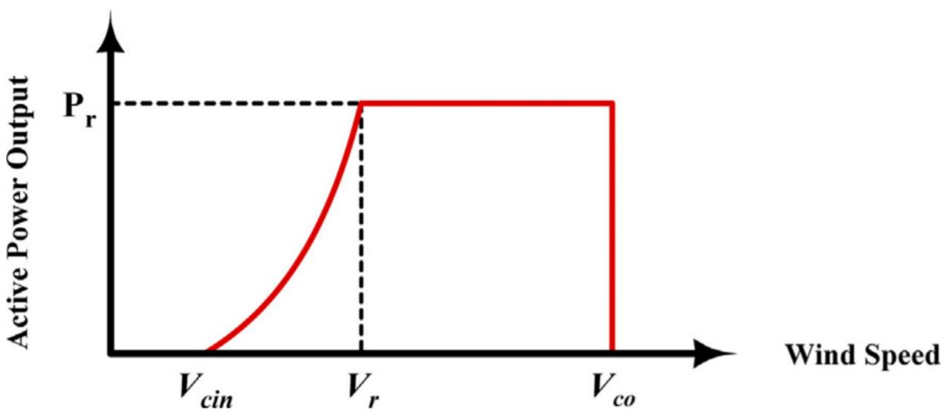


Figure 5.10: Wind Turbine Power Curve

Where V_{cin} , V_r , V_{co} and P_r are the Cut-in speed, Cut-out speed, Rated speed and Rated power of the wind turbine respectively.

The random attribute of wind speed could have an indirect effect in the TEP, therefore it should be involved in the expansion plan. Figure 5.6 of the wind power output that occurs more frequently was taken from [31]. Where a probabilistic approach based on Monte Carlo simulations (MCS) has been utilized to analyze the wind speed in South Korea. A historical wind speed data was collected for 2 years as a try to estimate the more frequently scenarios occur. Thereafter, the curve of the most frequent scenarios of wind power has been obtained as seen in Figure 5.11 below.

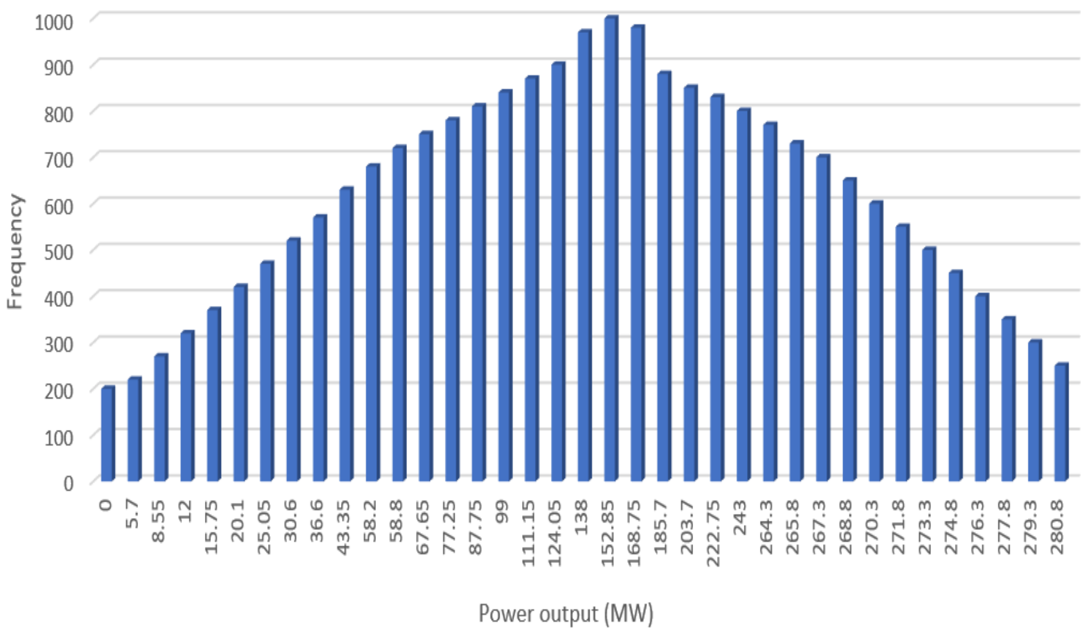


Figure 5.11: Curve of the most Frequent Wind Power Output

5.1.4.1 Case 4a (of Taking the Most Frequent Wind Energy Scenario of a Wind Farm as a System Input Variable)

As we can see in Figure 5.6 above, 152.85 MW was recorded the highest frequency, that followed by 168.75 MW which is almost the same as the injected power in case 2. The wind output power with the highest frequency was injected to the system thereafter the proposed approach for TEP was applied. Results demonstrated that the optimum set to be inserted into the network had some changes compared with the determined one in case 2. For example, line 5 -10 and 20 - 23 which were chosen in case 2 are not a part of the solution in this case, instead, line 3 -24 and an extra line in corridor 13- 14 has been chosen to be inserted while the remaining branches of the optimum set are the same, as seen in Table 5.17, where we can notice that, although the number of inserted branches remains the same, the expansion cost has been increased due to the total length difference of the inserted lines in each case.

