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**DEPARTMENT OF ELECTRICAL AND INFORMATION ENGINEERING**  
**POWER SYSTEM NETWORK EXPANSION PLANNING USING**  
**HYBRID HEURISTIC METHOD**

**PROJECT INDEX: 115**

**BY**

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## **DEDICATION**

This project is dedicated to my Dear family starting from my father and mother for believing in me and giving me all the support and encouragement throughout the course and my elder brother for being the best supportive brother.

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## **ABSTRACT**

Transmission network expansion planning (TNEP) is a large scale, mixed integer, complex, non-linear and non-convex optimization problem. Its main focus is to find the optimal structure and least cost transmission investment alternatives of the forecasted load and generation configuration. In this paper, transmission network expansion which focuses on alleviation of transmission line congestions in the considered base topology network is proposed. The proposed methodology is based on sensitivity analysis where by the moment the thermal rating of a particular transmission line (existing or candidate) is violated then an expansion is inevitable. Varieties of classical as well as heuristic algorithms can be employed to solve the network expansion problem. In this paper the hybrid heuristic method is considered. This is a combination of the forward and backward heuristic methods. The expansion plan will be done chronologically starting with the backward stage for the normal conditions and then the forward approach is applied for contingency conditions analysis. For all this the main aim is to minimize the total investment cost, but at the same time ensuring that the network is robust and stable under normal and contingency conditions. This expansion problem which optimize the total investment and operation cost is modeled using a multi-stage decision framework where by the 1<sup>st</sup> stage will be for the expansion of the network with the connected known loads and power generation and the 2<sup>nd</sup> and final stage will be the expansion of the network with the forecasted load (assuming 120% increase in load in next 10years). In this, the transmission expansion planning the location, type and number of extra transmission lines of the optimal network configuration are determined. For illustration purpose the resulting mixed-integer nonlinear programming problem tackled under hybrid heuristic method is developed and applied on the IEEE 30 bus test power system. The proposed model is implemented in Matlab software.



# CHAPTER ONE

## INTRODUCTION

### Background of the study

The electric power industry has evolved over many decades from a low power generator serving a limited area to a highly interconnected network serving a large number of countries, or even continents. Nowadays an electrical power system is one of the man-made largest scale system ever made comprising of large numbers of components; starting from low power electric appliances to very high power giant turbo- generators. Hence in a typical power system, the supply of electricity to load centers is carried out by the three main processes, Generation, Transmission, and distribution [1] [2] [3] [4]. The power generated at the generation stations will be transferred to the distribution centers through the high voltage transmission network. At distribution station the electrical power is reduced to lower voltage level and will be distributed to consumers. In the future due to the growing electricity consumption and renewable energy integration, the transmission network expansion planning is required to facilitate alternative paths for power transfers from power plants to load centers. This expansion should be done in timely and proper manner so that the network meet optimal operation, economical, technical and reliability criteria of the future power system.

The Transmission network expansion planning is usually performed by a constrained optimization approach that minimizes the cost of investment and load curtailment of the system. The planner selects the optimal transmission expansion for the forecasted demand level. Several optimization techniques have been researched on and applied in practical power system for various planning methods which include [3]

- Generation and maintenance scheduling
- Economic load dispatch
- Reactive power planning
- Generation expansion
- And last but not least the Transmission network expansion planning

Power system planning is basically a process in which the aim is to decide on the new as well as upgrading existing system elements to **adequately** satisfy the **loads** for a foreseen **future**. The elements here may be

- Generation facilities(turbines ,generators ,transformers coolers e .t .c)
- Substations (transformers ,insulators ,switches, capacitor banks e. t. c)
- Transmission lines and / or cables
- Capacitors/ reactors

The decision should be

- Where to allocate the element (for instance, the sending and receiving end of a line)
- When to install the element (for instance, 2015),
- What to select, in terms of the element specifications (for instance, number of bundles and conductor type).

Obviously, the loads should be adequately satisfied.

In Kenya there is only around below 25% connected customers to the national grid, this is a very low number compared to the standards required for any faster industrial growth. The existing network configuration was planned long time ago with a load growth rate that has been by far surpassed by the present demand. With the ambitious government project being undertaken to make sure that most of the households and places in Kenya are connected to the National grid by the year 2030 (vision 2030 flagship project) then the Kenya Electric network configuration will be quite enormous. At present though, there is a large load demand which has already overstretched the current generating and transmission capacity by far. Frequent power rationing especially during dry seasons, lot of power outages due to failure of cables or substations overloads, high cost of power production and high power bills to consumers are just but a few of the problems our Electric power system faces. These setbacks greatly affect the development of the nation as there is loss of revenue, development, investment, lives (i.e. in hospitals), equipment damage, and insecurity especially in places like kibera

Hence with the network expansion planning project we will be looking at possible solutions to expanding existing and developing new systems to meet the loads adequately at present i.e. short term expansion planning and at a foreseen future i.e. long term expansion planning (vision 2030), with reliable power supply to the loads at both normal and or contingency conditions so as to avoid any outages due to failures in any part of the system due to overload or any other circumstances. In short term planning it basically involves addition of transmission cables to existing overloaded sections to reduce the overload and possible failure during contingency conditions. The long term planning involves addition of new power plants and transmission lines to the grid to be able to meet demand at a certain foreseen future. In this paper we will concentrate more on the short term (I.e. pseudo dynamic approach) as a building block for the Dynamic (long term) planning.

### **Project objectives**

- The objective of Transmission network expansion planning is to propose least cost transmission expansion strategy while fulfilling all the operation and security constraints of the system. This is done by adding new network components that alter power flow through the existing transmission lines and alleviate congestion or by building new transmission lines either parallel with the existing ones as is the case with this project. In a nutshell the TNEP process tries to find the optimum routes between the generation buses (determined in generation expansion planning phase) and the load centers (determined from load forecasting) via substations (determined in substation

expansion planning phase) in such a way that loads are completely supplied (during both normal conditions and once some types of contingencies occur on some system elements) and least costs are incurred.

- Present the methodology used in developing the transmission development plan
- To develop a set of transmission network solution for the planning horizon year 2024

### **Specific objectives**

To determine the transmission paths between substations (both existing and new) as well as their characteristics (voltage levels, power delivered, line resistances and reactance's, number of circuits, conductor types and so on)

In doing so

- the investment cost should be minimized
- the operation cost should be minimized
- various constraints should be met during
  - (i) normal conditions
  - (ii) contingency condition

### **Scope of project**

The scope of the project includes developing a Hybrid Heuristic formulation of the TNEP problem with an objective function of total cost Minimization of the power system. The model is formulated based on the deterministic approach where the expansion plan is performed for a single general load condition taking into account the probable future load conditions (load forecasting) and the best expansion plan selected as the optimal investment solution. The proposed approach is implemented in the Mat Lab Optimization software.

### **Problem definition**

In this project, the network expansion concept aims at solving the network expansion planning problem chronologically. Planning starts with developing a network solution for the horizon planning year i.e. (backward stage) and then working backwards to identify network solutions required with minimal/no congestion and with least cost. There after the forward method is applied to cater for the outages of any line at a time. The process therefore ensures a coordinated development of an efficient and economical transmission system. The backward and the forward (hybrid) approaches are the best suited approaches this kind of expansion plan considering the methodology undertaken. However, in both approaches the minimization of the costs is to be carried out by comparing development variants.

## **Justification of the project**

- The demand for steady, efficient, reliable power is fast increasing as load increases very fast hence measures like load forecasting ,generation expansion, substation expansion and transmission expansion should be undertaken to cub all the problems of overload and contingency conditions
- Some equipment (hospital equipment) are quite sensitive in case of an outage due to contingency conditions or overloads hence measures need to be taken to avoid any loss of lives ,damage to equipment and possible loss of revenue
- Cost of transmission and maintenance of the power system is so high due to system overload and this trickles down to the consumer as they are forced to pay huge bills making electricity a luxury to many which since they cannot afford
- Kenya as the hub for East and central Africa integration and economic development requires agent electric power expansion planning to keep it afloat with some of the imaging turf players like Rwanda who are promising to overtake Kenya in many if not all ways from the monopoly it has been enjoying, the war is on and it starts with the energy (power) a country has and how vast is spread over the country for economic, political, cultural, and social growth prospects. As the European countries noted long time ago, Energy (power) is the necessary tool for any country to compete favorably in the ever competitive world lest you are left behind big time.

## **CHAPTER TWO**

### **LITERATURE REVIEW**

In recent years, by fast growing electric power consumption new circuits must be added to the existing transmission networks. Transmission network expansion planning(TNEP) facilitate finding a plan that must specify the number and location of transmission lines and transformers where power system can operate in a reliable as well as secure manner[5]. Since the transmission construction costs are very high, TNEP must minimize the total investment considering predefined time horizon. On the other hand , inherently a TNEP problem especially under large-scale interconnected transmission system structures is a mixed integer nonlinear optimization problem which desires the application of a hybrid heuristic optimization techniques .The TNEP can be solved in a regulated or deregulated environment as described below

#### **Regulated environment**

In a regulated power system environment, the responsible power system utility takes the task of maintaining and expanding the existing and future electric power generation, transmission and distribution. Therefore to meet the growing demand condition, the utility forecasts the future demand and performs the necessary generation and transmission expansion plan. In common practice it is usual that the generation plan comes prior to transmission network expansion is carried out .In other words the TNEP is performed after the new generator units to be installed and the old decommissioning are determined .In this condition the main focus of the transmission expansion planning is to select the optimal and least cost transmission investment alternatives.

#### **Deregulated environment**

In the Deregulated power system the objective of transmission expansion planning is changed. In the regulated environment, the main concern is to maximize the total social welfare , long-term reliability and efficiency of the network, while in the Deregulated environment, besides maximization of the social welfare , problem formulation TNEP investors or stakeholders profit are other constraints to be considered [6] .Therefore in Deregulated environment the decision of transmission expansion is made by taking the economic effect of the investment criteria. It's a complex process as the model take the **generator** expansion and **market uncertainties** into account .Hence main objective of transmission planning in the deregulated power systems is to provide a non-discriminatory competitive environment for all stakeholders, while maintaining power system reliability [7].

#### **Power system structure**

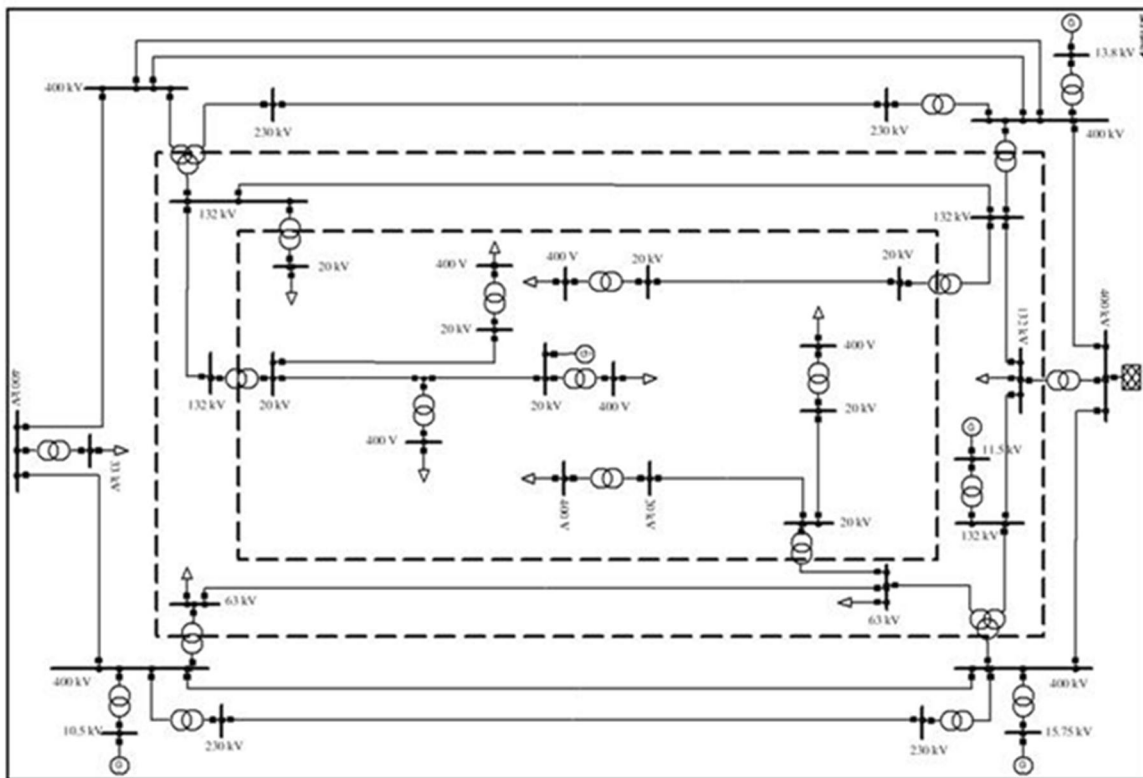
The structure below depicts a typical power system comprising of generators, interface and load [5]. The generators and the loads are distributed throughout the system as a result, some

interfaces should be provided to transfer the generated powers of the loads. The generators may be in the form of a small solar cell or a diesel generator to a very giant nuclear power plants. The loads start, also from a small shop/home to a large industrial complex. Due to both the technical and the economical viewpoints, the generation voltages may be as high as 33kv or so, while the load voltages may be much lower (i.e. 240v). The generation facilities are mainly far away from the load centers. To reduce the losses and to make the transmission possible, we have to convert the generation voltages to much higher values and reconvert them to lower ones at the receiving ends (load centers) as a result the interfaces between the generators and the loads may comprise of several voltages such as 20, 63, 132, 230, 400, 500kv or even higher, regardless of what available voltages are it is of normal industrial practice to classify these voltages to

- Transmission (for example 230kv and above)
- Sub-transmission (for example 63,132kv and similar)
- Distribution(for example ,20kv and 400v)

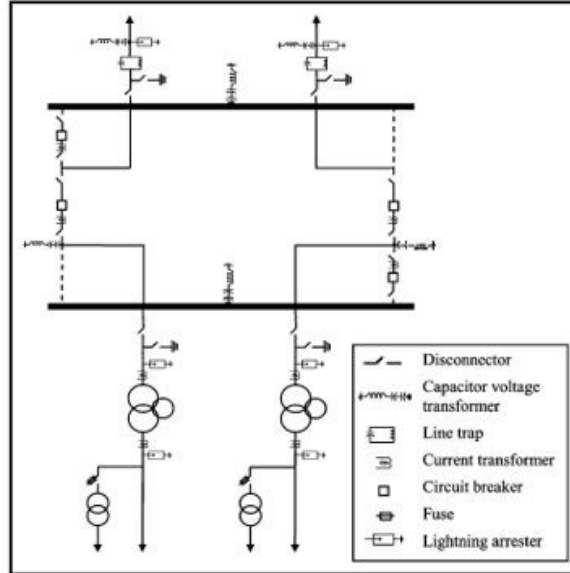
### Power System Structure

3



**Fig1:- Typical power system structure.**

Due to these various voltages , transformers are allocated through out the network in the so called substations,for example a 400kv:230kv transformers. Each substation is also equipped with circuit breakers, current and potential transformers protection equipments etc. The lay out representation of a typical sustation is as below ie Fig 2



**Fig 2:- Typical representation of a substation**

## **Classification of power system transmission network planning**

### **I) Static versus dynamic planning**

#### **1) Static planning**

Static expansion involves finding solution for single stage planning horizon answering only what transmission facilities must be added to the system and where it must .It determines optimal solution  $S_k$ , given by equation (2.4). Each partial solution can be 0 or integer multiples of 1. It corresponds to the number of circuits each branch is upgraded with. This method is easily extended to a multi-year context without difficult because its simpler and allows solving problems of large size in shorter period of time than the dynamic methodology [8].

$$S^k = [s_1^k \quad s_2^k \quad s_l^k \quad \dots \quad s_n^k] \text{-----(2.4)}$$

Where  $S_l$ = partial solution of the ith branch

n = number of network branches

k = candidate plan

l= current branch

In a such a situation, the decision marker is not interested in where the extra circuits should be installed, but only in finding the optimal network configuration for the projected future year [6]

## 2) Dynamic planning

Nevertheless, from its nature, the TEP is a dynamic problem. In the dynamic planning, several years/stages are considered and year-by-year expansion plan made that goes from the initial year through the horizon year making it very complex and large requiring enormous computational effort to obtain the optimal solution. For the dynamic (multistage) problem it is important not only to define where, but also when the grid re-inforcements should be implemented, which basically involves optimization through several intermediate stages between base year and final stage, in order to arrive at the solution matrix  $S_t^k$  given in the solution below [8] [6]

$$S_t^k = \begin{matrix} S_{11}^k & S_{12}^k & \dots & S_{1t}^k & \dots & S_{1n}^k \\ S_{21}^k & S_{22}^k & \dots & S_{2t}^k & \dots & S_{2n}^k \\ S_{y1}^k & S_{y2}^k & \dots & S_{yt}^k & \dots & S_{yn}^k \end{matrix}$$

Where  $S_{ti}$  = partial solution of the  $1^{th}$  branch for the  $t^{th}$  stage

Y = number of stages

t = current stage

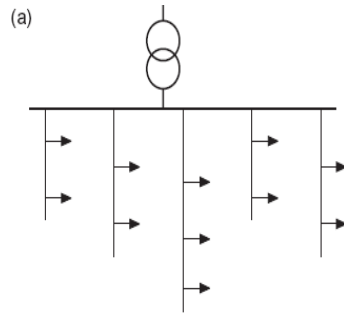
The dynamic formulation of the problem and the time constraints that optimising through several years introduced, renders the dynamic problem extremely complex. Due to this time dependent nature, the dynamic formulation of the problem results into prohibitive computational times [37].

To attain a reasonable computational time the dynamic problem has to be simplified. The simplest way is to solve a series of the static sub-problems (Pseudo-dynamic procedure) also referred to in other terms as semistatic, semi-dynamic, quasi-static or quasi-dynamic [3]. There are three fundamental approaches for the pseudodynamic TNEP which include the forward, backward and forward-backward approaches. This will be discussed in greater detail later.

## II) Transmission versus distribution planning

There are three main levels of power system structure namely transmission, sub-transmission and distribution. Distribution level is often planned; or at least operated radially as depicted below in the fig 3 (a) and (b)





**Fig 3:- Typical radial distribution networks**

Specific characteristics of a distribution system (such as its radial characteristics) its planning is normally separated from a transmission system although much of the ideas may be similar. In this project we mainly concerned with transmission planning.

In transmission we mean both transmission and /or sub-transmission levels, since the transmission and the sub transmissions levels are both interconnected as shown earlier in fig 1 hence both can be treated similarly

### **III) Long -term versus short - term planning**

There is no golden rule in specifying short-term or long -term planning issues, normally, < 1year falls into operational planning and operation issues in which the aim is typically to manage and operate available resources in an efficient manner. More than that falls into the planning stages. If installing new equipment and predicting system behaviour are possible in a shorter time (for instance , for distribution systems 1-3 years), the term of short term planning may be used. More than that (3-10 years and even higher) is called long- term planning (typically transmission planning) in which predicting the system behaviour is possible for these longer periods. Moreover, installing a new element (such as a 765kv UHV line or nuclear power plant) should be decided well in advance so that it would be available in due course.

