CONTINGENCY ANALYSIS IN POWER SYSTEM: Thesis of Master of Engineering in Power Systems & Electric Drives, Thapar University, Patiala.

Thesis · July 2011

DOI: 10.13140/RG.2.1.4481.4240

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CONTINGENCY ANALYSIS IN POWER SYSTEM

Thesis submitted in partial fulfillment of the requirements for the award of the degree of

Master of Engineering
in
Power Systems & Electric Drives

Thapar University, Patiala

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JULY 2011

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CERTIFICATE

I hereby declare that the work which is being presented in the Thesis entitled **"CONTINGENCY ANALYSIS IN POWER SYSTEM"**, in partial fulfilment of requirement for the award of degree of Master of Engineering in ***Power Systems & Electric Drives*** submitted in the Electrical & Instrumentation Engineering Department of Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of **Dr. Sanjay K. Jain**, Associate Prof., EIED.

The matter presented in this Thesis has not been submitted for the award of any other degree of this or any other university.

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ACKNOWLEDGEMENT

I would like to thank **Dr. Sanjay K. Jain, Associate. Prof., EIED** for the opportunity to work with him, for his invaluable guidance, encouragement, suggestions and untiring support. He has been an advisor in true sense both academically and morally though out this thesis work.

I am highly grateful to Thapar University, Patiala for providing all the necessary infrastructure to complete my M.E. Thesis work.

I extend my sincere thanks to **Dr. S. Ghosh, Professor & Head, EIED** and to **Dr. Yaduvir Singh**, **Associate. Prof., EIED** for their continuous inspiration during this thesis work.

I am also thankful to all other faculty members of EIED, Thapar University, Patiala for their intellectual support. Special thanks to my family members especially to my parents and friends whose uninterrupted love, inspiration and blessings helped me to complete my thesis study.

I thank and owe my deepest regards to all who have helped me directly or indirectly.

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ABSTRACT

Maintaining power system security is one of the challenging tasks for the power system engineers. The security assessment is an essential task as it gives the knowledge about the system state in the event of a contingency. Contingency analysis technique is being widely used to predict the effect of outages like failures of equipment, transmission line etc, and to take necessary actions to keep the power system secure and reliable. The off line analysis to predict the effect of individual contingency is a tedious task as a power system contains large number of components. Practically, only selected contingencies will lead to severe conditions in power system. The process of identifying these severe contingencies is referred as contingency selection and this can be done by calculating performance indices for each contingencies.

The main motivation of the work is to carry out the contingency selection by calculating the two kinds of performance indices; active performance index (PI_P) and reactive power performance index (PI_V) for single transmission line outage. With the help of Fast Decoupled Load Flow (FDLF), the PI_P and PI_V have been calculated in MATLAB environment and contingency ranking is made. Further the contingency selection has been done by using Radial Basis Function (RBF) Neural Network. This provides an effective mean to rank the contingencies for various loading and generation levels in a power system. The effectiveness of the method has been tested on 5-Bus, IEEE-14 Bus and IEEE-30 Bus test systems.

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CHAPTER-1

INTRODUCTION

1.1 OVERVIEW

It is well known that power system is a complex network consisting of numerous equipments like generators, transformers, transmission lines, circuit breakers etc. Failure of any of these equipments during its operation harms the reliability of the system and hence leading to outages. Thus one of the major agenda of power system planning and its operation is to study the effect of outages in terms of its severity. Installation of redundant generation capacity or transmission lines is essential in order to make the system run even when any of its components fails. But, power system being dynamic in nature does not guarantee that it will be 100 % reliable. Further, such arrangement may not be cost effective. Hence, a detailed security assessment is essential to deal with the possible failures in the system, its consequences and its remedial actions. This assessment is known as Power system security assessment.

Power system security involves system monitoring where the real time parameters of the system are monitored by using the telemetry systems or by the SCADA systems. It then involves the most important function of contingency analysis where the simulation is being carried out on the list of “credible” outage cases so as to give the operators an indication of what might happen to the power system in an event of unscheduled equipment outage. This analysis forewarns the system operator, and allows deciding some remedial action before the outage event.

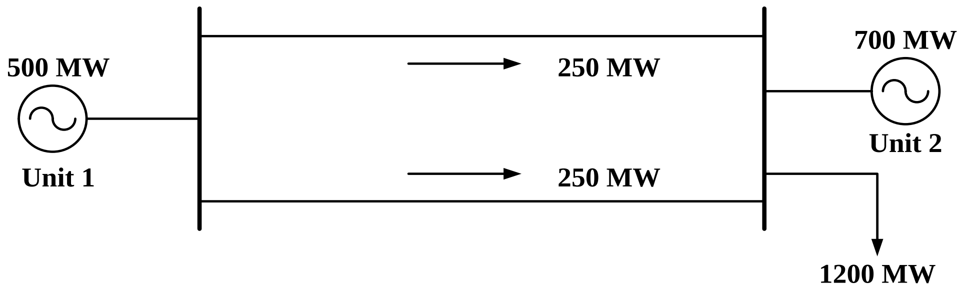
For a power system to be secure, it must have continuity in supply without a loss of load. For this security analysis is performed to develop various control strategies to guarantee the avoidance and survival of emergency conditions and to operate the system at lowest cost. Whenever the pre specified operating limits of the power system gets violated the system is said to be in emergency condition. These violations of the limits result from contingencies occurring in the system. Thus, an important part of the security analysis revolves around the power system to withstand the effect of contingencies. The system security assessment process is carried out by calculating system operating limits in the pre- contingency and post contingency operating states at an operation control centre or at the Energy Management System (EMS) of the utility company. The contingency analysis is time consuming as it involves the computation of complete AC load flow calculations following every possible outage events like outages occurring at various generators and transmission lines. This makes the list of various contingency cases very lengthy and the process very tedious. In order to mitigate the above problem, automatic contingency screening approach is being adopted which identifies and ranks only those outages which actually causes the limit violation on power flow or voltages in the lines. The contingencies are screened according to the severity index or performance index where a higher value of these indices denotes a higher degree of severity.