Table 5.17: Comparison of the results of the Hybrid Approach in Case 2 and Case 4a

Inserted branches	**Case 2**	**Case 4a**
5 - 10	1	0
3 - 24	0	1
6 - 7	1	1
8 - 9	1	1
13 - 14	2	3
16 - 23	1	1
20 - 23	1	0
25 - 3	2	2
Total number	**9**	**9**
Total cost (M$)	**162**	**176**

Table 5.18 and Table 5.19 below represents the flow in the added and primary lines for case 4.1.

Table 5.18: Power Flow in the Inserted Branches – Case 4a

Inserted branches	**power flow (pu)**
3 - 24	-2.56287
6 - 7	-1.09019
8 - 9	-2.45099
13 - 14	1.94044
13 - 14	1.94044
13 - 14	1.94044
16 - 23	-1.99234
25 - 3	1.43647

Table 5.19: Line Flow in the Primary Branches – Case 4a

From bus	**To bus**	**Power flow (pu)**
1	2	0.29858
1	3	-0.59492
1	5	0.48834
2	4	0.48592
2	6	0.18067
3	9	0.99977
3	24	-0.38183
4	9	-0.69808
5	10	-0.64766
6	10	-0.90515
7	8	-0.09019
8	9	-0.15959
8	10	-0.21561
9	11	-2.70470

9	12	-2.40418
10	11	-2.59447
10	12	-2.29395
11	13	-2.64590
11	14	-2.65327
12	13	-3.17560
12	23	-1.52253
13	23	0.04719
14	16	0.06405
15	16	-1.82085
15	21	-2.02293
15	21	-2.02293
15	24	2.94470
16	17	-1.62615
16	19	1.81169
17	18	-0.30376
17	22	-1.32239
18	21	-0.81588
18	21	-0.81588
19	20	-0.54216
19	20	-0.54216
20	23	-1.56616
20	23	-1.56616
21	22	-1.67761
25	3	0.09353

5.1.4.2 Case 4b (Of Finding the optimum network for case 2 and case 4a simultaneously)

As a try to find the optimum network that proper both cases simultaneously; case 4a and case 2 while supplying the load adequately in N and N-1 conditions, several attempts were carried out, and the best set of branches to be inserted has defined which is actually the same as the optimum set that has been chosen in case 4a in addition to one extra branch in the 6-10 corridor as seen in Table 5.20. The power flow in the inserted branches is shown in Table 5.21 below, followed by Table 5.22 which represents the power flow in the primary branches.

Table 5.20: Results of the Hybrid Approach – Case 4b

Inserted branches	**Capacity (Branch per corridor)**
3 - 24	1
6 - 7	1
6 - 10	1
8 - 9	1
13 - 14	3
16 - 23	1
25 - 3	2
Total number	**10**
Total Cost (M$)	**184.44**

Table 5.21: The Power Flow in the Selected Branches to be Inserted - Case 4b

Inserted branches	**power flow (pu)**
3 - 24	-3.01205
6 - 7	-0.99149
6 - 10	-1.08152
8 - 9	-2.69555
13 - 14	1.99092
13 - 14	1.99092
13 - 14	1.99092
16 - 23	-2.27876
25 - 3	1.69743

Table 5.22: Line Flow in the Primary Branches – Case 4b

From bus	To bus	Power flow (pu)
1	2	0.22089
1	3	-0.63709
1	5	0.60820
2	4	0.55740
2	6	0.03148
3	9	1.20394
3	24	-0.00898
4	9	-0.62660
5	10	-0.52780
6	10	-0.07151
7	8	0.00851
8	9	-0.00408
8	10	-0.02786
9	11	-2.63454
9	12	-2.28774
10	11	-2.58774
10	12	-2.24094
11	13	-2.44731
11	14	-2.77498
12	13	-3.05858
12	23	-1.47010
13	23	0.04135
14	16	0.09379
15	16	-1.88272
15	21	-2.03016
15	21	-2.03016
15	24	3.02103
16	17	-1.61169
16	19	2.05151
17	18	-0.29127

17	22	-1.32042
18	21	-0.80964
18	21	-0.80964
19	20	-0.42224
19	20	-0.42224
20	23	-1.44624
20	23	-1.44624
21	22	-1.67958
25	3	0.00257

Figure 5.12 and Figure 5.13 below illustrate the diminishing of the bus phase angle and power flow for the primary branches for both cases of case 4 (case 4a and case 4b) after the expansion process.