### **Issues in transmission planning**

The term used in literature commonly is transmission network expansion planning (TNEP), to show that we focus on long -term issues . The TNEP terminology has been used to emphasize the fact that transmission and subtransmission levels are considered. The general term of power system planning may also be used noting the fact that distribution planning is excluded from our discussions. Sometimes the terminology of network expansion planning (NEP) is also used to point out the same concepts. The basic issues in TNEP hence include

## 1) Load forecasting

The first crucial for any planning study is to predict the consumption for the study period (say 2014-2024), as all subsequent studies will be based on that, this is called load forecasting. In a short-term load forecasting, for predicting the load for instance, of the next week, we come across predicting the load for each hour of the coming week.

### 1.1) Load Driving parameters

The parameters affecting forecasted load of future are

- Time factors such as
  - Hours of the day (day and night)
  - Day of the week (week day or weekend)
  - Time of the year (season)
- Weather conditions (temperature and humidity)
- Class of customers (residual, commercial, industrial, agricultural, public etc)
- Special events (TV programmes, public holidays, etc)
- Economic indicators (per capita income, gross national product (GNP), GDP (gross domestic product))
- Trends in using new technologies
- Electricity price

Load forecasting methods are normally classified to STLF, MTLF, and LTLF [5]

From the forecasted load the load factor can be calculated as below

$$L.F = \frac{\text{Total energy (in MWh)}}{\text{Peak load (in MW)} \times 8760}$$

Based on the historical load factors of the region and on estimation for these values for the coming years, total energy may be forecasted. For this project total load is forecasted for the period of 2014-2024 (10yr long term plan).

## 2) Generation requirement

After predicting the load, the next step is to determine the generation requirements to satisfy the load. An obvious simple solution is to assume a generation increase equal to the load increase, but for safe margins the generation is usually higher (5-10%) than the load demand. This is so to cater for any surge in load growth and to reduce power constraint under any condition like sudden peak power demands.

### 3) Network expansion

After the load and the generation requirements are met the planner now proceeds with the main idea, and that is to expand the network to meet the forecasted load under normal and contingency conditions. In network expansion planning the load, generation, and substation quantities as inputs are provided and available to the planner [9].

#### Planning in presence of uncertainties

The electric power industry has drastically changed over the last two decades. It has moved towards a market oriented environment in which the electric power is transacted in the form of a commodity. Now the generation, transmission and distribution are unbundled and may belong to separate entities. In solving TNEP problem there are certain and uncertain information. The data which are not known at the time of planning are referred to as uncertain data. The factors causing these uncertainties include [7] [5]

- Environmental regulation
- Inflation and interest rates
- Economic growth
- Availability of fuels and technologies
- Individual power generating units (Ips)
- Demand growth
- Public opinion

The certainties can be classified as random and non-random. In random uncertainty the pattern of the parameters can be determined from the historical data and past observation. Uncertainties in the load, renewable power generation and generator cost are categorized in this group.

Non-random uncertainties are not repeatable and cannot be statistically represented from past experiments [7]. Transmission network expansion cost, shutting down of generators and the like are grouped in this category. From the perspective of uncertainties in power system, TNEP can be divided into two categories [7]

- a) Deterministic
- b) Non-deterministic

#### a) Deterministic TNEP Approach

Deterministic transmission expansion planning is formulated as a traditional optimization problem which analyzes single or two representative scenarios. These scenarios can be worst peak load level, N-1 contingency or outage of a generating unit [5]. The only drawback

of this method is that it tries to represent the past experience and future expectation by a single fact. Therefore, the expansion solution for the future condition becomes optimal only if it occurs as predicted. Otherwise, the solution may lead to inadequate or expensive planning decision. Besides the investment strategy of each stage is optimal for limited time of T period, usually fails to provide long term investment plan.

### **b) Non- Deterministic TNEP Approach**

To overcome the shortcomings(drawbacks) of the deterministic TNEP approach a non-deterministic TNEP problem is formulated by generating a set of possible scenarios of the uncertain parameters that may take place in the future hence using this approach a number of possible scenarios will be analyzed and evaluated using security and performance analysis criteria. Consideration of the uncertainties will help to identify a robust plan that is satisfactory under a range of possible outcome. In this condition, the TNEP problem can be solved by either by means of stochastic optimization-based formulation, where the objective function is typically formulated in term of an expected value or by means of a decision-making framework. This approach(non-deterministic TNEP) is a challenging task and a great effort and care must be taken while solving the problem[4][5] [7]

### **Optimization technique**

The decision making criterion is what is called optimization technique in which the aim is to find the optimum solutions ; where the optimum may either be the least or the most [5].

In most of the planning ie (NEP)or operational problems ,they consist of definition, Modeling and solution algorithms.

For any of the optimization problem ,the following are decided upon

- Optimization(or Decision (independent) and dependent variables)
- Constraints functions (which determine if specific decision variables lead to feasible solution)
- Objective functions(this is the function to be minimized(or maximized) depending on the decision variables)

### **1) Decision and dependent variables**

Decision variables are independent variables; their optimum values have to be determined and based on those, other variables(dependent ) can be determined. For instance in an optimum generation scheduling problem , the active power generations of power plants may be the decision variables, the dependent variables can be the total fuel consumption ,system losses etc which can be calculated once upon determining the decision variables.

## 2) Constraints functions

In a real time optimization problem some limitations may apply to the solution space. These are typically technical, economical, environmental and similar limitations; named as constraints which either directly or indirectly divide the solution space into acceptable (feasible) and unacceptable (non-feasible) regions.

## 3) Objective functions

From the various points within the feasible region of a problem, the most desirable point is selected [5]. An **objective function** is a function in terms of the decision variables by which the decision maker shows his/her desirable solution.

Hence in say an optimum Network expansion planning, the objective function may be chosen as the total line costs to be minimized.

## Problem modelling

Once the decision variables, the constraints and the objective function terms are decided, the problem should be modelled in a proper form to be solved. The modelling hence relies so much on the **tools** available and the **algorithms** for the problem solving, the accuracy required, the simplifications possible etc [8] [5]. Hence a **generic** optimization problem model would be in the form given as below

$$\begin{aligned} \text{Minimize or maximize } & C(x) \dots \dots \dots (i) \\ \text{Subject to } & g(x) \leq b \dots \dots \dots (ii) \\ & f(x) = a \dots \dots \dots (iii) \end{aligned}$$

- Where
- x- decision variable
  - C(x)- is the objective function
  - f(x)-equality function
  - $g(x) \leq b$  is the inequality constraint

The decision variables may be either real or integer. C and g may be either continuous or discrete functions of the decision variable in an explicit or implicit form; linear or non-linear

## Network expansion Techniques

The above three constraint optimization problems may be solved by some available optimization techniques. TNEP as described earlier is non-convex mixed-integer nonlinear programming problem. The presence of interger investment variable that requires the use of a **combinatorial algorithm** is the main difficult of searching the optimal solution of this problem. Another difficulty of the problem arises from the large number of variables associated with many economical and operational constraints to be considered [8]. Therefore to overcome these associated difficulties, different algorithms have been proposed by many researchers and are depicted as in the flow chart below [7].

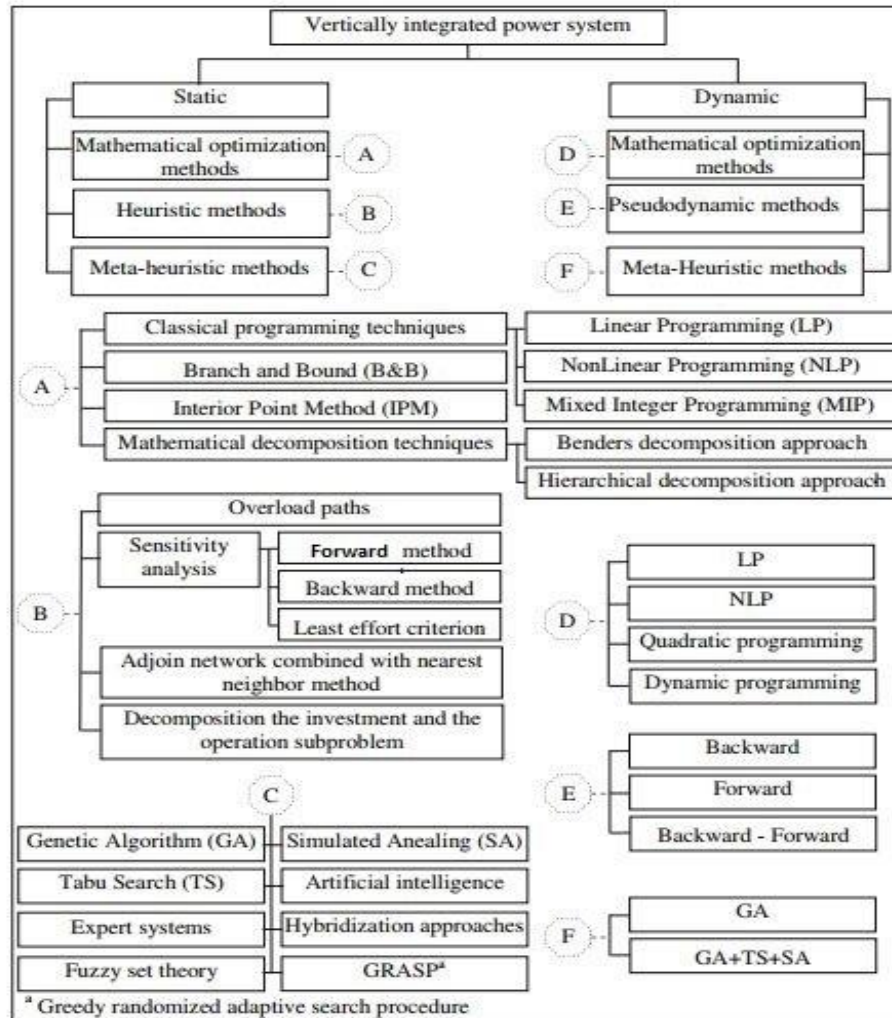


Fig 4:- Classification of TEP in a traditional environment

## I) Mathematical Algorithms

A mathematical optimization technique formulates the problem in a mathematical representation as given in (i)-(iii) (pg 13) provided the objective function and /or the constraints are **nonlinear** the resulting problem is designated as non linear optimization problem(NLP).A special case of the NLP is the quadratic programming in which the objective function is a quadratic function of  $x$  . If both the objective function and the constraints are linear functions of  $x$ , the problem is designed as a linear programming (LP)problem.Other categories may also be identified based on the nature of the variables.For instance if  $x$  is of integer type , the problem is denoted by integer programming (Ip).Mixed types such as MILP( mixed integer linear programming ) may also exist in which while the variables may be both real and integer,the problem is also of LP type.Generally speaking a mathematical algorithm may suffer from numerical problems and may be quite complex in implementation,however its coverage may be guaranteed but finding the global optimum solution may only be guaranteed for some types such as LP [10].

Mathematically, the MINLP problems are usually considered as one of the classes of problems that are the most difficult to solve due to their intrinsic complexity.In the world of complexity, problems are generally classified as P(polynomial) or Np (non-polynomial). Based on the effort needed to solve them e.g a class P problem can be solved in polynomial time by a deterministic turing machine, while a class NP problem cannot.Further, a problem is regarded as NP-hard if solving it in polynomial time would make possible to solve all the problems in class NP in polynomial time.pparticularly, if a problem is NP-hard and it is also an NP problem, then it is known as an NP-complete problem.The complexity of the MINLP problems is usually NP-hard or even NP-complete.If  $P \neq NP$ , then the relationship of P, NP, NP-hard and NP-complete problems can be described in fig 5 below

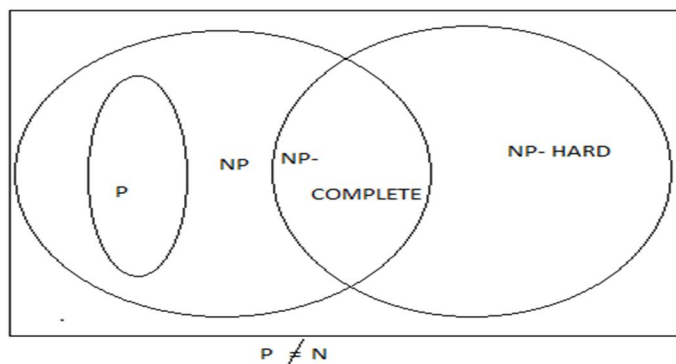


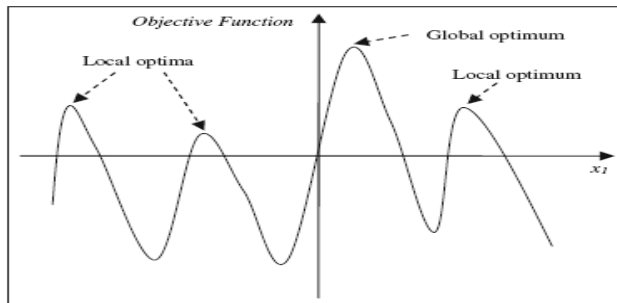
Fig 5:- Relationship of p, Np, NP-hard and the Np-complete problems

- **Dynamic Programming (DP) method**

Dynamic programming is a widely used technique in powersystem studies. It is, in fact, a mathematical technique used for multistage decision problems; A multistage decision problem is a problem in which optimal decisions have to be made over some stages. The stages may be different times, different spaces, different levels etc. The important point is that the output of each stage is the input to the next serial stage [7] [11].

## II) Heuristic algorithms

The term Heuristic is used to describe all techniques that undergo a step by step generating evaluating and selecting expansion option. A component of the solution is added at each step until good quality solution is found. It is robust random and guided search that converges quickly to the optimal solution to any case whether simple or complex [5], but for very large scale and highly complex problem it may converge to local solution that is very far away from the optimal solution. Most mathematical based algorithms can guarantee reaching an optimal solution; while do not necessarily guarantee reaching a global optimum



**Fig 6:-Objective function representation in local and global optima**

Global optimality may be only reached, checked or guaranteed for simple cases. If the problem is highly complex as most practical cases are we may not easily be able to solve them, at all, through mathematical algorithms [5].

Heuristic algorithms are devised to tackle the above mentioned points. They normally, can solve the combinatorial problems sometimes very complex, yet in a reasonable time. However, they seek good solutions, without being able to guarantee the optimality, or even how close the solutions are to the optimal point.

The first attempts to implement the so called heuristic approach was made by Fischl in 1972 who introduced the adjoint network concept. It used a DC load flow to guide the solutions towards a (pseudo) optimum.



Garver developed an approach to solve TNEP in which the problem was formulated as a power flow where by the objective function and constraints are described by the linear functions that neglect the ohmic power loss. Based on the results of flow estimate new lines will be added on the largest overloaded network and considering the added line, new linear flow is computed and the process continues until no overload exists in the system

For the Heuristic methods sensitivity analysis is the main criteria where by the sensitivity index can be built based on the algorithm that employs the electrical system performance like least effort criteria the relaxed version of their own mathematical model, load supply capability, optimal power flow in the circuit [11], use of expert systems, and guide numbers that build up the new expanded network one branch at a time. Tree formats have been also employed in order to decompose the original problem into sub-problems. Other heuristics methods include the forward, backward and hybrid heuristic methods. This are explained briefly as below

- (i) The Forward approach:- Determines sequentially the optimal network starting from the first stage and gradually configures the optimal solution for the final stage
- (ii) The Backward approach:- This is where the final stage is assumed to be the step that stresses the power grid the most. Therefore. It determines the final optimum network and proceeds with the backward changes till a better network stage is reached [14]. The backward approach generates better solutions than the forward approach
- (iii) Backward- forward approach (hybrid):- This method determines the optimum multistage expansion by comparing the backward and forward stages.

Since these are the methodologies applied in this project, they will be analysed in deep at later pages of this paper.

### **III) Meta- heuristics**

Some modified heuristic algorithms (meta-Heuristic algorithms) are developed in literature by which improved behaviours are attained, claiming that the optimal solutions are guaranteed. They combine characteristics of both the mathematical and heuristic modes [5]. Basically, all start from either a point or a set of points, moving towards a better solution; through a guided search. few are listed below

- **Generic algorithm(GA), based on genetics and evolution**

GA have been most commonly used to solve combinatorial optimization problems. GA applies on population of individuals, Each individual is a potential solution to a given problem and is typically encoded as a fixed length binary string which is an analogy with an actual chromosome. After an initial population is or heuristically generated, the algorithm evolves the population through sequential and iterative application of three operators: selection, crossover,

and mutation. A new generation is formed at the end of each iteration [13]. Mutation is usually in the range [0.001; 0.05]).

- **Particle swarm (PS), based on bird and fish movements**

It is an optimization technique started on the beginning of the 1990 by Kennedy and Eberhart through simulation of bird flocking in two dimensional space [12] [5]. Each individual is considered as an agent and moves in a two dimensional space by its position (x and y) and its velocity (vx and vy) with each agent optimizing its movements towards the destination by. Hence mathematically, new position of an agent  $i$  in iteration  $k+1$  ( $s_i^{k+1}$ ) can be determined from its current (iteration  $k$ ) position ( $s_i^k$ ); knowing its velocity at iteration  $k+1$  ( $v_i^{k+1}$ ). ( $v_i^{k+1}$ ) can be determined as

$$V_i^{k+1} = wv_i^k + c_1 \text{rand}_1(pbest - s_i^k) + c_2 \text{rand}_2(gbest - s_i^k) \dots \dots (i)$$

Where  $w$  is weighing function,  $c_1$  and  $c_2$  are weighing coefficients

- **Tabu search (TS), based on memory response**

Tabu means forbidden to search or to consider. Unlike other combinatorial approaches, TS is not related to physical phenomena. It tends to move to new solution space in a more aggressive or greedier way than GA or SA.

The steps involved in a TS optimization algorithm may be summarized as

- (a) Generate an initial solution,
- (b) Select move,
- (c) Update the solution. The next solution is chosen from the list of neighbors which is either considered as desired (aspirant) or not tabu and for which the objective function is optimum.

The process is repeated based on any stopping rule proposed [7].

- **Ant colony (AC), based on how ants behave**

It is based on the behaviors of insects, especially the ants with following steps

Initialization, Evaluation, Trail adding, Ants sending in and Evaporation with the steps being repeated to obtain the best solution [7].

Other metaheuristic may include simulated Annealing (SA), based on some thermodynamics principles.

## **Proposed deterministic pseudo dynamic approach**

This paper solves the Transmission network expansion planning in a regulated, deterministic and pseudo-dynamic nature using the Hybrid heuristic(backward-forward) method. Transmission planning is a planning process although having a dynamic nature, often is tackled by the simplified static transmission planning model [14] and or as in pseudodynamic planning model as will be considered also in this project. Traditionally transmission expansion planning is done by assuming the new candidate transmission line to be build have the same characteristic(impedance and maximum power transfer capacity) with the existing ones. This may not be the case in practice and the planner has the chance to select a new type of circuit sets that can be installed in parallel to the existing ones or other new right of way. In the Deterministic environment, the load forecasted is determined from past data and growth rate hence assumed to continue that way in the near future, but with some minner uncertainty considerations while doing the expansion planning .

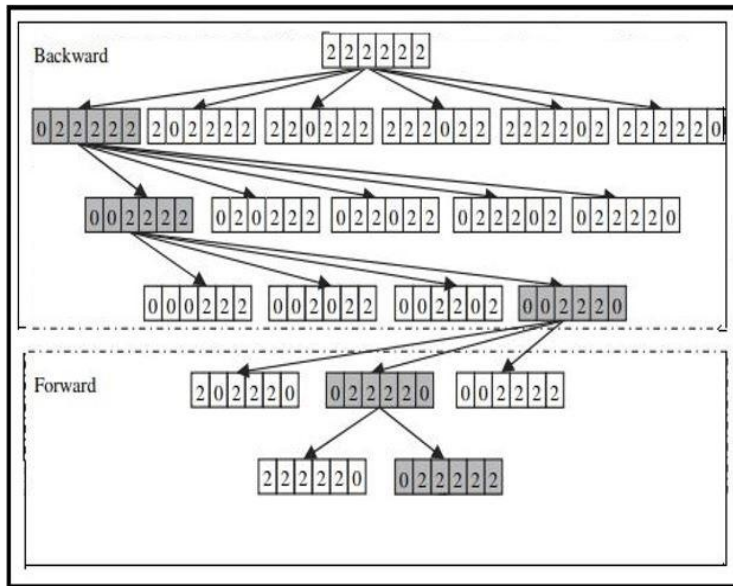
## **Congestion**

When a transmission line is operating at its maximum power transfer capacity (thermal rating) it is called congested. This means that any additional power transfer through this line is not allowed and in case of any line being out by any chance then the probability of system damage is soo high coupled with high chances of blackouts disrupting power flow transfer to the loads and consumers. When a line is switched onto or off the system through the action of circuit breakers or addition (ie during planning), line currents are redistributed throughout the network and bus voltages change, this in turn causes change in Zbus matrix and ofcourse Ybus matrix [18]. Overvoltages due to excessive line currents must be avoided and voltages that are too high or too low are not acceptable because they render the system more vulnerable to follow on successive outages .

The heuristic methods are employed in this project to expand the network to allow maximum power transfer to the forecasted loads in a stable, reliable, robust power system under any normal or contingency condition.

This method is as explained as below

Consider the figure given below to illustrate a small scale network expansion planning using the proporsed Garver 6 bus test system, This will be the stepping stone to implementing the proporsed IEEE 30 bus system that is employed in this project.



**Fig 7:-The Hybrid approach(forward-bachward)**

Hence from the figure the different stages are explained as below

### **Forward Heuristic Method**

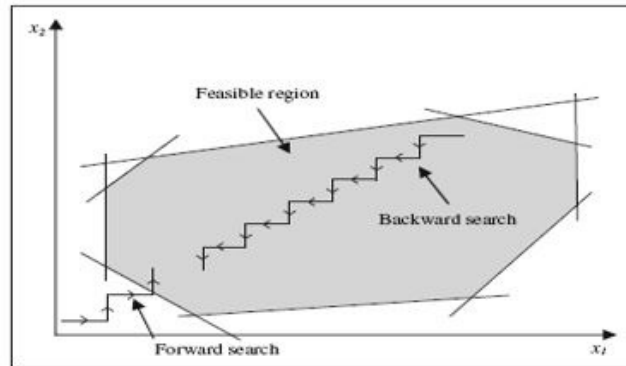
Considering initial network topology with the existing transmission lines in place, the forward heuristic method proceeds as in the case that the selected candidate lines are added one – by – one . This process continues in an iterative manner as long as the system conditions are acceptable for both normal and contingency conditions [7]. The evaluation function is calculated after each and every step then the step with the least evaluation function is chosen as the starting point for next level and the process repeated until a point of violation is reached in either normal and/or contingency (N-1) conditions. The best solution hence will be the one with least investment cost while there is no violation in both normal and N-1 conditions.

### **Backward Method**

The backward method is the opposite of the forward method in such a way that all candidates are initially added to the network and candidates are removed one-by- one so far as a violation happens in either normal or N-1 condition [5] [15]. Hence the planner sets the network initially at a feasible region with no violations under any condition and after removing certain number of lines the ones remaining with least evaluation function and with no constraint violation are considered

As number of candidates may be much higher than real number justified and required, the execution time of backward approach is normally higher than that of the forward approach. However, as it starts within the feasible region, the solutions will remain feasible throughout the solution process, hence as a result the solution may be more favourable than that for the forward approach especially when some feasible solutions are to be compared, but once there are new substations with no initial connections to the rest of the network, calculations of performance index fails as algorithm may fail reaching a solution at all.

In backward approach, we remain in feasible region throughout the solution process, the most costly candidates are normally removed first. However, in forward approach, as we start from a point outside the feasible region, the most effective candidates are initially selected. As a result typically, the backward process ends up with more justified candidates in comparison with the forward process; however with less costly paths. The trajectories for the two methods are as below with both the forward and backward methods moving towards the optimum solution



**Fig 8:- Forward-backward and the feasible region representation**

### **Hybrid approach (Backward- forward Method)**

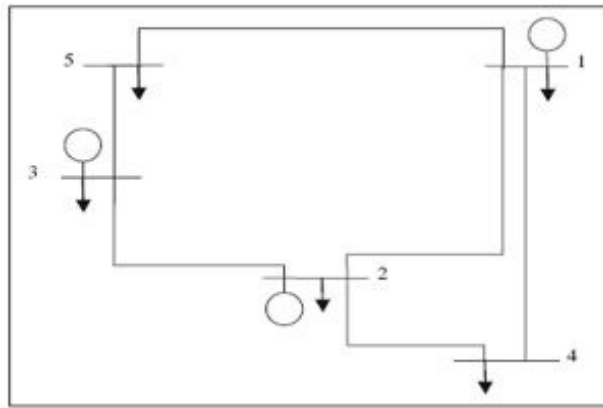
The use of forward approach is undesirable if a new substation is to be supplied from near by buses, while the search space is enormous for large scale systems, if the backward approach is tried for both normal and contingency conditions. So what do we have to do for a large scaled system [5].

The first step is to plan, initially the network for normal conditions (no contingency) using the backward approach (fig 7). As no contingency is considered at this stage, the solution speed will be high and acceptable. Thereafter, the forward approach is employed to find the solution in the presence of all foreseen contingencies(N-1).

In real systems the major cost of a line is the one due to the right-of-way of the route or the corridor. Once this right-of-way is acquired, there may be some alternatives of holding various capacities or types of transmission lines within that corridor. As a right-of-way acquiring cost is a major cost for a line, the optimal solution approach should initially search for the least cost corridors, once these corridors are selected, the types and capacities of the required transmission lines may be chosen, ie either a single circuit line or double –circuit line may be possible/or two single-circuit lines with capacities A and B may be assumed with  $A > B$ .

### ***Candidate selection***

Consider the garver system as in diagram below.



***Fig 9:- Garver test system***

For the above garver test system, Suppose then the number of existing lines to be N (6 in this case), the number of candidate corridors (path ways) to be M (10 in our case) and the number of candidate lines to be **feasible** in each corridor is K. It can be shown [7].

$(K+1)^M$  -----All possible system topologies(Physical lay out)

$\frac{K \times M}{K+1} + N$  -----Average number of contingencies for each topology

$(K + 1)^M [1+N+ \frac{K \times M}{K+1}]$  ---Total no of load flows required for all topologies and in normal and contingency condition

From above equations there may be at most  $59 \times 10^3$  topologies for this specific topology obviously many of them are not feasible as there may be some types of violations in either normal or N-1 conditions The solution time is also too high if number of candidates are too

many. To reduce the solution time, three mechanisms will be employed and one of them employed to reduce the number of candidate lines [5]. These include

- All possible candidates (APC)

In this stage, all possible candidates between any of two substations (either existing or new) are generated

- All feasible candidates (AFC)

The non-feasible solutions (due to environmental limitations, constraints violations, and so on) are then removed. AFC consists of feasible paths, by which all constraints are met during normal as well as contingency conditions.

- All Good candidates (AGC)

At this stage, the aim is to select the most attractive candidates with the least investment cost.

## CHAPTER THREE METHODOLOGY

### Tools overview

There are tools which will be used for the effective implementation of this project, they include Mat lab tool and to a lesser scale the Mat power tool

#### 1) Mat lab

Mat lab is a high-level language and interactive environment for numerical computation, visualization, and programming. Using Matlab you can analyse data, develop algorithms, and create models and applications. The language, tools and build-in math functions enable you to explore multiple approaches and reach a solution faster than with spreadsheets or traditional programming languages, such as c/c++ or Java [16].

#### Key Features

- High-level language for numerical computation, visualization and application development
- Interactive for iterative exploration, design and problem solving
- Mathematical functions for linear algebra, statistics, fourier analysis, filtering, optimization, numerical integration and solving ordinary differential equations
- Built in graphics for visualizing data and tools for creating custom plots
- Development tools for improving code quality and maintainability and maximizing performance
- Functions for integrating MATLAB based algorithms with external applications and language such as C, java.NET, and *Microsoft® Excell®*.

The generated Mat lab code for the Transmission network expansion will be run on the above Mat lab software at the editor section.

#### 2) Mat power

The Mat power software is used to obtain the IEEE 30 bus data values which will be input to the generated Mat lab code for expansion purposes.



## **Transmission network expansion planning**

Under normal conditions all system voltages from 132 kV and above (i.e. 132kV, 220kV, and 400kV) should be within  $\pm 5\%$  of the nominal value and should not exceed  $\pm 10\%$  at steady state following a single contingency. In order to maintain a satisfactory voltage profile both static and dynamic reactive power compensation may be deployed as required at the end of expansion exercise [17].

### **1) Equipment loading**

Classic planning criteria indicate that:

- Under normal conditions and at steady state following single contingencies all transmission equipment should not exceed 100% of the continuous rating.

### **2) Voltage selection and Reliability criteria**

Transmission development during the planning horizon will be based on 132, 220 and 400 kV. The future transmission system is planned to operate satisfactorily under the condition of a single element contingency, N-1 for transmission lines. However in assessing system reliability a double circuit line will be considered as two separate circuits [17].

### **Load flow**

Load flow solutions gives nodal voltages and phase angles and hence the power injection at all the buses and power flows through interconnecting power channels(transmission lines) [2]. Load flow solution is essential for designing a new power system and for planning extension of the existing one for increased load demand. These analysis require the calculation of numerous load flows under both normal and contingency(abnormal) operating conditions. A load flow solution of the power system requires mainly the following steps

- I. Formulation of the network equations
- II. Suitable mathematical technique for solution of the equations

In a power system each bus or node is associated with four quantities namely, Real and reactive powers, Bus voltage magnitude and its phase angle. In load flow solution two out of the four quantities are specified and the remaining two are required to be obtained through the solution of the equations. The load flow methods include the newton raphson(ac load flow), Gauss seidel(dc load flow), Fast decoupled and decoupled load flows.

## Bus classification

### 1) *Load bus:*

At this bus, real and reactive components of power are specified. It is required to specify only  $P_D$  and  $Q_D$  at such a bus as at a load bus voltage can be allowed to vary within the permissible values e.g 5%. Also phase angle of the voltage is not very important for the load.

### 2) *Generator Bus or Voltage controlled Bus:*

Here the voltage magnitude corresponding to the generation voltage and the real power  $P_G$  corresponding to its ratings are specified. It is required to find out the reactive power generation  $Q_G$  and phase angle of the bus voltage.

### 3) *Slack Bus or Reference Bus:*

In a power system there are mainly two types of buses: load and generator buses. For these buses we have specified the real power  $P$  injections. Now  $\sum_{i=1}^n P_i = \text{real power loss } P_L$ , where  $P_i$  is the power  $P$  injections at the buses, which is taken as positive for generator buses and is negative for load buses. The losses remain unknown until the load flow solution is complete. It is for this reason that generally one of the generator buses is made to take the additional real and reactive power to supply transmission losses. At this bus voltage magnitude  $V$  and phase angle  $\delta$  are specified where real and reactive powers  $P_G$  and  $Q_G$  are obtained through load flow solution [2]

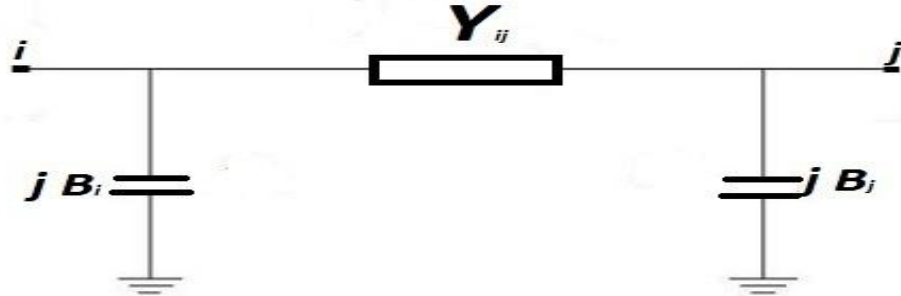
## Optimal power flow

Optimal power flow is modelled as an optimization problem that minimizes a given objective function subjected to a number of constraints. Most common objective function include Minimum operation cost, minimum active power losses. Minimum shift of generation or other control variable from an optimal operating points etc [3].

This constraints can be represented either using Ac powerflow (ACLF) or Dc powerflow (DCLF). In the ACLF equations are utilized and both reactive and active power balance at all nodes of the system are considered. In DCLF (the AC approximation), DCLF is used and only the active power balance of the system is taken into account.

## AC Optimal power flow

A long or not so very long transmission line can be represented by a nominal- $\pi$  equivalent circuit as in figure 10 below [8]



**Fig 10:-Nominal Pi representation of along transmission line**

$$Y_{ij} = G_{ij} + jB_{ij} = Z^{-1}_{ij}$$

Where

$$G_{ij} = \frac{R_{ij}}{R^2_{ij} + X^2_{ij}} \quad B_{ij} = \frac{-X_{ij}}{R^2_{ij} + X^2_{ij}}$$

Hence the complex power that flow through the transmission line connecting bus I and j is

$$S_{ij} = P_{ij} + jQ_{ij}$$

The impedance and the admittance relationship of the transmission line is as

- ❖ The y bus matrix of the transmission line can be found from this relationship quite easily

Active power flow that flows through bus I to bus j is hence given by

$$P_{ij} = V^2 G_{ij} - V_i V_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij})$$

And the reactive power flow is given by

$$Q_{ij} = -V^2 (B_{ij}) - V_i V_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij})$$

Hence the general mathematical formulation of the ACLF problem for power system including N number of buses, G number of generating units and  $L_e$  number of existing transmission lines can be formulated as [8]

$$\text{Min } F = \sum_{k=1}^G (CP_{GK}) = \sum_{k=1}^G (a_k P_{GK}^2 + b_k P_{GK} + G_k)$$

Where F is the total generating cost

$CP_{GK} \rightarrow$  is the real power generating cost of unit

$P_{GK} \rightarrow$  is the real power generation of the kth generator in MW

$a_k, b_k$  and  $G_{k \rightarrow}$  are the kth generator quadratic cost coefficients

## constraints

### 1) Power balance constraints

Power balance is applicable for each and every node of the transmission network. This is total power generation minus the total power demand at each bus which must be equal to the net power flow through the lines connected to it i.e

$$p_i = P_{Gi} - P_{Di}$$

$$Q_i = Q_{Gi} - Q_{Di}$$

Thus the equation of computing the real and reactive power injection at each bus is expressed as [8]

$$P_i = V_i \sum_{j=1}^N V_j [(G_{ij} \cos(\theta_i - \theta_j) + B_{ij} \sin(\theta_i - \theta_j))$$

$$Q_i = V_i \sum_{j=1}^N V_j [(G_{ij} \sin(\theta_i - \theta_j) + B_{ij} \cos(\theta_i - \theta_j))$$

### 2) Power flow limits

The apparent power flow through transmission line (bus i and j) have to be within the power bound of the power transfer capability limit of the line. This limit is based on the thermal consideration of the line and is given as [8] [15]

$$|S_{ij}| \leq S_{ijmax}$$

### 3) Generators capacity constraint

This constraint for maximum and minimum real and reactive power generation capability of the generating units. The power generations outside these limits are inapplicable due to technical measures

$$P_{Gimin} \leq P_{Gi} \leq P_{Gimax}$$

where  $P_{Gimin}$  and  $P_{Gimax}$  is minimum and maximum active power generation limits of generator at bus i

#### 4) Voltage constraint

This is the constraint specifying the limit on the maximum and minimum voltage magnitude at each bus  $i$  [8] [7]

$$V_{imin} \leq V_i \leq V_{imax}$$

where

$V_{imin}$  and  $V_{imax}$  are maximum and minimum voltage magnitudes at bus  $i$

The AC power flow have been analysed.....

#### DC optimal power flow (DCLF)

The DCLF equations are resultants of linearization of the AC active and reactive power flow solutions. These simplifying assumptions are

- I. Neglecting the resistance of Transmission lines as it is rather small compared to the reactance of the line. This means that the conductance of the transmission lines are zero ( $G_{ij}=0$ ) and admittance is represented only by the line susceptance ( $B_{ij}$ ). Independent power plants e.g diesel plants, gas turbines and many other power contributors like factories, which are quite many nowadays, that may not be site specific can be located almost anywhere, the preference for locating these close to the load centers also leads to preserve a moderate level of transmission losses (usually between 1% and 5%) Where the optimal generation plan leads to locate generation units at specific sites or regions (because the primary resource is located there), Hence in essence neglecting the line resistance has very minimal loss in accuracy but has a great deal of saving in computation time and speed. After applying this assumptions the power flow equations are then derived as shown [8] [5] [17]

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

$$Q_i = V_i \sum_{j=1}^N B_{ij} \cos(\theta_i - \theta_j)$$

- II. The phase angle difference between any two buses is rather small. Therefore

$$\sin(\theta_i - \theta_k) \approx \theta_i - \theta_k$$

And  $\cos(\theta_i - \theta_k) \approx 1$

III. The magnitudes of the voltages at each bus are equal to 1p.u

Therefore after applying all assumptions to the Ac optimal power flow(ACLF) formulation, the DC optimal power flow equations are

$$\text{Min} \sum_{k=1}^{Nj} C_{(PGK)} = \sum_{k=1}^G a_k p_{GK} + b_k p_{GK} + c_k$$

Subject to constraints

$$p_{Gi} = P_i - P_{Di}$$

$$p_i = \sum_{j=i}^N B_{ij}(\theta_i - \theta_j)$$

$$|p_{ij}| \leq p_{ijmax}$$

$$p_{ij} = \frac{1}{x_{ij}}(\theta_i - \theta_j) = B_{fij}(\theta_i - \theta_j)$$

$$p_{Gi} \leq p_{Gi} \leq p_{ijmax}$$

$B_{ij}$  → Imaginary part of ijth element of bus admittance matrix

$B_{fij}$  → susceptance of transmission line connecting bus i and j

The above Dc power flow is the one usually most extensively employed in solving long term TNEP problem formulation as it satisfies the basic conditions stated by the operation planning studies of the power system network [8] [2]. It has an integer decision variable which indicates the selection and number of candidate circuits of the optimal extension plan. The branch susceptance of each candidate circuit and the kirchoffs voltage law (KVL) is expressed as a function of the integer variable. These terms make the problem a mixed integer nonlinear programming (MINLP) problem that its complexity increases as size of the system increases hence sometimes AClF may be needed

## Problem formulation

Nep problem is an optimization problem as earlier stated and as below

Minimize (objective Function)

S.t (Constraints)

Where S.t = subject to

The objective function in our case consists of the investment cost for new transmission lines and the constraint term consists of load-generation balance and transmission limits

## Objective function

The aim is to minimize total cost (total) consisting of the investment cost for new transmission lines ( $C_{\text{New-line}}$ ) [5]

Hence

$$C_{\text{Total}} = C_{\text{New-line}}$$

Where

$$C_{\text{New-line}} = \sum_{i \in L_c} C_l(x_i) L_i$$

And where

$L_i$  is transmission length in kilometer(Km) of candidate

$L_c$  is set of candidates

$X_i$  is the transmission type of the candidates(set of various types such as number of bundles, conductorTypes and number of circuits)

$C_L(X_i)$  is the investment cost per kilometer(Km) for type  $X_i$

## Constraints

The load- generation balance should be observed during the optimization process .Moreover, the capacities of transmission lines should not be violated too as described below.