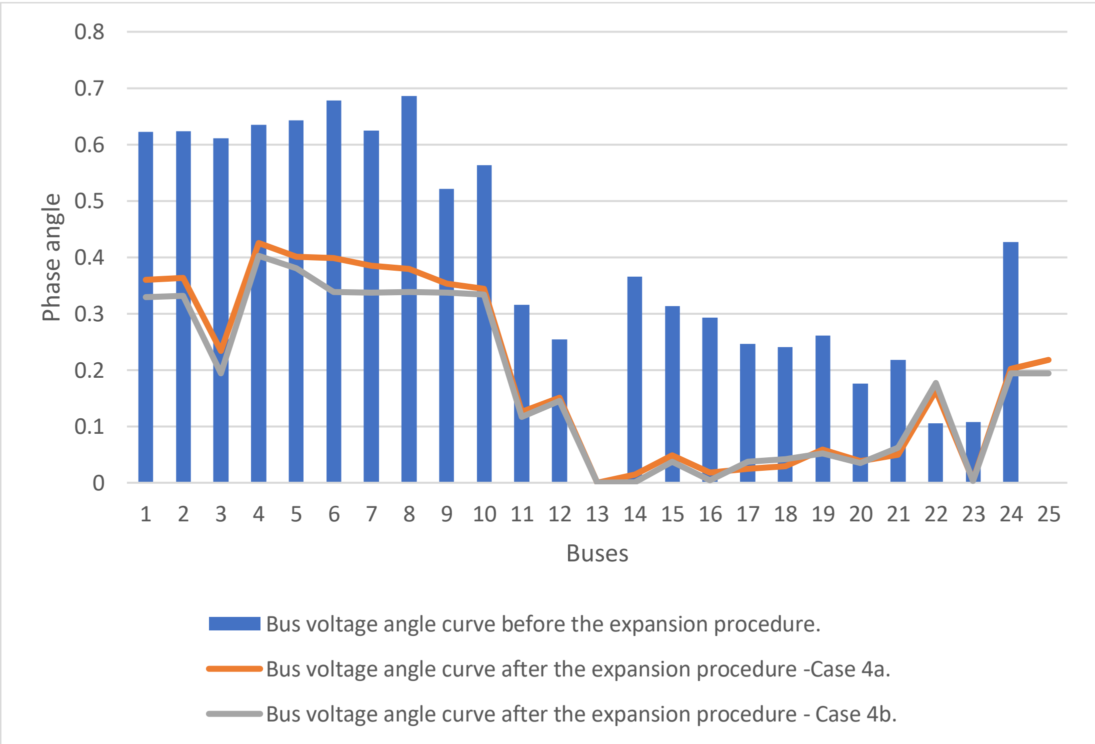


Figure 5.12: Variations of Bus Phase Angle – Case 4

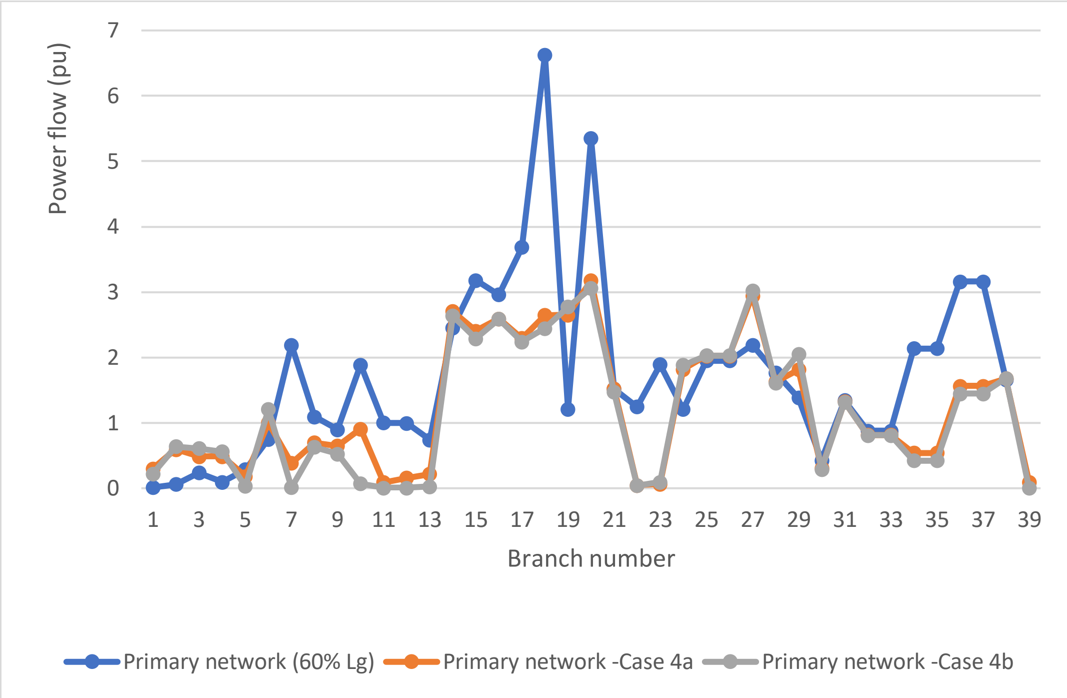


Figure 5.13: Primary Branches Power Flow before and after the Expansion – Case 4.

5.1.5 Case 5 (Case 3 with Consideration of the Wind Energy Uncertainty)

To test the effect of the wind energy uncertainty on the expansion plan in case of incorporating 2 similar wind farms into the system as mention in case 3, we assumed the most frequent wind power output curve in Fig 5.11 above for both wind farms that are connected to bus 3 and bus 4, where the wind output energy with the highest frequency were injected to the system and the proposed approach for TEP was implemented. The optimum set of the inserted branches was the same as in case 3, while the branches power flow was changed. Table 5.23 and Table 5.24 below represents the flow in the inserted and primary branches for case 5.