### 1) Load Flow Equations

For most planning methods its normal to use DCLF equations as we try to avoid any anxieties about voltage problems and possible convergence difficulties. Moreover especially for large – scale power systems, the solution time may be exceptionally high if ACLF is employed. Hence the DCLF to be used are in the form as given below [7] [8] [19]

$$\sum_{j=1}^N B_{ij}(\theta_i - \theta_j) = P_{Gi} - P_{Di} \quad \forall i \in n$$

$$\sum_{j=1}^N B_{ij}(\theta_i^f - \theta_j^f) = P_{Gi}^f - P_{Di}^f \quad \forall i \in n \cap f \in c$$

Where

- $\theta_i \rightarrow \theta_j$  → Voltage phase angles of buses i and j
- $P_{Gi}$  → Power(real) generation at bus i
- $P_{Di}$  → Power demand at bus i
- f → Its an index showing contingency parameters and variables
- c → Set of contingencies
- N → System number of buses
- $B_{ij}$  → Imaginary part of element i j of admittance matrix  $Y_{ij}$

### 2) Transmission Limits

In the planning , power transfer characteristics are very important and the transmission line should be checked that the power transfer should not violate its rating during both normal and contingency conditions(N-1). Hence the limits are as below [8] [7]

$$b_k(\theta_i - \theta_j) \leq P_k^{-No} \quad \forall k \in (L_e + L_c)$$

$$b_k^f(\theta_i^f - \theta_j^f) \leq P_k^{-co} \quad \forall k \in (L_e + L_c) \cap m \in c$$

where

- $P_k^{-No}$  → Line K rating during normal conditions
- $P_k^{-co}$  → Line K rating during contingency conditions
- $\theta_i^f$  and  $\theta_j^f$  → Voltage phase angles of line K following contingency f



$L_e$	→	Set of existing lines
$L_c$	→	set of candidate lines
$b_k$	→	Line admittance in normal condition
$b_k^f$	→	Lines admittance in contingency condition

### 3) The transmission power flow limit

This constraint helps the planner to know the exact location and number of new required lines. It is included in the expansion planning problem to define the maximum number and location of new circuit that can be installed in a specified location. This is because the planners have to meet the community standards of visual impact on the environmental along with the economic considerations. Mathematically it is given as [8]

$$0 \leq L_c \leq L_{cmax}$$

Where

$L_c$  is the set of possible candidate lines

$L_{cmax}$  is the maximum possible set of candidate lines

Per corridor

Hence the total objective function is as below

$$\text{Minimize } C_{\text{Total}} = \sum_{i \in L_c} C_l(x_i) L_i$$

$$\begin{aligned} \text{S.t} \quad & \sum_{j=1}^N B_{ij}(\theta_i - \theta_j) = P_{Gi} - P_{Di} & \forall i \in n \\ & \sum_{j=1}^N B_{ij}(\theta_i^f - \theta_j^f) = P_{Gi}^f - P_{Di}^f & \forall i \in n \cap f \in c \\ & b_k(\theta_i - \theta_j) \leq P_k^{-No} & \forall k \in (L_e + L_c) \\ & b_k^f(\theta_i^f - \theta_j^f) \leq P_k^{-co} & \forall k \in (L_e + L_c) \cap \end{aligned}$$

$m \in c$

$$0 \leq L_c \leq L_{cmax} \quad \forall k \in (L_c, L_{cmax})$$

The above objective function is used for the analysis of the investment cost for the algorithm under another function called the Evaluation function whose equation is as below

$$\text{Evaluation Function} = C_{\text{Total}} + \alpha(\text{Constraints violation})$$

Where  $C_{\text{Total}} \rightarrow$  Objective function

$\alpha \rightarrow$  is a constant chosen arbitrarily large

Constraint violations  $\rightarrow$  these are calculated as the sum of the absolute values of all violations

As a result the solution will end up with least cost choice and with no constraint violations [7].

### Islanding condition

For a more practical result, we suppose that in an intermediate stage in either normal or any of contingency conditions a situation happens that an isolated substation (bus) appears. This condition is referred to as an island and should be avoided during normal and contingency conditions, so

$$N_{\text{Island}} = 0$$

If line contingency is modelled in the algorithm by choosing a very high value for line **reactance**, an island is detected by checking the **phase angle** difference across the line to be a large number. This happens due to the fact that the far end of the line terminates at a load bus. To avoid any islanding condition the evaluation function is hence modelled as below

$$\text{Evaluation Function} = C_{\text{Total}} + \alpha(\text{Constraints violation}) + \beta (N_{\text{island}})$$

Where  $\alpha \gg 1$  and  $\beta \gg \alpha$

Provided  $\alpha$  and  $\beta$  are arbitrarily chosen very high, the final solution will end up with no island conditions as well as with no constraint violations.  $\beta$  is chosen to be much higher than  $\alpha$  for the following reasons [7].

- An islanding removal is considered to be more important than removal of a constraint violation.
- The quantity of the term representing the constraints violations is normally much higher than the term representing the number of islands.

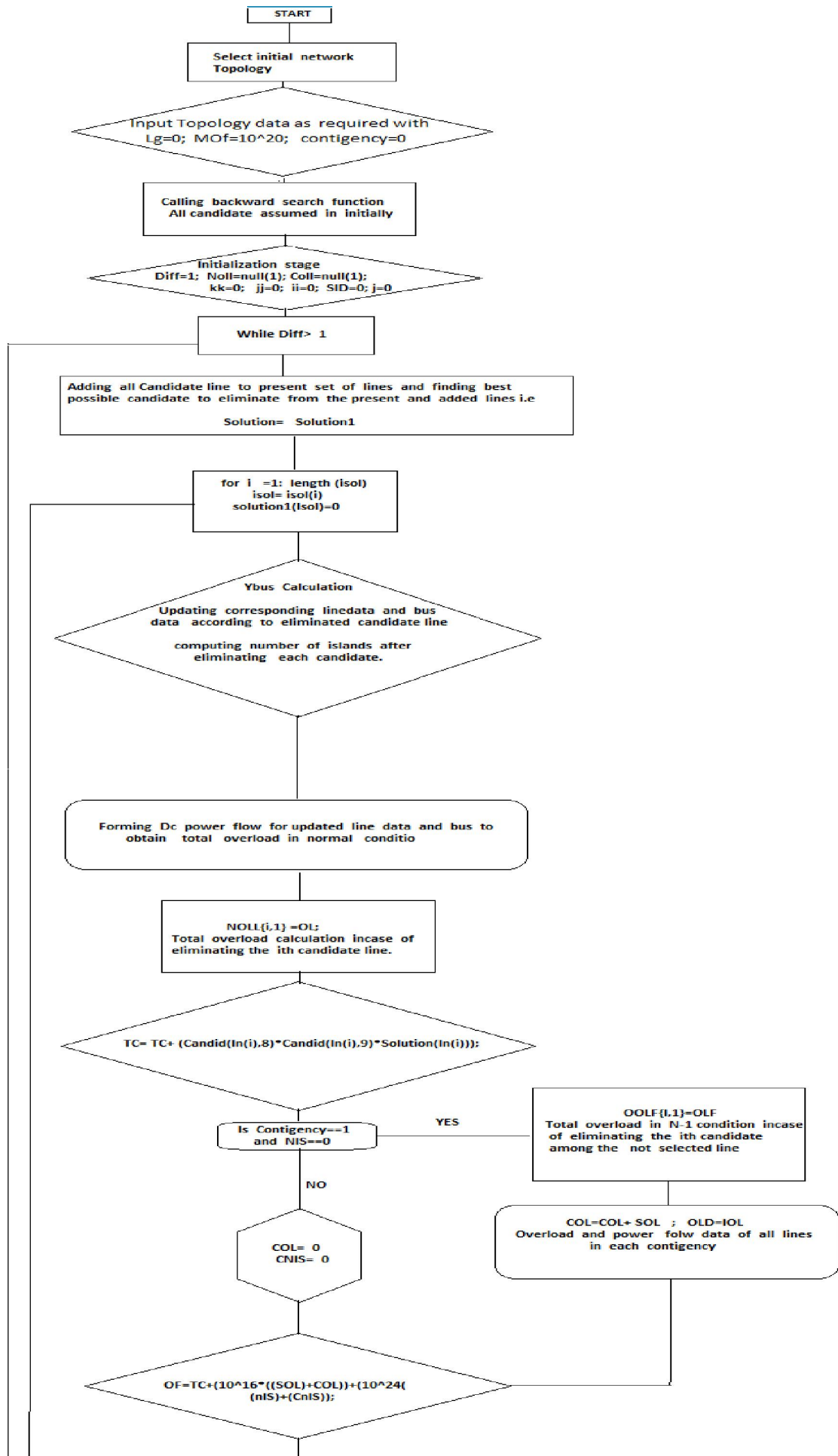
## **The Algorithm Flow**

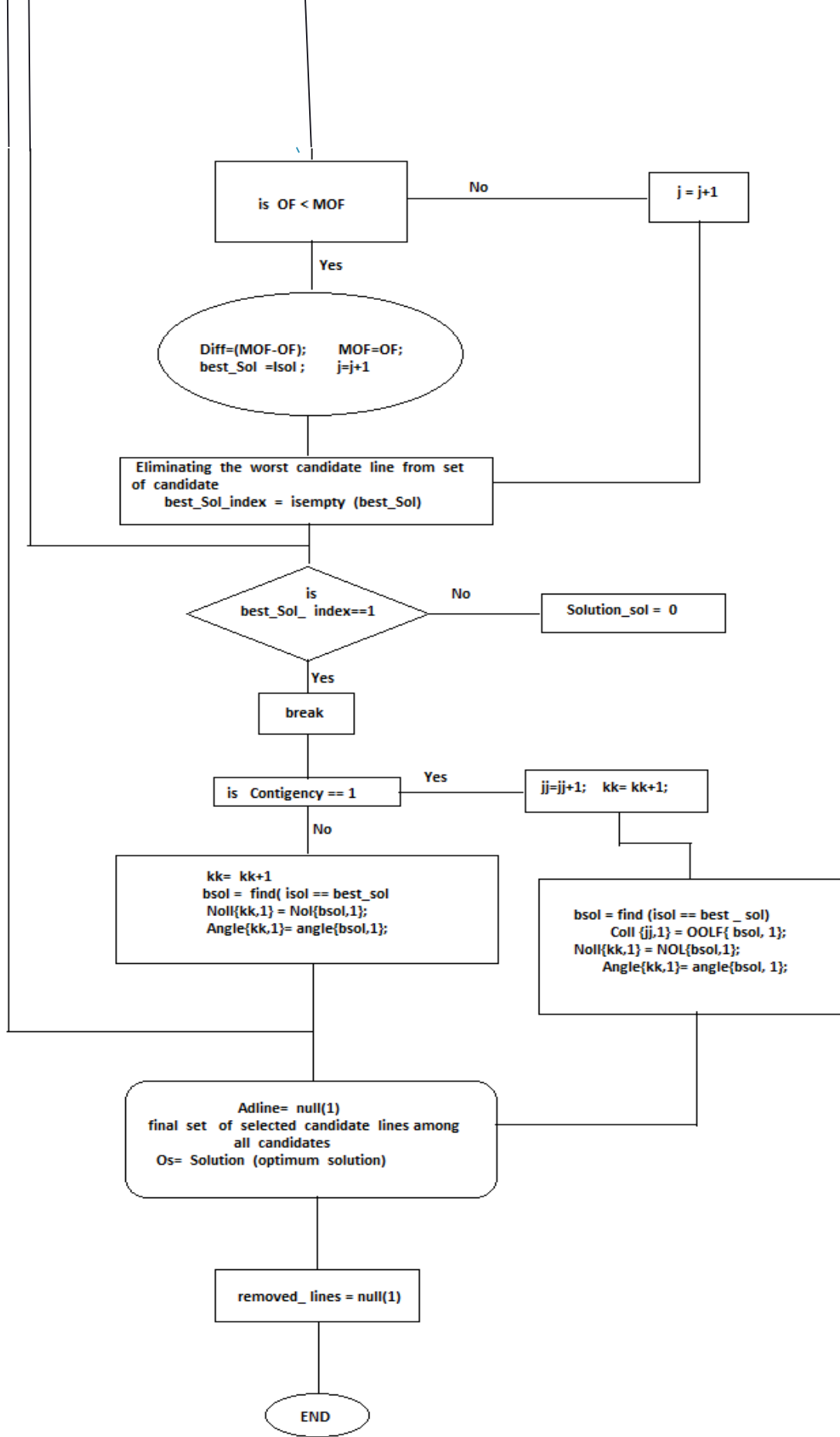
The above objective function will be solved using Hybrid approach which includes the backward and the forward stages . The backward stage is as earlier explained and for the solution, the following flow chart was developed from which the backward search function in MATLAB was derived.

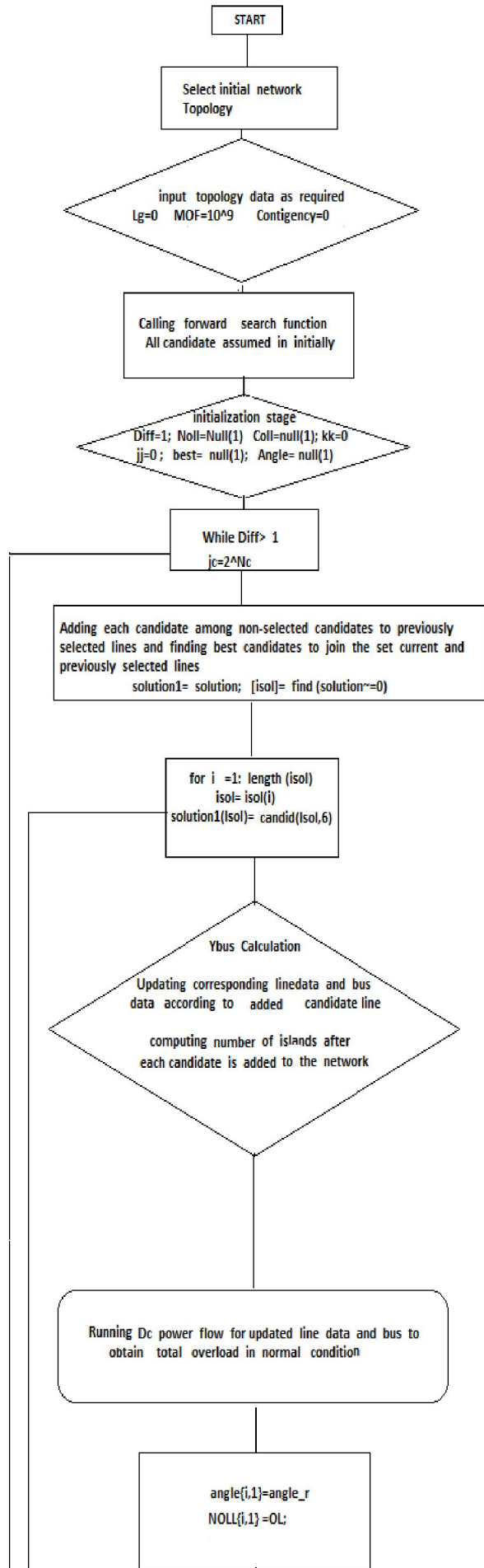
The next flow chart after the backward search is the flow for the forward chart.

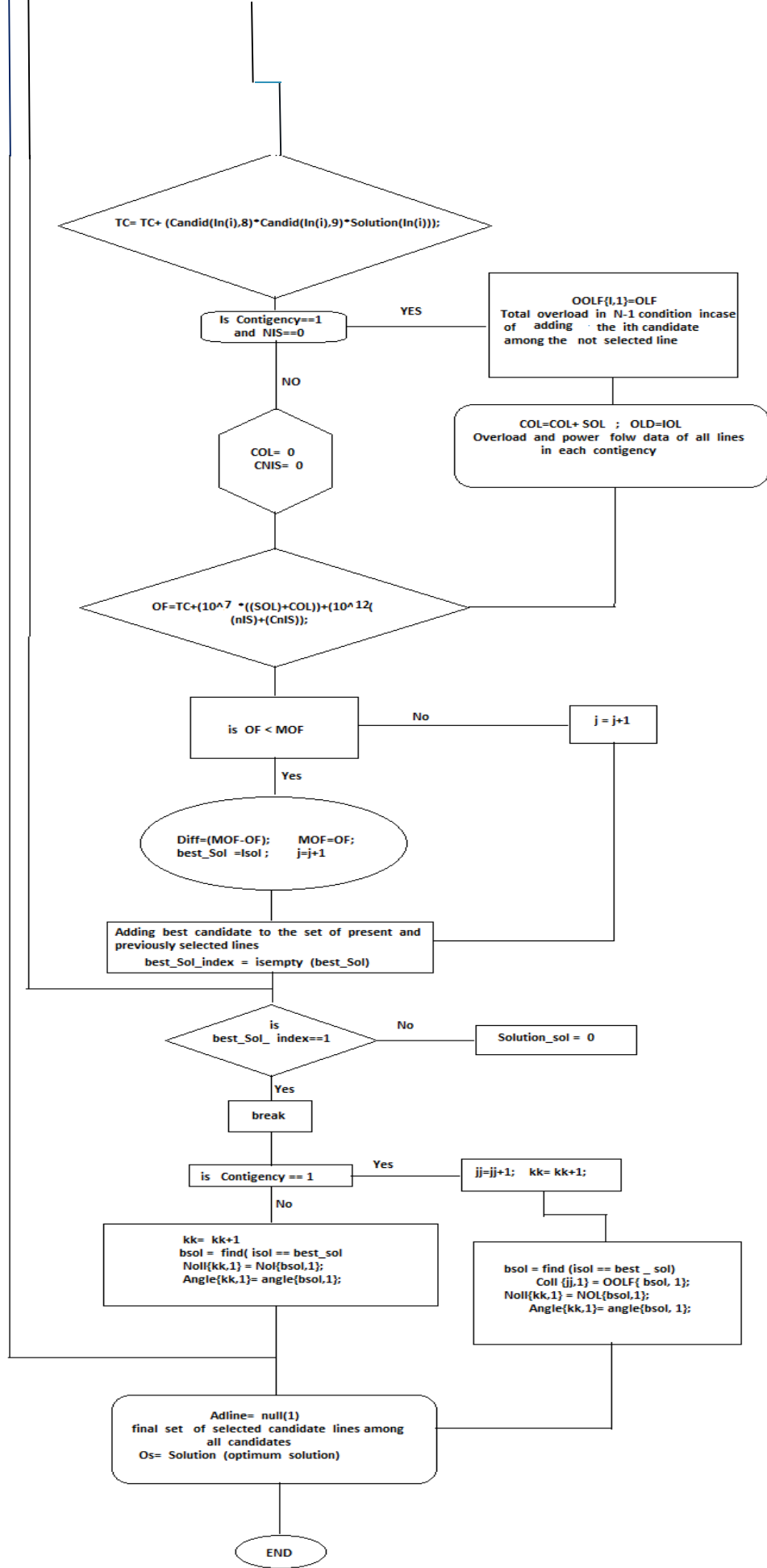
### ***Backward search flow chart***

The flow chart is as in next page.

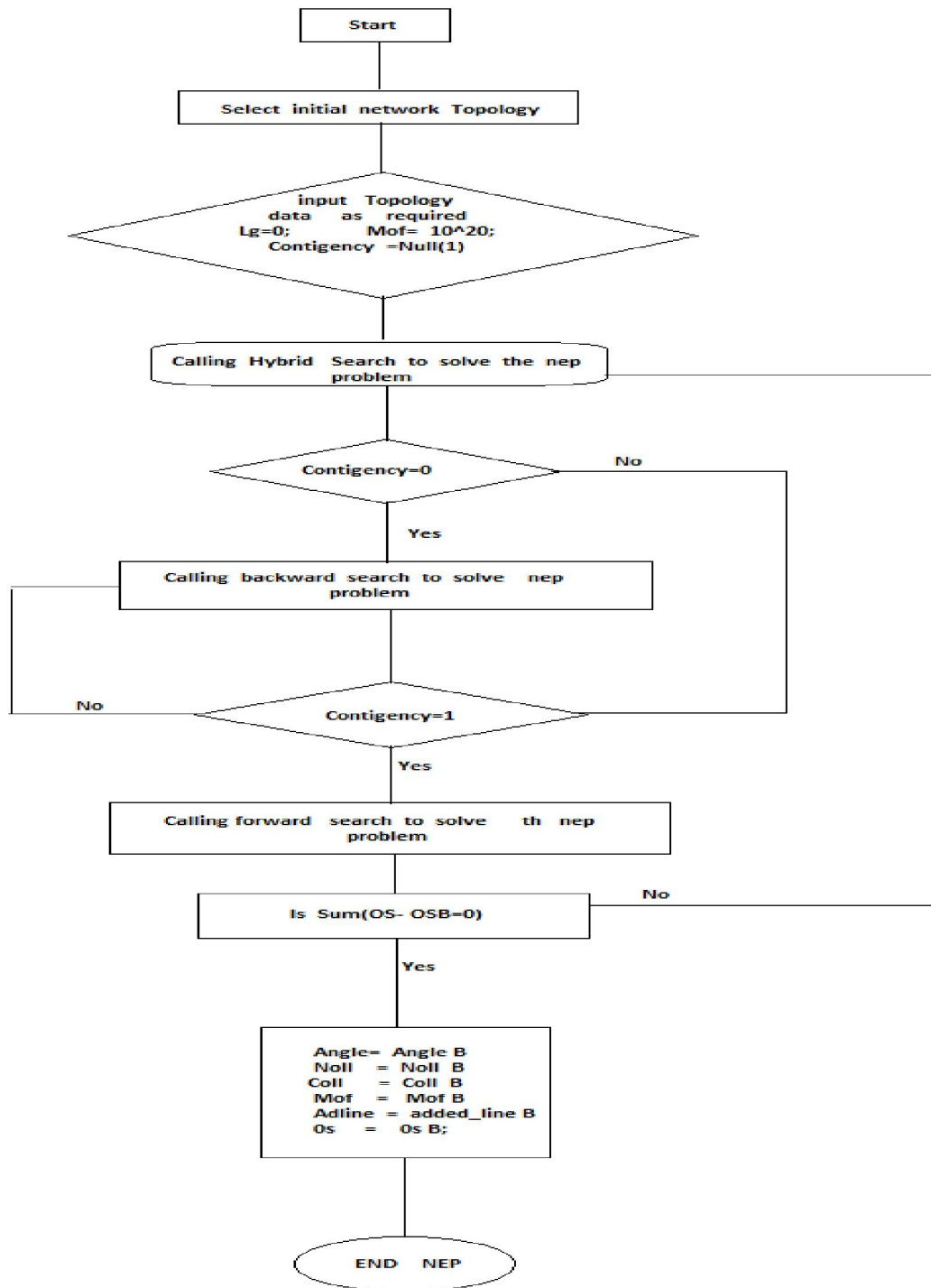








*Forward search flow*



*Hybrid search flow chart*



## Case Study

The proposed Expansion approach is applied on the IEEE 30 bus test power system network. This system as the name suggest has

- ❖ 30 buses
- ❖ 6 Generators
- ❖ 41 transmission lines

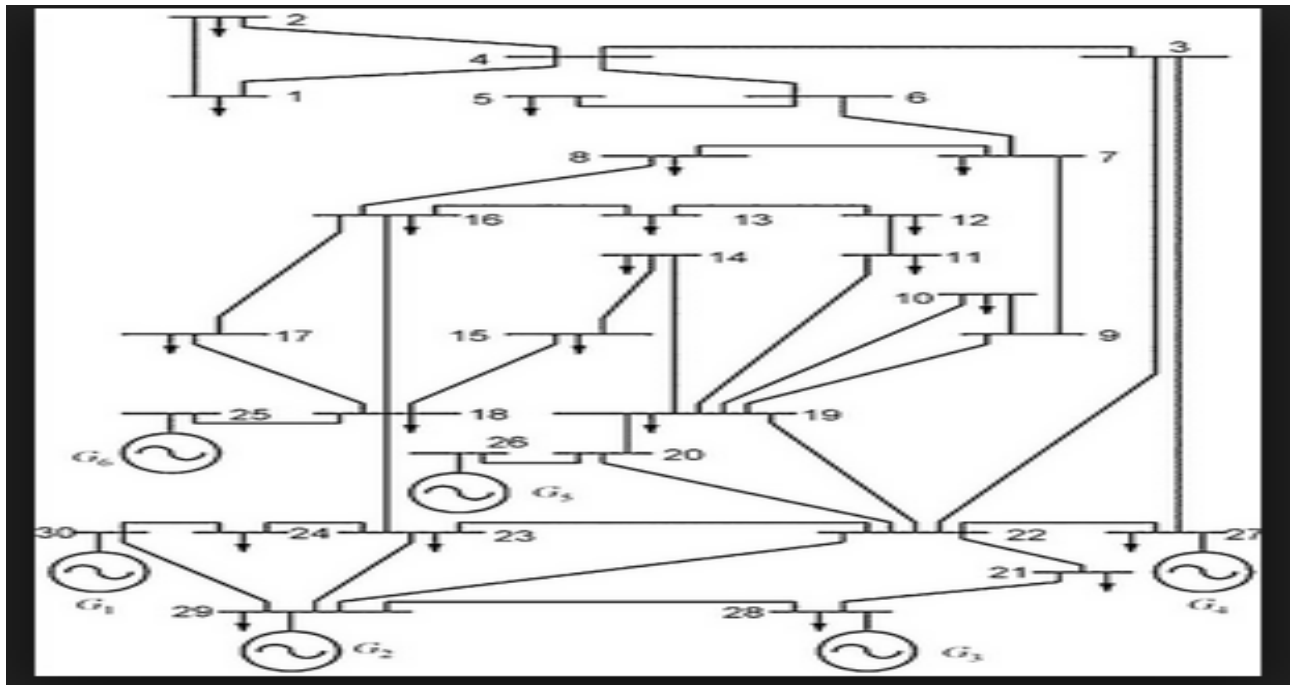
This power system is a test system from the IEEE site from the Mat power software

### The need for Test systems

Test systems are widely used in power system research and education. The reasons for using test systems rather than using a model of practical system are as follows.

- Practical power systems data are partially confidential
- Dynamic and static data of the systems are not well documented
- Calculations of numerous scenarios are difficult due to large set of data
- Lack of software capabilities for handling large set of data
- Less generic results from practical power system

The topological layout of the 30 bus test system is as in fig 11 below



**Fig 11:- IEEE 30 bus test system**

### ***Important data for the network model***

Transmission expansion planning is a complex problem as it is subjected to various uncertainty of the future data. Some of this data's can be forecasted as discussed earlier from past experiences and future expectations. For reasonably priced transmission planning of the future operation condition, getting the exact estimation of all the required data is crucial, and the required data have to be forecasted or determined before the planning process starts. Hence great care must be given.

The most important information I was forced to know as a planner before the planning for the expansion process were

- System network base topology of the base year
- Investment constraints
- Characteristics of the candidate transmission line circuits i.e the length in kilometers, line resistance and reactance and the authorized right of way of the transmission line.
- Possible types of transmission lines
- Cost of the specific transmission line per kilometer
- Power generation and demand profile of the planning horizon

For the project, the transmission network expansion planning is realized by assuming that the planner can select the expansion plan parallel to all the existing transmission lines without any restriction of right of way.

## CHAPTER FOUR RESULTS AND ANALYSIS

The proposed 30Bus system presented was analyzed using the DCLF analysis.

This analysis was done for the present and forecasted load. The proposed forecasted load is 120% for the final year of study assuming annual load increase of about 12%.

The analysis was carried out under normal and contingency conditions

### Normal condition analysis

The normal condition Analysis is done for the present load scenario and the forecasted load as in the table below

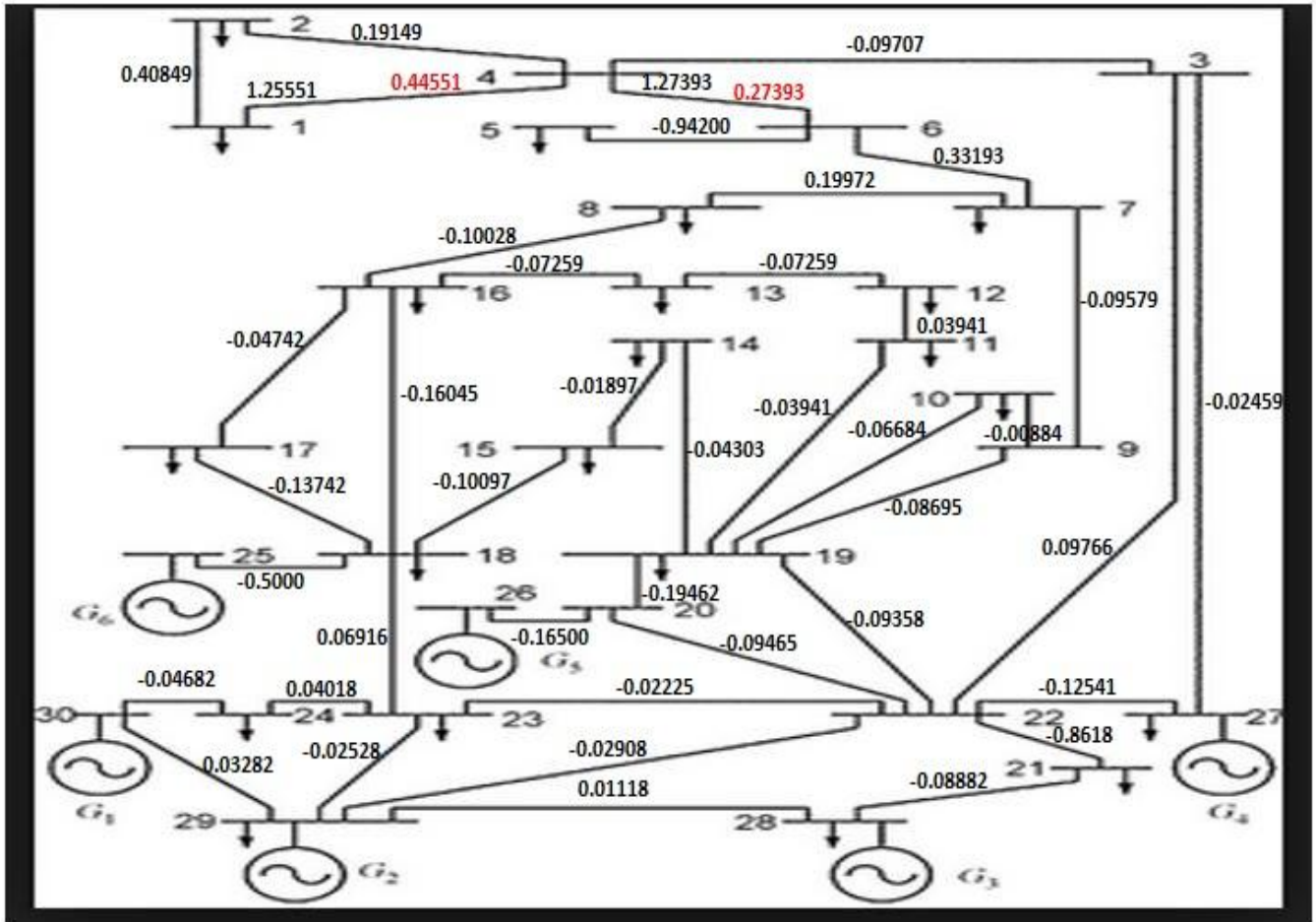
\*\*\*\*\*Bus data\*\*\*\*\*

Normal condition			
Base Network(0% load increase)		Base Network (120% load increase)	
Bus No	Angle (rad)	Bus No	Angle (rad)
1	0.00000	1	0.000000
2	-2.34880	2	-6.48754
3	-6.04283	3	-22.12767
4	-5.67492	4	-17.79312
5	-21.87617	5	-55.39776
6	-10.94897	6	-31.35792
7	-13.67077	7	-41.23172
8	-14.50957	8	-44.03630
9	-11.67835	9	-41.95482
10	-11.58107	10	-42.71939

11	-10.38380	11	-43.31517
12	-11.39233	12	-47.40284
13	-10.37607	13	-46.18956
14	-9.44576	14	-43.71393
15	-9.06691	15	-45.04605
16	-8.93375	16	-44.46757
17	-8.02188	17	-44.30596
18	-6.86068	18	-42.56184
19	-9.86987	19	-41.23219
20	-8.54647	20	-39.46902
21	-8.18291	21	-38.01576
22	-7.97953	22	-37.14611
23	-7.37866	23	-42.27722
24	-9.80057	24	-50.46099
25	0.63432	25	-35.06684
26	-2.27647	26	-34.79502
27	-5.60929	27	-28.00760
28	-6.32920	28	-37.67133
29	-6.77186	29	-40.97777
30	-8.25939	30	-48.63015

**Table 1:-Bus number and angle for the base topology**

For the present load and generation bus power flow was calculated using the DCLF for the initial topology and is as depicted in fig 12 below. The flow is in megawatts but it's converted into per unit for each case for easier analysis.

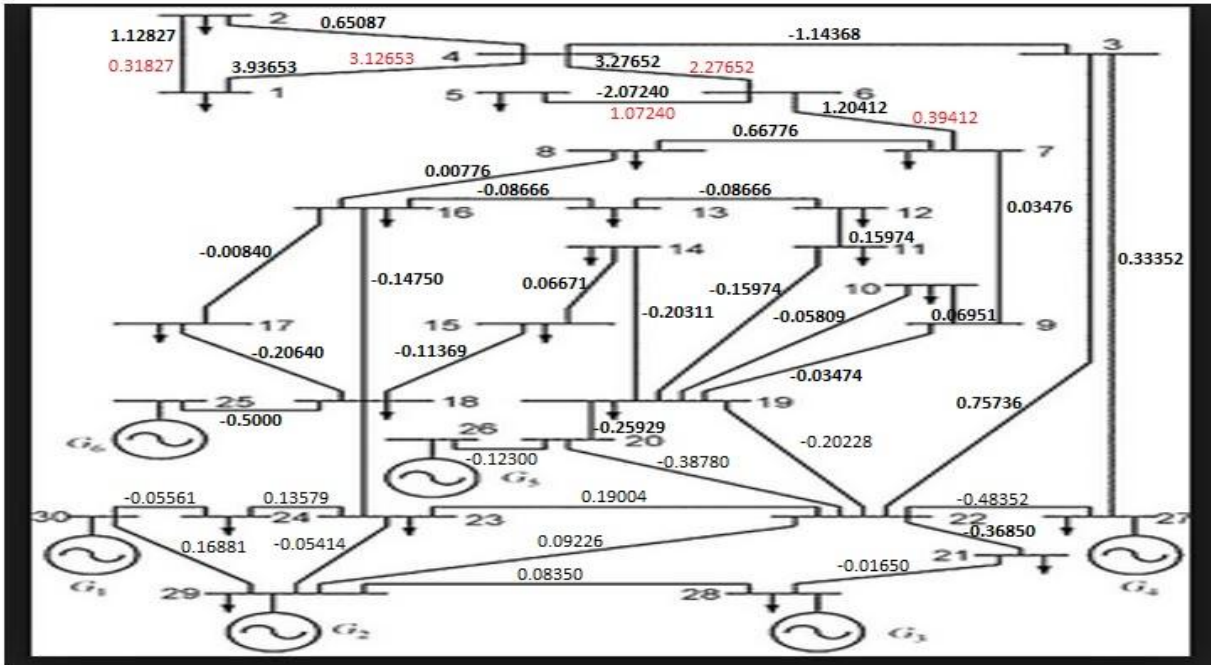


**Fig 12:- power flow in branches for 30bus system after performing DCLF analysis**

❖ **NB:** power flow is in per unit

It can be seen that there are clear violations to the voltage constraint, placed on the objective function that was earlier described. This is shown by the power flow observation of corridors 1-4 and 4-6 with the numbers in red indicating the overload in PU for the particular corridor under normal conditions as shown in fig 12. As shown in this corridors the flow in corridors 1-4 is 1.25551, and the thermal rating of that corridor is 0.8p.u, hence there is an

overload of 0.4451pu.this is also true for the corridors 4-6 .In fig 13 there are overloads in line 1-4, 4-6 , 6-7 and 5-6 respectively for the normal condition with 120% load increase over a period of 10 years as shown .The overload figures are depicted in red colors in the affected corridors.



**Fig 13:- power flow in branches for 30bus system with 120% load increase after performing DCLF analysis**

❖ **NB:** power flow is in per unit

Hence briefly, from the two figures we can say

**Overload at Normal:** Total overload of normal condition for fig 12 is 0.71944 pu

**Overload at Normal:** Total overload of normal condition with 120% load increase for fig 13

Is 7.18784 Pu

### Contingency (n-1) condition analysis

After the normal condition considerations were done and analyzed the system stability was further investigated under the contingency condition .The following table depicts the scenario of overload in N-1 conditions (i.e. Outages of each line consecutively)

The first column depicts the total no of line and the outage consecutively, the second column depicts the branch that is out at that particular time and the overload effects to other lines due to that line outage shown on the third column. Column four shows the total summation of lines overload for that particular outage at that branch.

Line no	Line outage	Lines overloaded	Overall overload per outage
1	1-2	1-4 , 4-6	1.12793
2	1-4	1-2, 2-4, 4-6	1.57493
3	2-4	1-4, 4-6	0.91093
4	3-4	1-4, 4-6	0.81651
5	3-22	1-4 ,4-6	0.76343
6	3-27	1-4, 4-6	0.71187
7	4-6	1-4 ,3-4 , 6-7	0.74851
8	5-6	1-4, 4-6	0.71944
9	6-7	1-4	0.44551
10	7-8	1-4 , 4-6	0.60951
11	7-9	1-4, 4-6	0.7851
12	8-16	1-4, 4-6	0.77464
13	9-19	1-4, 4-6	0.74620
14	9-10	1-4, 4-6	0.72134
15	10-19	1-4, 4-6	0.71468
16	12-13	1-4, 4-6	0.72202
17	11-12	1-4, 4-6	0.72202
18	11-19	1-4, 4-6	0.71468
19	13-16	1-4, 4-6	0.71809
20	14-15	1-4, 4-6	0.72239
21	16-17	1-4, 4-6	0.71225
22	15-18	1-4, 4-6	0.73711
23	16-18	1-4, 4-6	0.75544
24	19-20	1-4, 4-6	0.72250
25	14-20	1-4, 4-6	0.72799
26	17-18	1-4, 4-6	0.70354
27	18-23	1-4, 4-6	0.71944

28	18-25	1-4, 4-6	0.72390
29	21-22	1-4, 4-6	0.73317
30	19-22	1-4, 4-6	0.75805
31	22-27	1-4, 4-6	0.71663
32	22-23	1-4, 4-6	0.72112
33	24-30	1-4, 4-6	0.71944
34	20-26	1-4, 4-6	0.72002
35	21-28	1-4, 4-6	0.71765
36	28-29	1-4, 4-6	0.71800
37	22-29	1-4, 4-6	0.72062
38	23-24	1-4, 4-6	0.72133
39	29-30	1-4, 4-6	0.73746
40	23-29	1-4, 4-6	0.71854
41	20-22	1-4, 4-6	0.91698

**Table 2: Over load analysis in N-1 condition**

Hence from the normal and the contingency condition analysis, the network was found to be unstable. This meant that the loads to be supplied by the system were not adequately supplied and in case of an outage, then the system would be completely congested. Hence an expansion plan had to be carried out to stabilize the system for the present and the future forecasted loads and the generation requirements. The expansion plan was carried out as below.