Table 5.23: Power Flow in the Inserted Branches – Case 5

Inserted branches		power flow (pu)
6	7	-1.19812
8	9	-2.68367
13	14	2.493235

13	14	2.493235
16	23	-1.88461
25	3	1.48176
26	4	1.48178

Table 5.24: Line Flow in the Primary Branches – Case 5

From bus	To bus	Power flow (pu)
1	2	-0.20382
1	3	-0.19013
1	5	0.58595
2	4	-0.08508
2	6	0.24926
3	9	0.45042
3	24	-1.99055
4	9	0.26092
5	10	-0.55005
6	10	-0.72862
7	8	-0.19812
8	9	-0.08737
8	10	-0.16308
9	11	-2.55127
9	12	-2.30844
10	11	-2.40228
10	12	-2.15946
11	13	-2.46018
11	14	-2.49337
12	13	-2.88818
12	23	-1.57971
13	23	-0.17483
14	16	-0.61090
15	16	-1.04746

15	21	-1.93255
15	21	-1.93255
15	24	1.99055
16	17	-1.80691
16	19	1.98316
17	18	-0.45986
17	22	-1.34705
18	21	-0.89393
18	21	-0.89393
19	20	-0.45642
19	20	-0.45642
20	23	-1.48042
20	23	-1.48042
21	22	-1.65295
25	3	0.04824
17	22	0.04822

Fig 5.14 below represent the decreasing of the bus phase angle after the expansion process. Whereas Figure 5.15 shows the variation in the power flow for the primary branches before and after the expansion, where the branches power flow was notably lessened after the expansion procedure.