### **Expansion Analysis and results**

The congestion in various lines under normal and contingency condition is the main factor to be put in check during the expansion process so that loads are adequately and completely supplied

Hence applying the hybrid heuristic formulation to the 30 bus base topology network the expansion plan is carried out in two stages

Case 1:- Considering the already available load demand and generation data

Case2:- Considering the forecasted load and Generation growth for our network in the study period

Hence this is a two stage expansion plan which proposes to expand the network into a robust and efficient structure.



### Case1:- expansion results

#### *Normal condition analysis*

Below is the bus voltage angle for the 30bus system after running the hybrid search code for the expansion to eliminate overloads and supply the load adequately for the normal condition.

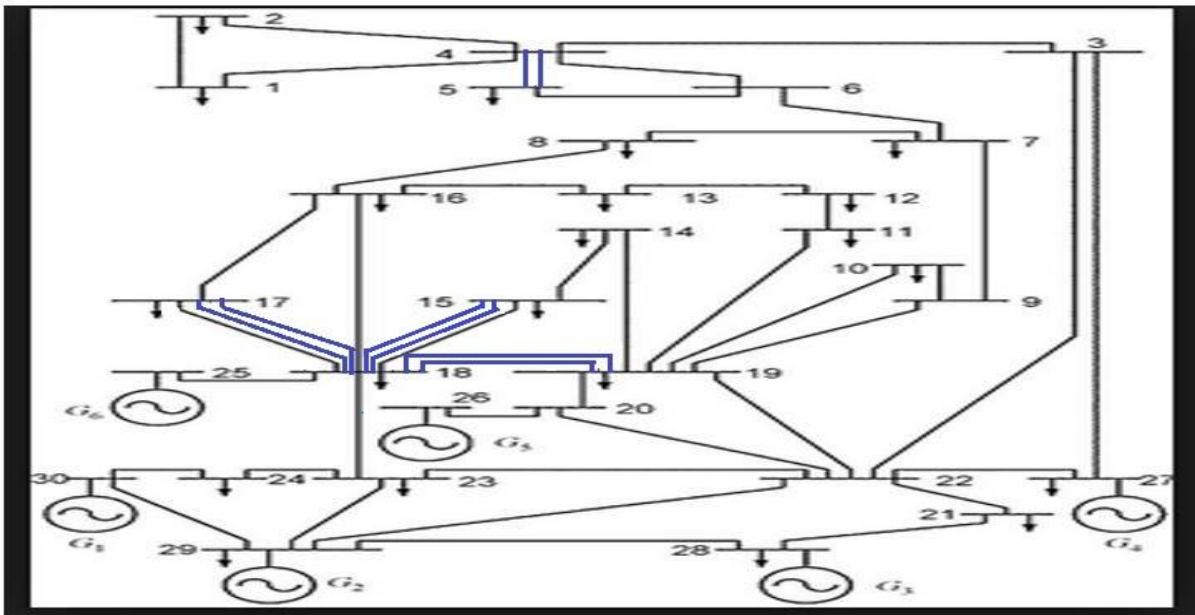
Normal condition	
Bus no	Angle (rad)
1	0.00000
2	-2.27659
3	-2.62774
4	-2.60753
5	-5.22358
6	-4.03134
7	-4.21380
8	-4.80389
9	-2.71863
10	-2.90842
11	-3.07232
12	-4.47548
13	-3.98848
14	-3.99298
15	-2.96019
16	-3.88080
17	-2.70793
18	-2.73871
19	-2.74544
20	-2.67759
21	-2.76230
22	-2.63258
23	-2.50361
24	-1.11378
25	-0.10032
26	3.59241
27	-2.14022
28	-2.26697
29	-1.42109
30	-0.53096

**Table 3:- Bus number and angle (phase) after expansion process**

As seen from table 3, the phase angle after expansion process had reduced considerably due to stability attained in the system. For the first case after expansion process, four corridors are selected each having two candidates. This corridors are:-

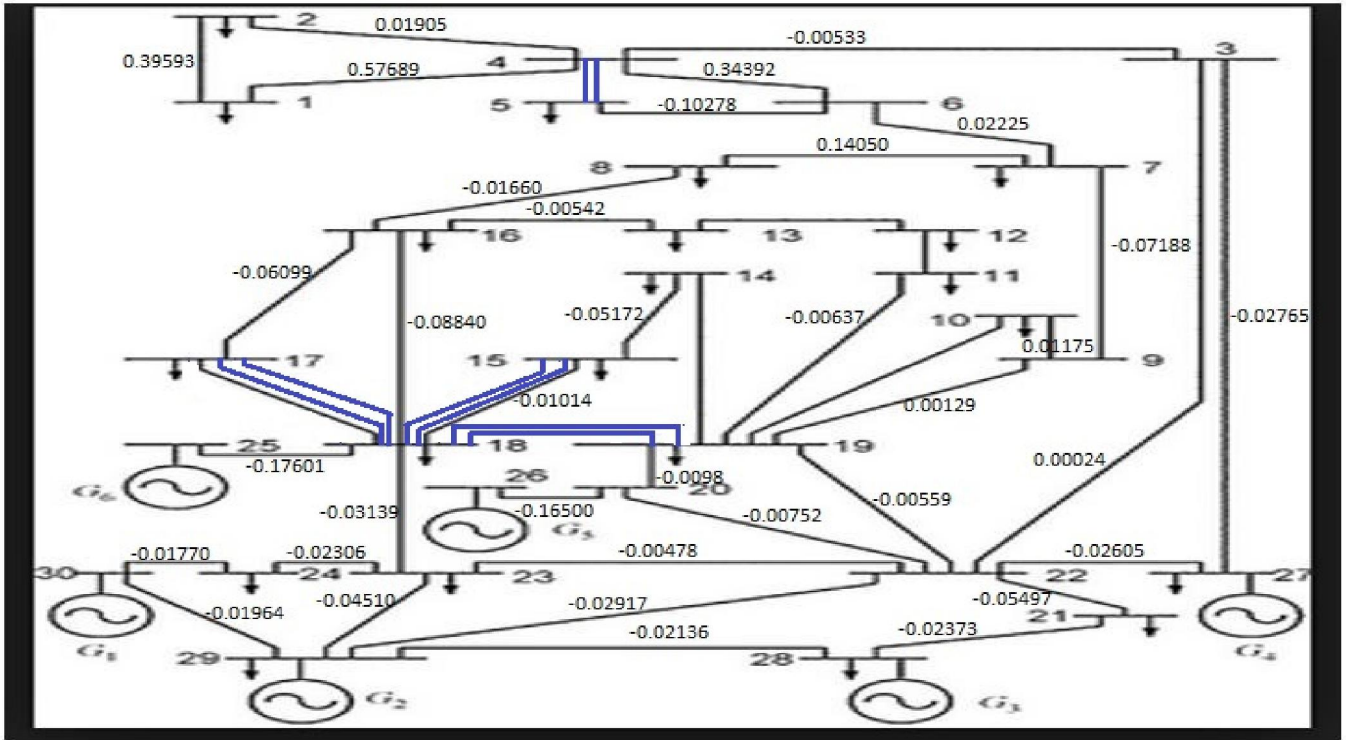
From bus	To bus	capacity
4	5	2
15	18	2
17	18	2
18	19	2

Hence the Base topology after expansion is as below ,with the lines in blue being the added ones after the code finding the least cost paths for the expansion in the respective expanded corridors.



**Fig 14:- 30bus system representation after expansion procedure**

The power flow in each branch after running the DCLF for the expanded network was hence as below



**Fig 15:- Power flow analysis for the 30bus expanded network**

The power flow for the Candidate lines placed in the network was also as below

From bus	To bus	capacity	Line flow (Pu)	Overload (Pu)
4	5	2	0.39593	0.00000
15	18	2	0.57689	0.00000
17	18	2	0.01905	0.00000
18	19	2	-0.00533	0.00000

As seen from the power flow for the expanded network and through the candidate lines selected, there was no overload for normal condition and hence briefly

➤ **Overload at normal:- Total overload of normal condition is 0.00000 Pu**

Hence the network met the normal (N) condition satisfactorily

### **Contingency (n-1) condition analysis**

The N-1 condition was also considered and the network found to be robust and efficient as there were no overloads experienced for any outages of any single line consecutively at any given time. Hence briefly

- No overload in N-1 condition

Hence from the results found after expansion the network met both the N and N-1 condition as intended.

### **case2:- expansion results**

Case2 takes into account the forecasted load growth for the expanded network topology in case 1

Assuming a load growth of 12% every year for 10year gives us a roughly 120% load increase by year 2024 .This load demand needs to be satisfied by

- i) The transmission facility and
- ii) The generation capacity at that particular time period

Hence using the 120% load growth rate the forecasted load is calculated to be

Initial load =223.4Mw =100%

$$\text{Forecasted load} = \left(\frac{100+120}{100}\right) * 223.4 = 492 \text{ Mw}$$

Hence from the load forecasted the generation requirement is supposed to be within the range of 5%-10% more than the load forecasted which gives us roughly 495Mw generation for the time 2024, from the normal 223.4 Mw generation for year 2014.

With the data for the forecasted load and generation requirements at hand, the final stage network expansion planning was undertaken as below.

### Normal condition analysis

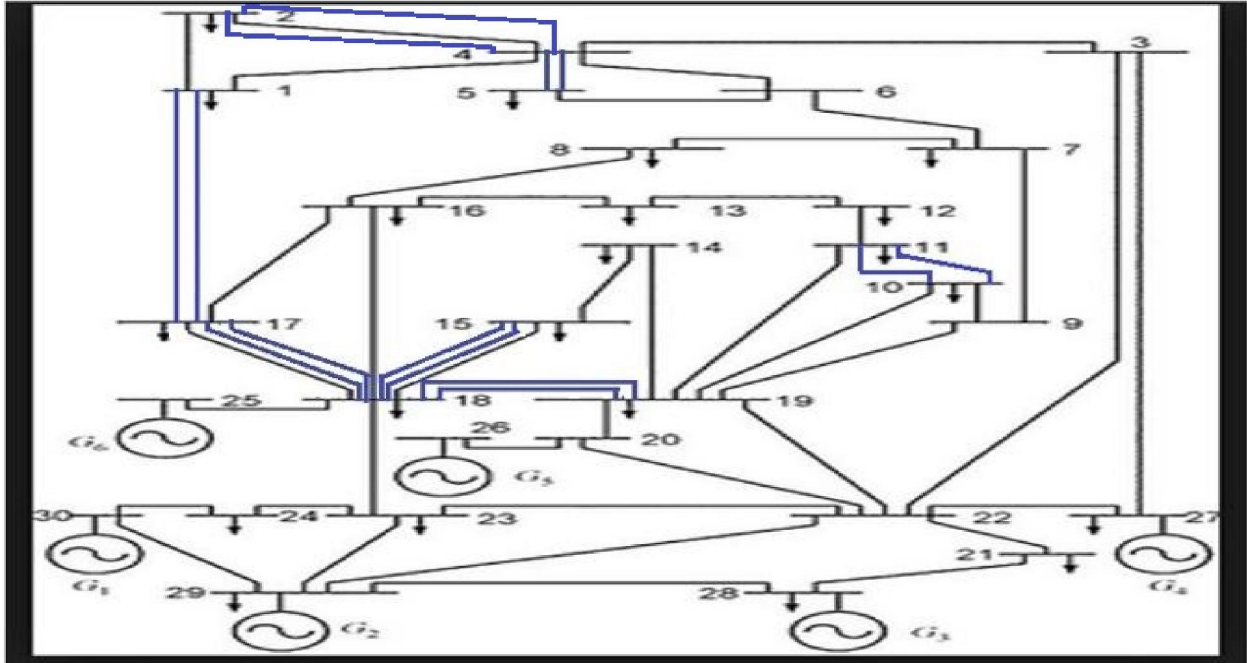
The final phase angle voltage for the expanded network is as below

Bus no	Angle (rad)
1	0.00000
2	-2.60713
3	-1.97729
4	-2.60267
5	-4.766955
6	-3.70010
7	-3.66986
8	-4.53278
9	-1.51230
10	-2.18490
11	-2.44031
12	-4.74466
13	-3.80950
14	-4.09300
15	-2.77222
16	-3.58307
17	-0.89779
18	-1.64249
19	-1.88984
20	-2.39353
21	-0.73936
22	-1.19801
23	-1.12481
24	0.66868
25	2.60039
26	-5.31953
27	0.57899
28	0.16249
29	1.58741
30	2.43977

**Table 4:- Final phase Angle for 30bus expanded network**

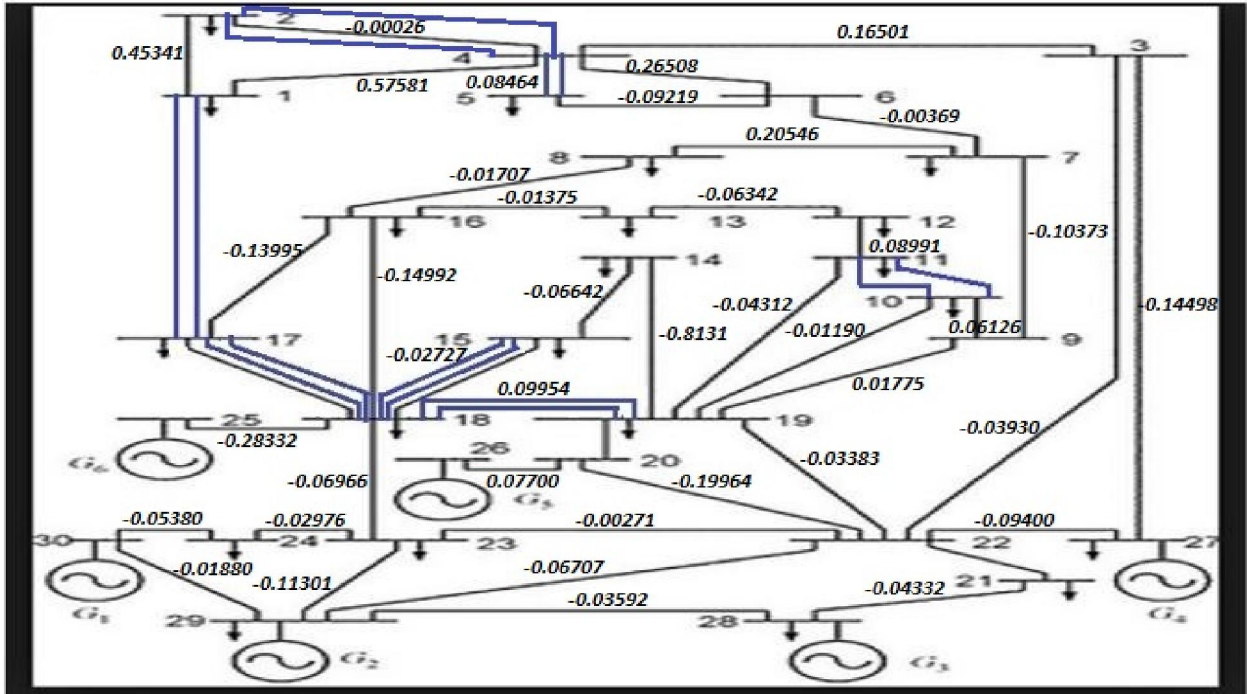
The phase angle was reduced and in agreement with the expansion requirements of the network as the network had stabilized into an efficient and reliable utility able to supply the loads efficiently and effectively under normal and contingency conditions.

Hence the final expanded network after stage two considering the load growth and generation increase was as below.



**Fig 16:- 30bus system expansion after considering 120% load growth and generation expansion**

The load flow analysis after running the DCLF for Fig 16, the final expanded network was as below



**Fig 17: Load flow analysis for the Final expanded network**

Additional candidate lines to the final expanded network are as follows:

From bus	To bus	Power flow	overload
1	17	0.45341	0.00000
10	11	0.57581	0.00000
2	4	-0.00026	0.00000

From Fig 17 it can be seen clearly that there is no overload in the normal condition after expansion hence the loads are sufficiently supplied as intended in the project.

Hence briefly

- **Overload at normal :-Total overload of normal condition is 0.00000 pu**

### **Contingency (n-1) condition analysis**

Under N-1 condition, there was no overload in case of an outage of any of the existing lines consecutively from the first to the last line (i.e. 42<sup>nd</sup>line), This meant that the expansion process was successful in that the N-1 condition considered had no violations observed to the network and the loads were sufficiently supplied during that condition .

Hence briefly:

- **No overload in N-1 condition**

After certifying the above objectives the cost analysis was analyzed and was as presented below

### **Cost Analysis for the Results obtained**

For the entirety of the expansion plan only one conductor type was used. This was the cheapest conductor in the market and yet having a fairly good thermal and line flow properties for its effective use in the expansion plan. Below are the list of other conductor types.

Conductor type	Cost	rating
1*400mm <sup>2</sup> single canary	220KUSD/unit	315Mw
2*400mm <sup>2</sup> twin canary	270KUSD/unit	630Mw
4*400mm <sup>2</sup> quad lark	320KUSD/unit	-----
4* 400mm <sup>2</sup> quad lark	320KUSD/unit	1405 Mw
3*900mm <sup>2</sup> triple canary	400KUSD/unit	1718Mw

All of the above candidate types were options for my expansion planning but for the fact that they were all abit expensive, I decided to pick on the local standard conductor type whose cost per kilometer in **USD is 9, 1000**.

This value is not constant as it changes depending on the market trends.

### **Case1: Cost analysis at a glance**

Corridors selected = 4

Candidate used in expansion in the chosen Corridors=  $2*4=8$

Total length (Km) for selected candidate lines =124Km

Total cost for the expansion process=  $124*91000 =11.284$ million USD

### **Case2: Cost analysis at a glance**

Corridors selected = 3

Candidate used in expansion in the chosen Corridors= $2*3=6$

Total length (Km) for selected candidate lines =200Km

Total cost for the expansion process=  $200*91000 =18.2$ million USD

Hence total expansion cost for the network=  $18.2+11.284=29.484$ million USD.

This Cost is very much expected and low compared to the expansion process undertaken.

The above selected corridors in each case are the **least cost corridor** found by the algorithm yet also able to eliminate the overloads and congestions in the N and N-1 conditions. Hence the total cost incurred at the end of the entire expansion period is accurately represented and minimal compared to the many expansion options that the network availed.



## CHAPTER FIVE

### CONCLUSION AND RECOMMENDATIONS

#### **Conclusion**

Congestion management is one important issue in power systems, and Pseudo dynamic approaches are the required methodological solution for this kind of problem especially in the case of transmission network expansion. A general formulation of the transmission expansion problem in Deterministic load environment is proposed in this project. The Main purpose of this formulation is to minimize total cost for both the operational and security constraint of the system. The transmission expansion problem is composed of two interrelated problems:

- (1) The optimum network problem for future loads and Generation capacities, and
- (2) The reference network problem that is part of the optimum network problem.

The TEP problem is a complex mixed integer non-linear programming problem. This project proposes an efficient Hybrid Heuristic method as the tool for the solution of the TEP problem. The proposed method is applied on the IEEE 30-bus test system and the results indicate to the fact that the objectives of the project are met as

1. Optimum routes between the generation buses, load centers and substations are found
2. Load are completely supplied during normal and contingency condition
3. Least cost are incurred in the expansion plan, as the optimum routes selected are also the least cost corridors that the network found comparing to the rest of the optimum routes which were abit costly.