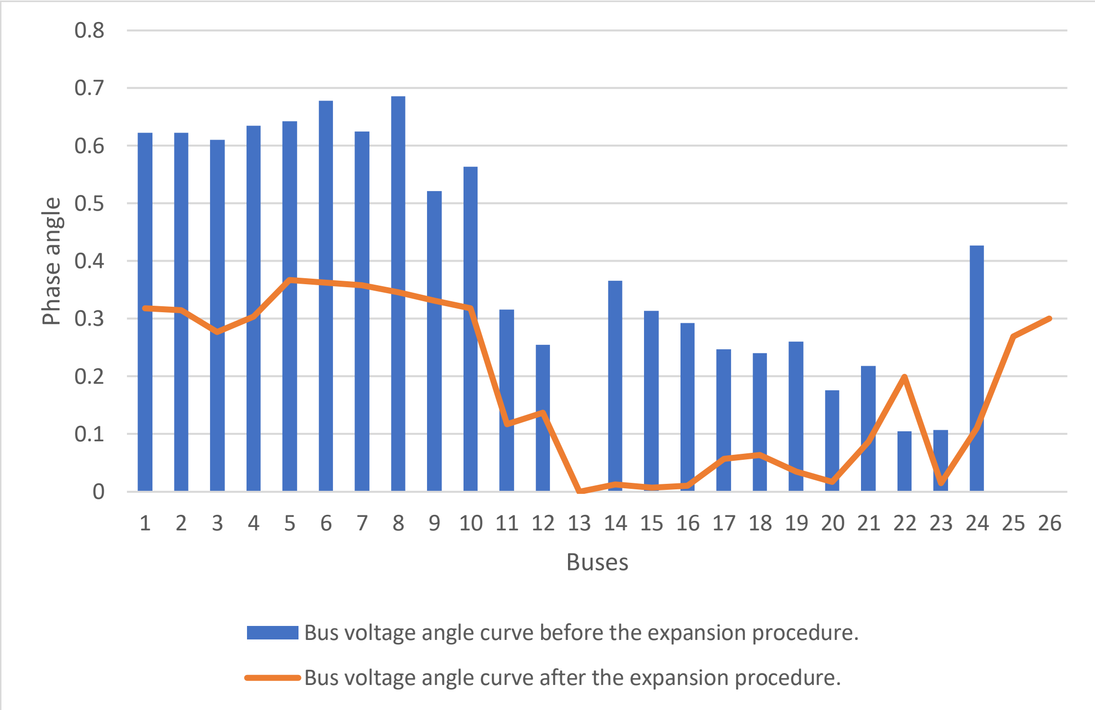


Figure 5.14: Variations of Bus Phase Angle – Case 5

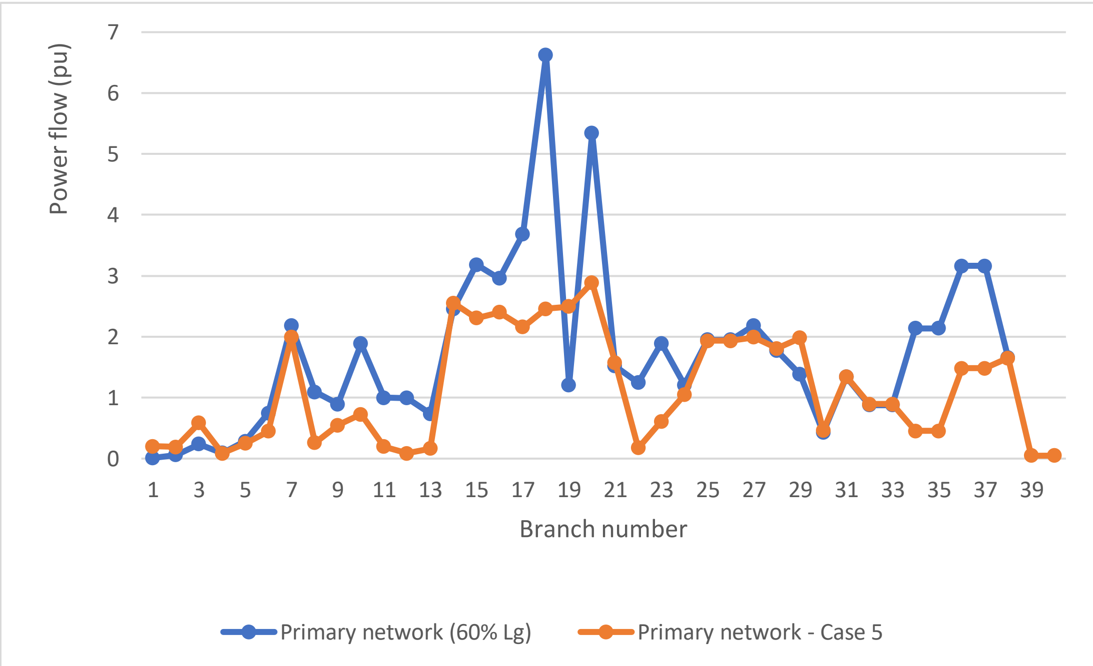


Figure 5.15: Primary Branches Power Flow before and after the Expansion – Case 5

We can conclude with Figure 5.16 below which illustrate the variations of the investment cost of the transmission grid expansion according to the wind energy generation.

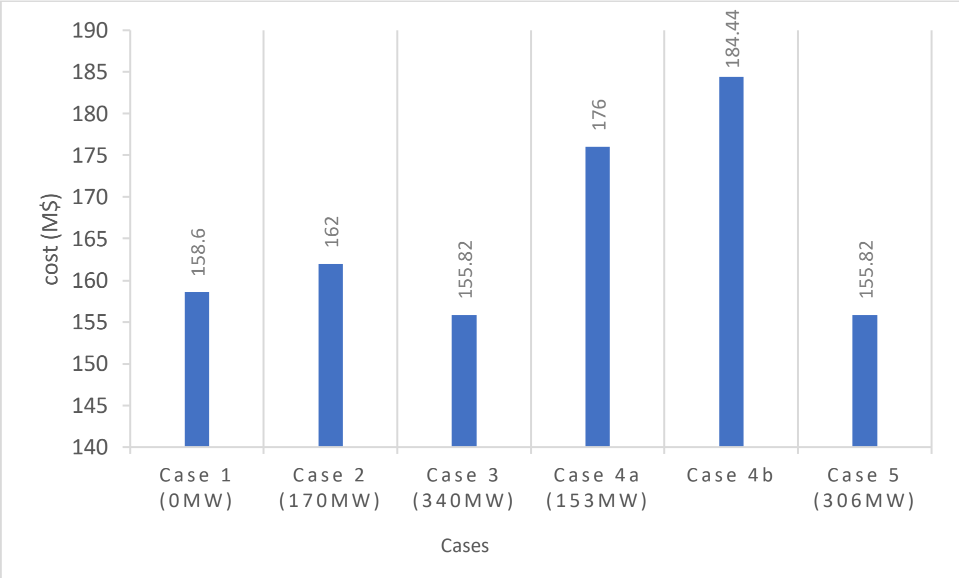


Figure 5.16: TEP Cost of all Cases

Where it is noted that the impact of increasing the wind power system penetration on the cost of expansion of the transmission network depends on the injected power in each case. As we can see, the highest cost was in the case 4b, which seeks to find the optimal network in order to supply future loads in a secure and economical manner while taking into account the uncertainty of the wind energy generation. In contrast, the lowers cost was in case 3 and case 5 although the number of branches to be inserted are higher than in case 1, that because in case 3 and 5 as two wind farms have been connected to the system in two different places, the loads were supplied by branches with less total length which means less cost since the cost of expansion depends on the total length of the inserted transmission lines.

Chapter 6

CONCLUSIONS

6.1 Conclusion

This dissertation suggested an effective Hybrid Heuristic approach to obtain the best solution for the TEP problem with consideration of the RE resources, where the essential aims of the research are to lessen the new lines construction expense, finding the optimum transmission network to supply the predicted loads in the planning period for both N and N-1 conditions , and to accommodate the RE generation facilities and know its effect in the network expansion plan.

The proposed Hybrid approach (Backward- Forward search) which formulated using DC formulation had been applied to the IEEE RTS of 24 nodes where a deterministic load method and scenario-based methods were used to represent the uncertainties of the forecasted load and wind energy generation respectively. The results denote that the aims of the thesis had been achieved where:

- The optimum transmission network was found for different cases of wind energy permeation.
- The predicted load was perfectly supplied for the two conditions the normal and contingency N-1.
- The uncertainties of wind farms generation were considered in the TEP problem as a trying to secure the practicality of the optimum plans.

6.2 Recommendations

The suggested optimization model neglects the power loss in the transmission lines. Although many researchers were taking the reduction of the power loss in the transmission lines into consideration while studying the TEP problem, modeling the losses has a negative effect on the optimization model where it makes it more complex computationally which leads to an increment of time and efforts for solving it. Thus, further work must be done to study the effect of the losses on the obtained expansion plan.

In addition to that, yearly load growth is not as deterministic as proposed, where it can be growing arbitrarily during the planning years. Therefore, it is recommended to develop the method so that several scenarios of load variations can be considered during the planning period.

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APPENDIX

Appendix A: IEEE 24 - Bus Test System Data

Table A.1: Bus Data

Bus number	Bus type	P_G (pu)	P_L (pu)	Q_L (pu)	Base KV
1	2	1.92	1.08	0.22	138
2	2	1.92	0.97	0.2	138
3	1	0	1.8	0.37	138
4	1	0	0.74	0.15	138
5	1	0	0.71	0.14	138
6	1	0	1.36	0.28	138
7	2	3	1.25	0.25	138
8	1	0	1.71	0.35	138
9	1	0	1.75	0.36	138
10	1	0	1.95	0.4	138
11	1	0	0	0	230
12	1	0	0	0	230
13	3	5.91	2.65	0.54	230
14	2	0	1.94	0.39	230
15	2	2.15	3.17	0.64	230
16	2	1.55	1	0.2	230
17	1	0	0	0	230
18	2	4	3.33	0.68	230
19	1	0	1.81	0.37	230
20	1	0	1.28	0.26	230
21	2	4	0	0	230
22	2	3	0	0	230
23	2	6.6	0	0	230
24	1	0	0	0	230

1: Load bus.
2: Generator bus.
3: Slack bus.

Table A.2 Existing Branches Data

Line No	From	Bus	R (pu)	X (pu)	Line Capacity Limits (pu)	Path Length (Miles)
1	1	2	0.0026	0.0139	1.75	3
2	1	3	0.0546	0.2112	1.75	55
3	1	5	0.0218	0.0845	1.75	22
4	2	4	0.0328	0.1267	1.75	33
5	2	6	0.0497	0.192	1.75	50
6	3	9	0.0308	0.119	1.75	31
7	3	24	0.0023	0.0839	4	50

8	4	9	0.0268	0.1037	1.75	27
9	5	10	0.0228	0.0883	1.75	23
10	6	10	0.0139	0.0605	1.75	16
11	7	8	0.0159	0.0614	1.75	16
12	8	9	0.0427	0.1651	1.75	43
13	8	10	0.0427	0.1651	1.75	43
14	9	11	0.0023	0.0839	4	50
15	9	12	0.0023	0.0839	4	50
16	10	11	0.0023	0.0839	4	50
17	10	12	0.0023	0.0839	4	50
18	11	13	0.0061	0.0476	5	66
19	11	14	0.0054	0.0418	5	58
20	12	13	0.0061	0.0476	5	66
21	12	23	0.0124	0.0966	5	67
22	13	23	0.0111	0.0865	5	134
23	14	16	0.005	0.0389	5	54
24	15	16	0.0022	0.0173	5	24
25	15	21	0.0063	0.049	5	68
26	15	21	0.0063	0.049	5	68
27	15	24	0.0067	0.0519	5	72
28	16	17	0.0033	0.0259	5	36
29	16	19	0.003	0.0231	5	32
30	17	18	0.0018	0.0144	5	20
31	17	22	0.0135	0.1053	5	146
32	18	21	0.0033	0.0259	5	36
33	18	21	0.0033	0.0259	5	36
34	19	20	0.0051	0.0396	5	55
35	19	20	0.0051	0.0396	5	55
36	20	23	0.0028	0.0216	5	30
37	20	23	0.0028	0.0216	5	30
38	21	22	0.0087	0.0678	5	94
*39	25	3	0.0427	0.1651	175	43
*40	26	4	0.0218	0.0845	175	22

*: Indicates wind farms have been connected to bus 3 and bus 4.

Table A.3 : The New Corridors of The Candidate Lines

No	From	Bus	Path Length (Miles)
1	1	8	35
2	2	8	33
3	6	7	50
4	13	14	31
5	14	23	43
6	16	23	27
7	19	23	42

All the candidate lines have the same line type and the same properties (R= 0, X= 0.00025, and Line Capacity Limits = 500 MW).