#### **Recommendation**

The proposed Hybrid heuristic method is based on normal (N) and Contingency (N-1) conditions and hence in case of an N-2, N-3.....N-n (where n=1, 2, 3,.....) Conditions the expanded network may not be able to meet the set objectives and constraints and hence may fail to supply the loads adequately and completely .Also the nature of the loads are not that deterministic as proposed in the project. As various scenarios come into play, load trends can change arbitrary for the forecasted year. The major Recommendation is therefore to explore an improved method that takes into account the above mentioned scenarios albeit with least cost incurred.

Right of way acquisition is a major problem and cost demanding, this rendered creation of new buses to our expanded network not possible due to the increased cost, also transformer upgrade considerations were not taken into account. Hence another major recommendation will be to propose an improved method that take into account right of way acquisition for various bus creation and at the same time considering transformer upgrade in case of upgrading a

transmission line from one voltage level to another. This should also be done with cost reduction considerations in mind.

The Hybrid Heuristic method is a method that undergo a step by step generating evaluating and selecting expansion option, but for improved performances Meta-Heuristics like Genetic Algorithm(GA), particle Swarm optimization(PSO), simulated annealing(SA) which are intelligent search methods can be employed .This Meta-Heuristics can also be combined to form Hybrid Meta-Heuristic methods like combining GA and PSO. This Hybrid Meta-Heuristic methods are highly favorable to tackle the above expansion planning problem in a more robust way.

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## NOMENCLATURE

### **Acronyms:**

TEP → Transmission Expansion Planning

STEP → Static Transmission Expansion Planning

DTEP → Dynamic Transmission Expansion Planning

GA → Genetic Algorithm

TS → Tabu Search

GRASP → Greedy Randomization Adaptive Search Procedure

OPF → Optimal Power flow

AC OPF → Alternating Current Optimal Power Flow

DC OPF → Direct Current Optimal Power Flow

KCL → Kirchhoff's Current Law

KVL → Kirchhoff's Voltage Law

MINLP → Mixed Integer Non-linear Programming

$P_{ij}$  → active power through transmission line i-j

$Q_{ij}$  → reactive power through transmission line

$S_{ij}$  → Complex/ apparent power through transmission line i-j

$L_i$  → is transmission length in kilometer(Km) of candidate

$L_c$  → is set of candidates

$X_i$  → is the transmission type of the candidates(set of various types)

$C_L(X_i)$  → is the investment cost per kilometer(Km) for type  $X_i$

$C_{ploss}$  → is the cost per unit losses

- A → is losses of new lines
- B → is losses of existing lines
- $P_k^{-No}$  → Line K rating during normal conditions
- $P_k^{-co}$  → Line K rating during contingency conditions
- $\theta_i^f$  and  $\theta_j^f$  → Voltage phase angles of line K following contingency f
- $b_k$  → Line admittance in normal condition
- $b_k^f$  → Lines admittance in contingency condition
- $P_{Di}$  → Total power demand at bus i
- $p_i$  → Real power injection at bus i
- $Q_{Gi}$  → Reactive power generation at bus i
- $Q_{Di}$  → Reactive power injection at bus i
- $P_{Gi}$  → Total power generated at bus i
- $S_{ij}$  → is the apparent flow through transmission line i-j
- $S_{ijmax}$  → is the maximum capacity transfer of apparent power over branch i-j
- $B_{ij}$  → Imaginary part of ijth element of bus admittance matrix

### **Sets**

- N → set of all buses
- $L_e$  → set of existing lines
- $L_c$  → set of candidate lines
- L → set of all lines (Existing and candidate)
- G → set of all generators
- T → set of stage

## **APPENDIX**

### **APPENDIX A**

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## APPENDIX C

### Data for NEP problem.

#### Line Data.

No	fbus	tbus	r	x	b	Smax	Length (km)	cost
1	1	2	0.0192	0.0575	0.0528	81	15	1365
2	1	4	0.0452	0.0452	0.0408	81	25	2275
3	2	4	0.057	0.1737	0.0168	100	25	2275
4	3	4	0.0132	0.0379	0.0084	120	65	5915
5	3	22	0.0472	0.1983	0.0418	120	110	10010
6	3	27	0.0581	0.1763	0.0374	100	90	8190
7	4	6	0.0119	0.0414	0.009	100	22	2002
8	5	6	0.046	0.116	0.0204	100	22	2002
9	6	7	0.0267	0.082	0.017	81	22	2002
10	7	8	0.012	0.042	0.009	120	28	2548
11	7	9	0	0.208	0	120	32	2912
12	8	16	0	0.556	0	120	28	2548
13	9	19	0	0.208	0	180	30	2730
14	9	10	0	0.11	0	180	15	1365
15	10	19	0	0.256	0	180	35	3185
16	12	13	0	0.14	0	81	22	2002
17	11	12	0.1231	0.2559	0	81	15	1365
18	11	19	0.0662	0.1304	0	73	36	3276
19	13	16	0.0945	0.1987	0	100	22	2002
20	14	15	0.221	0.1997	0	90	20	1820
21	16	17	0.0524	0.1923	0	120	22	2002
22	15	18	0.1073	0.2185	0	70	20	1820
23	16	18	0.0639	0.1292	0	70	35	3185
24	19	20	0.044	0.068	0	80	15	1365
25	14	20	0.0936	0.209	0	100	22	2002
26	17	18	0.0324	0.0845	0	150	21	1911
27	18	23	0.0348	0.0749	0	150	25	2275
28	18	25	0.0727	0.1499	0	100	20	1820
29	21	22	0.0116	0.0236	0	150	17	1547
30	19	22	0.1	0.202	0	100	45	4095
31	22	27	0.115	0.189	0	80	22	2002
32	22	23	0.132	0.27	0	80	15	1365
33	24	30	0.1885	0.3292	0	100	17	1547
34	20	26	0.2544	0.380	0	100	15	1365
35	21	28	0.1093	0.2087	0	120	30	1365
36	28	29	0	0.396	0	90	32	2730
37	22	29	0.2198	0.4153	0	90	35	2912
38	23	24	0.3202	0.6027	0	90	15	3185
39	29	30	0.2399	0.4533	0	80	24	1365
40	23	29	0.0636	0.24	0.0428	80	22	2184
41	20	22	0.0169	0.05990	0.013	80	45	4095

NB: the values for the length of existing line per corridor are fictitious but are applicable to real data situations where physical measurements of transmission corridors are known beforehand.

### Bus data

Bus_i	type	Pd	pg	Qd	Gs	Bs	area	Vm	baseKV	Vmax	Vmin
1	3	0	0	0	0	0	1	1.06	132	1.06	0.94;
2	2	21.7	0	12.7	0	0	1	1.043	132	1.06	0.94;
3	1	2.4	0	1.2	0	0	1	1.021	132	1.06	0.94;
4	1	7.6	0	1.6	0	0	1	1.012	132	1.06	0.94;
5	2	94.2	0	19	0	0	1	1.01	132	1.06	0.94;
6	1	0	0	0	0	0	1	1.01	132	1.06	0.94;
7	1	22.8	0	10.9	0	0	1	1.002	132	1.06	0.94;
8	2	30	0	30	0	0	1	1.01	132	1.06	0.94;
9	1	0	0	0	0	0	1	1.051	11	1.06	0.94;
10	1	5.8	0	2	0	19	1	1.045	33	1.06	0.94;
11	2	0	0	0	0	0	1	1.082	11	1.06	0.94;
12	1	11.2	0	7.5	0	0	1	1.057	33	1.06	0.94;
13	2	0	0	0	0	0	1	1.071	11	1.06	0.94;
14	1	6.2	0	1.6	0	0	1	1.042	33	1.06	0.94;
15	1	8.2	0	2.5	0	0	1	1.038	33	1.06	0.94;
16	1	3.5	0	1.8	0	0	1	1.045	33	1.06	0.94;
17	1	9	0	5.8	0	0	1	1.04	33	1.06	0.94;
18	1	3.2	0	0.9	0	0	1	1.028	33	1.06	0.94;
19	1	9.5	0	3.4	0	0	0	1.026	33	1.06	0.94;
20	1	2.2	0	0.7	0	0	1	1.03	33	1.06	0.94;
21	1	17.5	0	11.2	0	0	1	1.033	33	1.06	0.94;
22	1	0	0	0	0	0	1	1.033	33	1.06	0.94;
23	1	3.2	0	1.6	0	0	1	1.027	33	1.06	0.94;
24	1	8.7	0	6.7	0	4.3	1	1.021	33	1.06	0.94;
25	1	0	50	0	0	0	1	1.017	33	1.06	0.94;
26	1	3.5	20	2.3	0	0	1	1	33	1.06	0.94;
27	1	0	15	0	0	0	1	1.023	33	1.06	0.94;
28	1	0	10	0	0	0	1	1.007	132	1.06	0.94;
29	1	2.4	10	0.9	0	0	1	1.003	33	1.06	0.94;
30	1	10.6	12	1.9	0	0	1	0.992	33	1.06	0.94;

### Candidate data

No	Fbus	Tbus	r	x	capacity	Smax	length (km)	cost (KUSD)
1	1	4	0.0452	0.1852	2	100	25	2275
2	1	17	0.0581	0.1763	2	120	60	5460
3	2	4	0.0119	0.0414	2	120	25	2275
4	3	9	0.0000	0.2080	2	73	70	6370
5	4	5	0.0000	0.2560	2	120	10	910
6	4	6	0.0000	0.1400	2	120	20	1820
7	5	6	0.0945	0.1987	2	81	20	1820
8	5	8	0.2210	0.1997	2	120	15	1365
9	5	16	0.0824	0.2185	2	120	25	2275
10	6	7	0.0639	0.0680	2	81	20	1820
11	6	8	0.0340	0.2090	2	81	24	2184
12	7	10	0.0116	0.2020	2	73	37	3367
13	8	12	0.2544	0.2087	2	83	26	2366
14	9	19	0.0169	0.1983	2	180	40	3640
15	9	22	0.0192	0.0575	2	120	30	2730
16	10	11	0.0452	0.1652	2	120	15	1365
17	10	19	0.0132	0.0379	2	180	30	2730

18	12	14	0	0.208	2	81	25	2275
19	13	16	0	0.11	2	100	20	1820
20	14	16	0.0945	0.1987	2	100	26	2366
21	15	16	0.221	0.1997	2	120	24	2184
22	15	18	0.0524	0.1923	2	70	18	1638
23	15	20	0.1073	0.2185	2	70	25	2275
24	17	18	0.0324	0.0845	2	150	18	1638
25	18	19	0.0116	0.0236	2	100	16	1456
26	18	25	0.2544	0.38	2	120	20	1820
27	21	27	0.0639	0.1292	2	120	17	1547
28	22	28	0.0480	0.0749	2	90	60	5460
29	24	25	0.1885	0.3292	2	100	24	2184
30	25	30	0.000	0.3690	2	120	22	2002

## APPENDIX D

### CODE FOR NEP PROBLEM

#### HYBRID HEURISTIC CODES

➤ Hybrid search script

```
clear
clc
num=30;
busd = busdata;
Linedata = linedata;
Candid = Candidatedata;
LineType = linetype;
Gend =Gendata;
Lg =null(1,1);
%% Mof: minimum fitness, which is kept at high value for
% the first iteration of the forward search algorithm
Mof = null(1,2);
Solution = Candid(:,6);
[Os, Adline, Noll, Coll, Angle, Mof]=HS(busd,...
    linedata, Candid, linetype, Solution,...
    Lg, Mof);
%% 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
fid = fopen('results.txt', 'wt');
fprintf(fid, '-----');
fprintf(fid, '\n Added candidate lines are as follows:\n');
fprintf(fid, '-----\n');
fprintf(fid, ' From bus  To bus\n');
fprintf(fid, ' -----  -----');
fprintf(fid, '\n %10.0f %15.0f', Adline');
fprintf(fid, '\n\n*****');
fprintf(fid, '*****');
fprintf(fid, '\n Normal');
fprintf(fid, ' condition\n');
fprintf(fid, '*****');
fprintf(fid, '*****\n');
if(isempty(Noll) == 1)
fprintf(fid, 'No overloaded in normal condition\n');
else
NNOLL = Noll{size (Noll,1),1};
NL = size (Linedata,1);
NS = length (find (Os ~= 0));
fprintf(fid, '\n Overload at normal');
fprintf(fid, 'Total overload of normal condition is');
fprintf(fid, '3.5pu\n', sum(NNOLL(:,4))');
fprintf(fid, '*****');
```

```

fprintf(fid, '*****');
fprintf(fid, '\n***** Candidate');
fprintf(fid, 'branches *****\n');
fprintf(fid, '*****');
fprintf(fid, '*****\n');
fprintf(fid, '\n From bus To bus Line flow');
fprintf(fid, ' (pu) Overload (pu)\n');
for i = 1:NS
fprintf(fid, '\n %10.0f %15.0f %20.5f %20.5f\n', ...
NNOLL(i,:));
end
fprintf(fid, '*****');
fprintf(fid, '*****');
fprintf(fid, '\n***** Existing');
fprintf(fid, ' branches *****\n');
fprintf(fid, '*****');
fprintf(fid, '*****\n');
fprintf(fid, '\n From bus To bus Line flow');
fprintf(fid, ' (pu) Overload (pu)\n');
for i=1:NL
fprintf(fid, '\n %10.0f %15.0f %20.5f %20.5f\n', ...
NNOLL(i,:));
end
fprintf(fid, '\n*****');
fprintf(fid, '*****');
fprintf(fid, '*****\n');
end
nco = size (Coll,1);
oc = Coll(nco,1);
nc = size (oc,1);
ocl = 0;
for i = 1:nc
occ = oc(i,1);
ocl =occ(1,1);
end
if ocl=0;
fprintf(fid, '\n No overload in N-1 condition\n');
fprintf(fid, '\n*****\n');
else
fprintf(fid, '\n*****');
fprintf(fid, '*****');
fprintf(fid, '*****\n');
LCOLL =size(Coll,1);
fprintf(fid, ' Overloaded lines in');
fprintf(fid, ' N-1 condition');
for i = 1: size (LCOLL,1)
iLCOLL = LCOLL(i,1);
iL = iLCOLL(1,:);
if iL(1,1) ~= 0
fprintf(fid, '\n*****');
fprintf(fid, '*****');
fprintf(fid, '*****\n');
fprintf(fid, 'Total overload for outage of line:');
fprintf(fid, '');
fprintf(fid, 'From bus %3.0f to bus %3.0f is %6.5f\n',iL);
fprintf(fid, '*****');
fprintf(fid, '*****');

```

```

fprintf(fid, '*****\n');
fprintf(fid, ' Following lines are overloaded');
fprintf(fid, ' in this outage\n');
fprintf(fid, '*****\n');
fprintf(fid, '*****\n');
fprintf(fid, '*****\n');
fprintf(fid, ' From bus To bus');
fprintf(fid, ' Overload (pu)\n');
fprintf(fid, ' *****\n');
fprintf(fid, '*****');
for j = 2:size (iLCOLL,1);
fprintf(fid, '\n %6.0f %7.0f %18.5f\n',...
iLCOLL(j,:));
end
end
end
end

LAngle = Angle(size (Angle,1),1);
fprintf(fid, '\n*****\n');
fprintf(fid, '\n*****Bus data*****\n');
fprintf(fid, ' No. bus Voltage angle (Rad)\n');
fprintf(fid, '*****\n');
for i = 1:size (busd,1);
fprintf(fid, '\n %10.0f %27.5f \n',busd (i), LAngle(i,1));
end
fclose(fid);
fid = fopen('results1.txt', 'wt');
fprintf(fid, '-----\n');
fprintf(fid, '\n Added candidate lines are as follows:\n');
fprintf(fid, '-----\n');
fprintf(fid, ' From bus To bus\n');
fprintf(fid, ' -----\n');
fprintf(fid, '\n %8.0f %11.0f', Adline');
fprintf(fid, '\n\n*****\n');
fprintf(fid, '*****\n');
fprintf(fid, '\n Normal');
fprintf(fid, ' condition\n');
fprintf(fid, '*****\n');
fprintf(fid, '*****\n');
if(isempty(Noll) == 1)
fprintf(fid, 'No overloaded in normal condition\n');
else
NNOLL = Noll(size (Noll,1),1);
NL = size (linedata,1);
NS = length (find (Os~=0));
fprintf(fid, '\n Overload at normal');
fprintf(fid, 'Total overload of normal condition is');
fprintf(fid, '%3.5f pu\n', sum(NNOLL(:,4)));
fprintf(fid, '*****\n');
fprintf(fid, '*****\n');
fprintf(fid, '\n***** Candidate');
fprintf(fid, ' branches *****\n');
fprintf(fid, '*****\n');
fprintf(fid, '*****\n');
fprintf(fid, '\n From bus To bus Line flow');
fprintf(fid, ' (pu) Overload (pu)\n');

```

```

for i=1:NS
fprintf(fid, '\n %6.0f %10.0f %20.5f %20.5f\n', ...
NNOLL(i,:));
end
fprintf(fid, '*****');
fprintf(fid, '*****');
fprintf(fid, '\n***** Existing');
fprintf(fid, ' branches *****\n');
fprintf(fid, '*****\n');
fprintf(fid, '*****\n');
fprintf(fid, '\n From bus    To bus      Line flow');
fprintf(fid, '      (pu) Overload (pu)\n');
for i=1:NL
fprintf(fid, '\n %6.0f %10.0f %20.5f %20.5f\n',...
NNOLL(i,:));
end
fprintf(fid, '\n*****');
fprintf(fid, '*****');
fprintf(fid, '*****\n');
end
nco=size (Coll,1);
oc=Coll(nco,1);
nc=size (oc,1);
ocl=0;
for i=1:nc
occ=oc(i,1);
ocl=occ(1,1);
end
if ocl=0;
fprintf(fid, '\n No overload in N-1 condition\n');
fprintf(fid, '\n*****\n');
else
fprintf(fid, '\n*****');
fprintf(fid, '*****\n');
LCOLL=(size (Coll,1));
fprintf(fid, ' Overloaded lines in N-1');
fprintf(fid, ' condition');
for i=1: size (LCOLL,1)
iLCOLL=LCOLL(i,1);
iL=iLCOLL(1,:);
if iL(1,1)~=0
fprintf(fid, '\n*****');
fprintf(fid, '*****');
fprintf(fid, '*****\n');
fprintf(fid, ' Total overload for outage of line');
fprintf(fid, ': from bus');
fprintf(fid, ' %3.0f to bus %3.0f is%6.5f\n',iL);
fprintf(fid, '*****');
fprintf(fid, '*****');
fprintf(fid, '*****\n');
fprintf(fid, ' Following lines are overloaded in');
fprintf(fid, ' this outage\n');
fprintf(fid, '*****');
fprintf(fid, '*****');
fprintf(fid, '*****\n');
fprintf(fid, ' From bus      To bus');
fprintf(fid, ' Overload (pu)\n');

```

```

fprintf(fid, ' ***** ***** *****');
fprintf(fid, '*****');
for j=2:size (iLCOLL,1);
fprintf(fid, '\n %6.0f %7.0f %18.5f\n',...
iLCOLL(j,:));
end
end
end
end
LAngle=Angle(size (Angle,1),1);
fprintf(fid, '\n*****\n');
fprintf(fid, '\n*****Bus Data*****\n');
fprintf(fid, ' No. Bus Voltage Angle (Rad)\n');
fprintf(fid, '*****\n');
for i=1:size (busd,1);
fprintf(fid, '\n %10.0f %27.5f \n', busd(i), LAngle(i,1));
end
fclose(fid);
clc
type results1.txt
%delete results1.txt
%fopen(fid, '\n***** TNEP BY MACHESO MARTIN SIMIYU *****\n');