Appendix B: Matlab M-files Codes

- **Hybrid Heuristic Code**

```
function [Os, Adline, Noll, Coll, Angle,Mof] = HS(Busdata, Linedata, Candid,
Linetype, Solution, Lg, Mof)
if nargin<7 | isempty(Mof), Mof = 10^20; end
if nargin<6 | isempty(Lg), Lg = 0; Mof = 10^20; end
if nargin<5 | isempty(Solution)
Solution = ones(size(Candid,1),1); Lg = 0; Mof = 10^20;
end
if nargin<4 | isempty(Linetype)
fprintf('Input argument "Linetype" containing the');
fprintf(' information of different types of lines.');
error('"Linetype" is undefined.');
end
if nargin<3 | isempty(Candid)
fprintf('Input argument "Candid" containing');
fprintf(' the information of candidate lines.');
error('"Candid" is undefined.');
end
if nargin<2 | isempty(Linedata)
fprintf('Input argument "Linedata" containing');
fprintf(' the information of existing lines.');
error('"Linedata" is undefined.');
end
%% Problem outputs:
%% Os: Optimal solution of the NEP problem
%% Adline: final set of selected candidate lines among all candidates.
%% Noll: overload of the existing and selected candidate lines in normal condition
after adding optimal candidate line in each iteration (or in order of priority)
%% Coll: overload of the existing and selected candidate lines in N-1 condition after
adding optimal candidate line in each iteration
%% Angle: voltage phase angle at each bus
%% Problem inputs:
%% Busdata
%% Linedata
%% Candid( data of candidate lines)
%% Linetype
%% Solution: the initial solution, which is a zero vector for hybrid search algorithm
%% Contingency: if contingency=1, the problem is solved by considering N-1
condition.
%% Lg: load growth rate
%% Mof: minimum fitness
 contingency = 0;
[OSB, added_lineB, NOLLB, COLLB, AngleB, MOFB] = BS(Busdata, Linedata,
Candid, Linetype, Solution,contingency, Lg, Mof);
contingency = 1;
[Os, Adline, Noll, Coll, Angle, Mof] = FS(Busdata, Linedata, Candid, Linetype, OSB,
contingency, Lg, Mof);
```

```
if sum(Os-OSB) == 0
Angle = AngleB;
Noll = NOLLB;
Coll = COLLB;
Mof = MOFB;
Adline = added_lineB
Os = OSB;
end
```

- **Backward Search Code**

```
function[Os, Adline, Noll, Coll, Angle, Mof] = BS(Busdata, Linedata, Candid,
Linetype, Solution, ...
Contingency, Lg, Mof);
if nargin<8 | isempty(Mof), Mof = 10^20; end
if nargin<7 | isempty(Lg), Lg = 0; Mof = 10^20; end
if nargin<6 | isempty(Contingency)
Contingency = 0; Lg = 0; Mof = 10^20;
end
if nargin<5 | isempty(Solution)
Solution = ones (size(Candid,1),1);
Contingency = 0; Lg = 0; Mof = 10^20;
end
if nargin<4 | isempty(Linetype)
fprintf('Input argument "Linetype" containing the');
fprintf(' information of different types of lines.');
error('"Linetype" is undefined.');
end
if nargin<3 | isempty(Candid)
fprintf('Input argument "Candid" containing the');
fprintf(' information of candidate lines.');
error('"Candid" is undefined.');
end
if nargin<2 | isempty(Linedata)
fprintf('Input argument "Linedata" containing');
fprintf(' the information of existing lines.');
error('"Linedata" is undefined.');
end
%% Backward search algorithm
%% Initialization
diff = 1; SID = 0; j = 1;
ii = 0; jj = 0; kk = 0;
Noll = null(1); Coll = null(1);
while diff>0 | j<=2^nc
Solution1 = Solution;
[isol] = find(Solution1 ~= 0);
best_sol = null(1);
for i = 1:length (isol)
Isol = isol(i);
Solution1 (Isol) = 0;
```

```
[Ybus, linedata, busdata, nIs, nbus, bus_number] = ybus_calculation(Busdata,
Linedata, Solution1, Candid, Linetype, Lg);
[angle_r, angle_d, PF, OL, SOL] = dcpf(busdata, linedata, Ybus);
NOL{i,1} = OL;
angle{i,1} = angle_r;
Isoln = find(Solution1~=0);
[TC] = Total_Cost(Isoln, Solution1, Candid, Linetype);
if Contingency == 1 & nIs == 0
[COL, CnIs, OLF] = contingency(linedata, busdata);
%% OOLF{i,1}: total overload in N-1 condition, in case of
OOLF{i,1} = OLF;
else
COL = 0; CnIs = 0;
end
nline = size (linedata,1);
OF = TC+(10^9*((SOL)+COL))+(10^12*((nIs)+(CnIs)));
if OF < Mof
diff = (Mof-OF);
Mof = OF;
best_sol = Isol;
j = j+1;
else
j = j+1;
end
Solution1(Isol) = Candid(Isol,6);
end
best_sol_index = isempty(best_sol);
if best_sol_index == 1;
break
else
Solution(best_sol) = 0;
ii = ii+1;
best(ii,1) = best_sol;
best(ii,2) = Mof;
if Contingency == 1
jj = jj+1;
bsol = find (isol == best_sol);
Coll{jj,1} = OOLF{bsol,1};
kk = kk+1;
Noll{kk,1} = NOL{bsol,1};
Angle{kk,1} = angle{bsol,1};
clear angle NOL
else
kk = kk+1;
bsol = find(isol == best_sol);
Noll{kk,1} = NOL{bsol,1};
Angle{kk,1} = angle{bsol,1};
clear angle NOL
end
end
```

```
end
Os = Solution; % Optimal solution
al = find(Os~=0);
if length(al)~=0;
lb = length(best);
for i = 1:length(al)
Adline(i,1) = Candid(al(i),2)
```

- **Forward Search Code**

```
function[Os, Adline, Noll, Coll, Angle, Mof] = FS(Busdata, Linedata, Candid,
Linetype, Solution, Contingency, Lg, Mof)
if nargin<8 | isempty(Mof), Mof = 10^9; end
if nargin<7 | isempty(Lg), Lg = 0; Mof = 10^9; end
if nargin<6 | isempty(Contingency)
Contingency = 0; Lg = 0; Mof = 10^9;
end
if nargin<5 | isempty(Solution)
Solution = zeros(size(Candid,1),1);
Contingency = 0; Lg = 0; Mof = 10^9;
end
if nargin<4 | isempty(Linetype)
fprintf('Input argument "Linetype" containing the');
fprintf(' information of different types of lines.');
error('"Linetype" is undefined.');
end
if nargin<3 | isempty(Candid)
fprintf('Input argument "Candid" containing the');
fprintf(' information of candidate lines.');
error('"Candid" is undefined.');
end
if nargin<2 | isempty(Linedata)
fprintf('Input argument "Linedata" containing the');
fprintf(' information of existing lines.');
error('"Linedata" is undefined.');
end
ncr = length (find(Solution == 0));
%% Forward search algorithm
%% Initialization
diff = 1; j = 1; ii = 0; jj = 0;
kk = 0; Noll = null(1); Coll = null(1);
best = null(1); Angle = null(1);
while diff>0 |j<=2^ncr
Solution1 = Solution;
[isol] = find(Solution1 == 0);
best_sol = null(1);
for i = 1:length (isol)
Isol = isol(i); % Selecting a candidate
Solution1(Isol) = Candid(Isol,6);
```

```
[Ybus, linedata, busdata, nIs, nbus, bus_number]= ybus_calculation (Busdata, Linedata, Solution1, Candid, Linetype, Lg);
[angle_r,angle_d, PF, OL, SOL] = dcpf(busdata, linedata, Ybus);
NOL{i,1} = OL;
angle{i,1} = angle_r;
Isoln = find(Solution1~=0);
[TC] = Total_Cost(Isoln,Solution1,Candid,Linetype);
if Contingency == 1 & nIs == 0
[COL,CnIs,OLF] = contingency(linedata,busdata);
%% OOLF{i,1}: total overload in N-1 condition, in case of adding the i-th candidate line among not selected candidates
OOLF{i,1} = OLF;
else
COL = 0; CnIs = 0;
end
OF = TC+(10^9*((SOL)+COL))+(10^12*((nIs)+(CnIs)));
if OF < Mof
diff = (Mof-OF);
Mof = OF;
best_sol = Isol;
j = j+1;
else
j = j+1;
end
Solution1(Isol) = 0;
end
best_sol_index = isempty(best_sol);
if best_sol_index == 1;
break
else
Solution(best_sol) = Candid(best_sol,6);
ii = ii+1;
best(ii,1) = best_sol;
best(ii,2) = Mof;
if Contingency == 1
jj = jj+1;
bsol = find (isol == best_sol);
Coll{jj,1} = OOLF{bsol,1};
kk = kk+1;
Noll{kk,1} = NOL{bsol,1};
Angle{kk,1} = angle{bsol,1};
clear angle NOL
else
kk = kk+1;
bsol = find (isol == best_sol);
Noll{kk,1} = NOL{bsol,1};
Angle{kk,1} = angle{bsol,1};
clear angle NOL
end
end
```

```
end
Os = Solution; % Optimal solution
al = find(Os~=0);
if length(al)~=0;
lb = length(best);
for i = 1:length(al)
Adline(i,1) = Candid(al(i),2);
Adline(i,2) = Candid(al(i),3);
end
else
Adline = null(1);
end
```

- DCLF Code

```
function [angle_r,angle_d, PF, OL, SOL] = dcpf(busdata, linedata, Ybus)
if nargin<3 | isempty(Ybus)
error('Input argument "Ybus" is undefined');
end
if nargin<2 | isempty(linedata)
fprintf('Input argument "Linedata" containing the');
fprintf(' information of lines.');
error('"Linedata" is undefined.');
end
if isempty(busdata)
fprintf('Input argument "busdata" containing the');
fprintf(' information of buses.');
error('"busdata" is undefined.');
end
nbus = size (busdata,1);
nl = linedata(:,2);
nr = linedata(:,3);
Smax = linedata(:,6);
nbr = length(nl);
Ps1 = (busdata(:,3)-busdata(:,4));
code = busdata(:,2);
[aa] = find(code~=3);
for n = 1:length(aa)
for m = 1:length(aa)
Ymn = Ybus(aa(n),aa(m));
B(n,m) = -imag(Ymn);
end
Ps(n,1) = Ps1((aa(n)),1);
end
Binv = inv(B);
ang1 = Binv*Ps;
angle_r = zeros(nbus,1);
for i=1: length(aa)
aaa = aa(i);
angle_r(aaa) = ang1(i);
```

```
end
angle_d = angle_r*(180/pi);
jay = sqrt(-1);
for i = 1:nbr
PF(i,1) = nl(i); OL(i,1) = nl(i);
PF(i,2) = nr(i); OL(i,2) = nr(i);
PF(i,3) = (angle_r(nl(i))-angle_r(nr(i)))/(linedata(i,5));
if abs(PF(i,3))>Smax(i)
OL(i,3) = abs(PF(i,3));
OL(i,4) = abs(PF(i,3))-Smax(i);
else
OL(i,3) = PF(i,3);
OL(i,4) = 0;
end
end
SOL = sum(OL(:,4));
```