```

➤ HS function

```

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 = Candid(:,6);
    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

```

if nargin<1 || isempty(busdata)
    fprintf('Input argument "busdata" containing');
```



```

fprintf(' the information of existing lines. ');
error('"Linedata" is undefined. ');
end
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
end

```

➤ Backward search function

```

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 = Candid(:,6);
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
nc = size (find(Solution ~= 0),1);
%% Backward search algorithm %%
%% Initialization
diff = 1; SID = 0; j = 1;
ii = 0; jj = 0; kk = 0;
Noll = null(1); Coll = null(1);
OF=0;

```

```

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;
%% Updating corresponding line data and bus data according
% to the eliminated candidate line;
[Ybus, linedata, busdata, nIs, nbus, bus_number] ...
= ybus_calc(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;
%% Computing the total cost (TC) after eliminating
% each candidate line
Isoln = find(Solution1~=0);
[TC] = Total_Cost(Isoln, Solution1, Candid);
if Contingency == 1 & nIs == 0
[COL, CnIs, OLF] = contingency(linedata, busdata);
%% OOLF{i,1}: total overload in N-1 condition, in case of eliminating a
candidate
OOLF{i,1} = OLF;
else
COL = 0; CnIs = 0;
end
nline = size (linedata,1);
%% Formation of fitness function (OF: NEP Objective Function)
OF = TC+(10^18*((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
%% Adline: final set of selected candidate lines
% among all candidates
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
for i = 1:lb
removed_line(i,1) = Candid(best(i),2);
removed_line(i,2) = Candid(best(i),3);
removed_line(i,3) = (best(i,2)/10^7);
end
else
Adline = null(1);
end
end

```

### ➤ Forward search function

```

function[Os, Adline, Noll, Coll, Angle, Mof] = FS...
(busdata, linedata, Candid, linetype, Solution, ...
Contingency, Lg, Mof)
if nargin<8 || isempty(Mof)
Mof = 10^12; end
if nargin<7 || isempty(Lg)
Lg = 0;
Mof = 10^12;
end
if nargin<6 || isempty(Contingency)
Contingency = 0;
Lg = 0;
Mof =10^12;
end
if nargin<5 || isempty(Solution)
Solution = zeros(size(Candid,1),1);
Contingency = 0;
Lg = 0;
Mof = 10^12;
end
if nargin<4 || isempty(linetype)
fprintf('Input argument "linetype" containing the');
fprintf(' information of different types of lines.');
```

```

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));
diff = 1; j = 1; ii = 0; jj = 0;
kk = 0; Noll = null(1); Coll = null(1);
while diff >0 || j<=2^ncr
Solution1 = Solution;
%% Finding not selected candidate lines
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_calc (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;
%% Computing Total Cost (TC) for adding each candidate line
Isoln = find(Solution1~=0
[TC] = Total_Cost(Isoln,Solution1,Candid);
% Contingency=1; nIs=0;
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
%% Formation of fitness function
%% OF: NEP Objective Function
OF = (TC)+(10^9*((SOL)+COL))+(22*((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
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% added_line: final set of selected candidate lines
% among all candidates.
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
end

```

➤ DCLF function

```

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(:,7);
nbr = length(nl);
%% Computing net power of buses
Ps1 = (busdata(:,4)-busdata(:,3));
baseMva=100;
Mv=baseMva;
Pmax=(Smax/Mv);
%% Finding non-slack buses in the busdata matrix
code = busdata(:,2);
[aa] = find(code~=3);
%% Forming Network suceptance matrix (B)
for n = 1:length(aa+1)
for m = 1:length(aa+1)
Ymn = Ybus(aa(n),aa(m));
B(n,m) = -imag(Ymn);
end
Ps(n,1) = Ps1((aa(n)),1);
end
%% Computing voltage angle values of all buses
Binv = inv(B);
ang1 = Binv*Ps;
%% angle_r: volatge angle based on radian
angle_r = zeros(nbus,1);
for i=1: length(aa)
aaa = aa(i);
angle_r(aaa) = ang1(i);
end
%% angle_d: voltage angle based on degree
angle_d = angle_r*(180/pi);
%% Computing Power flow and overload of all lines
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))/Mv);
if abs(PF(i,3))>Pmax(i)
OL(i,3) = abs(PF(i,3));
OL(i,4) = abs(PF(i,3))-Pmax(i);
else
OL(i,3) = PF(i,3);
OL(i,4) = 0;
end
end
%% Computing total overload of the network
SOL = sum(OL(:,4));
end

```

### ➤ Contingency function

```

function[COL, Cnis, OLD] = contingency(linedata, busdata)
if isempty(busdata)
fprintf('Input argument "busdata" containing the');

```

```

fprintf(' information of buses. ');
error('"busdata" is undefined. ');
end
if isempty(linedata)
fprintf('Input argument "linedata" containing the ');
fprintf(' information of lines. ');
error('"linedata" is undefined. ');
end
Cnis = 0;
COL = 0;
for i = 1:size (linedata, 1)
%% Updating linedata after outage of each line
esl = setxor (linedata (:,1), i); % Exsiting lines
ulinedata = linedata; ulinedata(i,4) = 10^10;
ulinedata(i,5) = 10^10; ULD = ulinedata;
ulinedata1 = linedata (42,:); ULD1 = ulinedata1;
%% Computing number of islands in each contingency
nl = ULD1(:,2); nr = ULD1(:,3);
%% Exsiting buses:
nbs = intersect (busdata (:,1), union(nl,nr));
Is = setxor(nbs,busdata (:,1)); % Islanded buses
UBD = busdata;
nbus = size(busdata,1);
Cnis = Cnis+length(Is); % Number of islands
%% Computing Ybus for updated bus data (UBD) and updated
% line data (ULD) for each contingency
[Ybus]= ybus_calc(UBD, ULD, [], [], [], []);
%% Running dc power flow for UBD and ULD
[angle_r,angle_d, PF, OL, SOL]= dcpf(UBD, ULD, Ybus);
%% Computing overload and power flow data of all lines
% in each contingency (each iteration)
COL=COL+SOL;
OL(:,3)=[];
idOL= OL(:,3)~=0;
OLF=OL(idOL,:); IOL(1,1)=linedata(i,2);
IOL(1,2)=linedata(i,3); IOL(1,3)=SOL;
for j=2:size(OLF,1)+1
IOL(j,:)=OLF(j-1,:);
end
OLD{i,1}=IOL;
%clear IOL
end

```

➤ Ybuscalculation function

```

function[Ybus, linedata, busdata, nIs, nbus, bus_number]...
= ybus_calc(busdata, linedata, Solution, ...
Candidateline, linetype, Lg)
if isempty(Lg), Lg = 0;end
if isempty(linedata)
fprintf('Input argument "Linedata" containing the ');
fprintf(' information of network lines. ');
error('"Linedata" is undefined. ');
end
if isempty(busdata)

```

```

fprintf('Input argument "Busdata" containing the');
fprintf(' information of network buses.');
```

error('"Busdata" is undefined.');

```

end
Bd = busdata;
Ld = linedata;
Sol = Solution;
Cl = Candidateline;
Lt = linetype;
%% Finding suggested solutions %%
Iz = find (Solution~=0);
nIz = length(Iz);
nline = size (linedata,1);
for i = 1:nIz
can(1,1) = size (linedata,1)+i; can(1,2) = Cl(Iz(i),2);
can(1,3) = Cl(Iz(i),3);
%candid(1,4)=(Lt((Cl(Iz(i),4)),2)*Cl(Iz(i),5))/...
% (Cl(Iz(i),6));
can(1,4) = 0;
can(1,5) = (Lt((Cl(Iz(i),3)),1)*Cl(Iz(i),5))/...
(Cl(Iz(i),6));
can(1,6) = (Lt((Cl(Iz(i),3)),1))*(Cl(Iz(i),6));
can(1,7) = Cl(Iz(i),7);
can(1,8) = Cl(Iz(i),8);
can(1,9) = Cl(Iz(i),9);
can(1,1:9)
Ld(nline+i,:) = can(1,:);
end
linedata = Ld;
exl = size (linedata,1);
%% Islanding detection and updating bus data
busnumber = Bd(:,1);
nl = Ld(:,2);
nr = Ld(:,3);
nlr = union(nl,nr);
%Is = setdiff (nlr, busnumber);
Is = setxor(nlr,busnumber);
bus_number = setxor(busnumber,Is);
nbus = length(bus_number);
nIs = length (Is);
for i = 1:nbus
busdata (i,:) = Bd(bus_number(i),:);
end
busdata(:,4) = busdata(:,4).*(1+Lg); busdata(:,5) = ...
busdata(:,5).*(1+Lg);
j = sqrt(-1);
i = sqrt(-1);
X = Ld(:,5);
nbr = length(Ld(:,1));
Z = (j*X);
y = ones(nbr,1)./Z; % Branch admittance
Ybus = zeros(nbus,nbus); % Initialize Ybus to zero
%% Formation of the off diagonal elements
for k = 1:nbr;
Ybus(nl(k),nr(k)) = Ybus(nl(k),nr(k))-y(k);
Ybus(nr(k),nl(k)) = Ybus(nl(k),nr(k));
end

```



```
%% Formation of the diagonal elements
for n = 1 : nbus
for m = (n+1) : nbus
Ybus(n,n) = Ybus(n,n) - Ybus(n,m);
end
for m = 1 : (n-1)
Ybus(n,n) = Ybus(n,n) - Ybus(n,m);
end
end
end
```

## DCLF CODES

### ➤ DCLF script

```
clear
clc
num=30;
busd = busdata;
Linedata = linedata;
Lg = null(1,1);
[Angle_r,Angle_d, Pf, Ol, Sol] = PFDC(busd, linedata, Lg);
[Col, Old] = contingent(busd, linedata, Lg);
fid = fopen('results.txt', 'wt');
fprintf(fid, '*****');
fprintf(fid, '*****');
fprintf(fid, '\n Normal');
fprintf(fid, ' condition\n');
fprintf(fid, '*****');
fprintf(fid, '*****\n');
fprintf(fid, '\n*****Bus data*****\n');
fprintf(fid, ' No. bus Voltage angle (Rad)\n');
fprintf(fid, '***** \n');
for i = 1:size (busd,1);
fprintf(fid, ' %10.0f %27.5f \n', ...
busd(i), Angle_r(i,1));
end
if Sol == 0
fprintf(fid, '\n No overload in normal condition\n');
else
NL = size (linedata,1);
fprintf(fid, '\n Overload at normal:');
fprintf(fid, '\n Total overload of normal condition is');
fprintf(fid, ' %3.5f pu\n',Sol);
fprintf(fid, '*****');
fprintf(fid, '*****');
fprintf(fid, '\n***** Power flow and overload');
fprintf(fid, ' values of branches *****\n');
fprintf(fid, '*****');
fprintf(fid, '*****\n');
fprintf(fid, '\n From bus To bus Circuit ID ');
fprintf(fid, ' Line flow (pu) Overload (pu)\n');
for i = 1 : NL
fprintf(fid, '\n %1.0f %14.0f %15.0f %20.5f %20.5f\n'...
, Ol(i,:));
end
end
fprintf(fid, '\n\n*****');
fprintf(fid, '*****');
fprintf(fid, '*****');
fprintf(fid, '\n N-1 condition\n');
fprintf(fid, '*****');
fprintf(fid, '*****');
if(Col == 0)
fprintf(fid, '\n No overload in N-1 condition\n');
fprintf(fid, '\n*****\n');
else
fprintf(fid, '\n*****');
end
```

```

fprintf(fid, '*****');
fprintf(fid, '*****\n');
LCOL=Old{size (Col,1),1};
fprintf(fid, ' Overload values of ');
fprintf(fid, 'branches in N-1 condition');
for i = 1 : size (Old,1)
iOLD = Old{i,1};
iL = iOLD(1,:);
fprintf(fid, '\n*****');
fprintf(fid, '*****');
fprintf(fid, '*****\n');
fprintf(fid, ' Total overload for outage of line: ');
fprintf(fid, '');
fprintf(fid, 'From bus %3.0f to bus %3.0f and', iL(1:2));
fprintf(fid, ' circuit ID %3.0f is %6.5f pu\n', iL(3:4));
fprintf(fid, '*****');
fprintf(fid, '*****');
fprintf(fid, '*****\n');
fprintf(fid, ' following lines are overloaded in');
fprintf(fid, ' this outage\n');
fprintf(fid, '*****');
fprintf(fid, '*****');
fprintf(fid, '*****\n');
fprintf(fid, ' From Bus To Bus  Circuit ID  ');
fprintf(fid, 'Overload (pu)\n');
fprintf(fid, ' *****  *****  *****  ');
fprintf(fid, '*****');
for j = 2 : size (iOLD,1);
fprintf(fid, '\n %5.0f %10.0f %8.0f %18.5f\n', ...
iOLD(j,:));
end
end
end
fclose(fid);
%% Print in the command window
fprintf('*****');
fprintf('*****');
fprintf('\n Normal condition\n');
fprintf('*****');
fprintf('*****\n');
fprintf('\n*****Bus data*****\n');
fprintf(' No. bus  Voltage angle (Rad)\n');
fprintf('*****\n');
for i = 1 : size (busd,1);
fprintf(' %10.0f %27.5f \n', busd(i), Angle_r(i,1));
end
if Sol == 0
fprintf('\n No overload in normal Condition\n');
else
NL = size (linedata,1);
fprintf('\n overload at Normal:');
fprintf('\n Total overload of normal condition is ');
fprintf('%3.5f pu\n', Sol);
fprintf('*****');
fprintf('*****');
fprintf('\n***** Power flow and overload ');
fprintf('values of branches *****\n');

```

```

fprintf('*****');
fprintf('*****\n');
fprintf('\n From bus  To bus  Circuit ID ');
fprintf(' Line flow (pu) Overload (pu)\n');
for i = 1 : NL
fprintf('\n %6.0f %12.0f %14.0f %16.5f %19.5f\n',...
Ol(i,:));
end
end
fprintf('\n\n*****');
fprintf('*****');
fprintf('\n N-1 condition\n');
fprintf('*****');
fprintf('*****\n');
if(Col == 0)
fprintf('\n No overload in N-1 condition\n');
fprintf('\n*****\n');
else
fprintf('\n*****');
fprintf('*****\n');
LCOL=Old{size (Col,1),1};
fprintf(' Overload values of branches in');
fprintf(' N-1 condition');
for i = 1 : size (Old,1)
iOLD = Old{i,1};
iL = iOLD(1,:);
fprintf('\n*****');
fprintf('*****');
fprintf('*****\n');
fprintf(' Total overload for outage of line: from ');
fprintf('bus %3.0f to bus %3.0f and ',iL(1:2));
fprintf('circuit ID %3.0f is %6.5f pu\n',iL(3:4));
fprintf('*****');
fprintf('*****');
fprintf('*****\n');
fprintf(' Following lines are overloaded ');
fprintf('in this outage\n');
fprintf('*****');
fprintf('*****');
fprintf('*****\n');
fprintf(' From Bus To Bus Circuit ID ');
fprintf('Overload (pu)\n');
fprintf(' ***** ***** ***** ');
fprintf('*****');
for j = 2 : size (iOLD,1);
fprintf('\n %5.0f %10.0f %8.0f %18.5f\n',...
iOLD(j,:));
end
end
end

```

➤ Contingency function

```
function[Col, Old] = contingent(busdata, linedata, Lg)
if nargin<3 || isempty(Lg), Lg = 0;end
Col = 0;
for i = 1:size (linedata, 1)
    %% Updating Linedata after outage of each branch
    esl = setxor (linedata (:,1), i); %Exsiting branchs
    ulinedata = linedata; ulinedata(i,4) = 10^10;
    ulinedata(i,5) = 10^10; ULD = ulinedata;
    ulinedata1 = linedata(esl,:); ULD1 = ulinedata1;
    UBD = busdata; nbus = size(busdata,1);
    [angle_r,angle_d, PF, OL, SOL] = PFDC(UBD, ULD, Lg);
    Col = Col+SOL;
    OL(:,4) = [];
    idOL = find(OL(:,4) ~= 0);
    OLF = OL(idOL,:);
    IOL(1,1) = linedata(i,2); IOL(1,2) = linedata(i,3);
    IOL(1,3) = linedata(i,7); IOL(1,4) = SOL;
    for j = 2:size(OLF,1)+1
        IOL(j,:) = OLF(j-1,:);
    end
    Old{i,1} = IOL;
    clear IOL
end
```

➤ PFDC function

```
function [Angle_r,Angle_d, Pf, Ol, Sol] = ...
PFDC(busdata, linedata, Lg)
if nargin<3 || isempty(Lg), Lg = 0;end
Busname=busdata(:,1);
nbus = length(Busname);
Busnumber = 1:nbus;
NL = linedata(:,2);
NR = linedata(:,3);
save namedata Busname Busnumber NL NR
for i = 1:length(NL)
    for j = 1:length(Busnumber);
        if NL(i) == Busname(j)
            nnl(i) = Busnumber(j);
        end
        if NR(i) == Busname(j)
            nnr(i) = Busnumber(j);
        end
    end
end
LD = linedata; LD(:,2) = nnl; LD(:,3) = nnr';
BD = busdata; BD(:,1) = Busnumber;
[Ybus, linedata, busdata] = Ybuscal(BD, LD, Lg);
nbus = size (busdata,1);
nl = linedata(:,2);
nr = linedata(:,3);
```

```

Smax = linedata(:,7);
nbr = length(nl);
Ps1 = (busdata(:,4)-busdata(:,3));
baseMva=100;
Mv=baseMva;
Pmax=(Smax/Mv);
%% Finding non-slack buses in the busdata matrix
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);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%end
%% Calculation Power flow and over load values
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) = linedata(i,7); Ol(i,3)=linedata(i,7);
Pf(i,4) = ((Angle_r(nl(i))-Angle_r(nr(i)))/...
(linedata(i,5))/Mv);
if abs(Pf(i,4))>Pmax(i)
Ol(i,4) = Pf(i,4);
Ol(i,5) = abs(Pf(i,4))-Pmax(i);
else
Ol(i,4) = Pf(i,4);
Ol(i,5) = 0;
end
end
end
Sol = sum(Ol(:,5));
end

```

➤ Ybuscal function

```
function[Ybus, linedata, busdata] = ...
Ybuscal(busdata, linedata, Lg)
if nargin<3 || isempty(Lg), Lg = 0;end
%%
busdata(:,4) = busdata(:,4).*(1+Lg);
busdata(:,5) = busdata(:,5).*(1+Lg);
%% Computation of admittance of all branches
j = sqrt(-1);
i = sqrt(-1);
X = linedata(:,5);
nbr = length(linedata(:,1));
nbus = size (busdata,1);
nl = linedata(:,2); nr = linedata(:,3);
Z = (j*X);
y = ones(nbr,1)./Z; % Branch admittance
Ybus = zeros(nbus,nbus); % Initialize Ybus to zero
%% Formation of the off diagonal elements
for k = 1 : nbr;
Ybus(nl(k),nr(k)) = Ybus(nl(k),nr(k))-y(k);
Ybus(nr(k),nl(k)) = Ybus(nl(k),nr(k));
end
%% Formation of the diagonal elements
for n = 1 : nbus
for m = (n+1) : nbus
Ybus(n,n) = Ybus(n,n)-Ybus(n,m);
end
for m = 1 : n-1
Ybus(n,n) = Ybus(n,n)-Ybus(n,m);
end
end
```