1.1.1 STATES IN SECURITY ANALYSIS

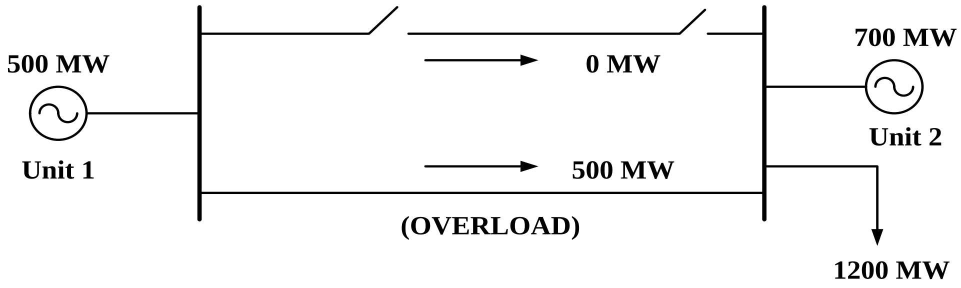
Security analysis involves the power system to operate into four operating states [1]:

- **Optimal dispatch:** In this state the power system is in prior to any contingency. It is optimal with respect to economic operation, but it may not be secure.
- **Post contingency:** It is the state of the power system after a contingency has occurred, it is being assumed that this condition has a security violation such as line or transformer are beyond its flow limit, or a bus voltage is outside the limit.
- **Secure dispatch:** It is the state of the system with no contingency, but with corrections to the operating parameters to account for security violations.
- **Secure post-contingency:** This is the state where the contingency is applied to the base operating condition with corrections.

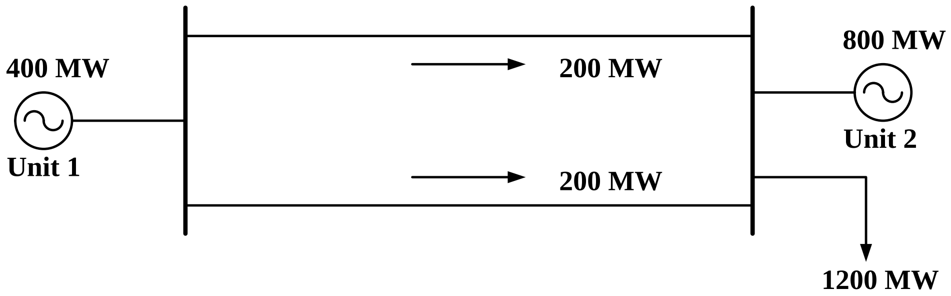
The concept of security analysis has been illustrated with a following example. Suppose a power system consisting of two generators, a load, and a double circuit line, is to be operated with both generators supplying the load as shown in Fig. 1.1(a) and ignoring the losses it is assumed that the system as shown is in economic dispatch i.e. 500 MW is allotted for unit 1 and the 700 MW for unit 2 as the optimum dispatch. Further, it is asserted that each circuit of the double circuit line can carry a maximum of 400 MW, so that there is no loading problem in the base-operating condition. This condition is being referred to as the optimal dispatch.



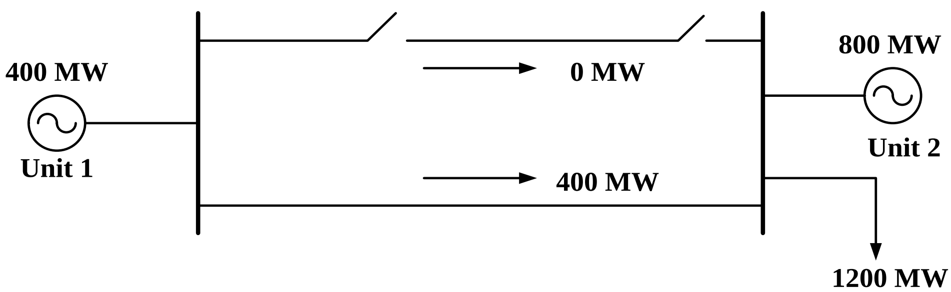
(a) Optimal Dispatch



(b) Post Contingency State



(c) Secure Dispatch



(d) Secure Post Contingency State

Fig. 1.1 Various operating states of Power System

Now, a failure in one of the two transmission lines has been postulated and it can be said that a line contingency has occurred and this results in change in power flows in the other line causing the transmission line limit to get violated. The resulting flows have been shown Fig. 1.1(b), this sate of power system is being said to be post contingency state.

Now there is an overload on the remaining circuit. If the above condition is to be avoided, the following security corrections have been done. The generation of unit 1 has been lowered from 500 MW to 400 MW and the generation of unit 2 is raised from 700 MW to 800 MW. This secure dispatch is illustrated in Fig. 1.1(c). Now, if the same contingency analysis is to done, the post-contingency condition power flows is illustrated in Fig. 1.1(d)

Thus by adjusting the generation on unit 1 and unit 2, the overloading in other line is prevented and thus the power system remains secure. These adjustments are called “security corrections.” Programs which can make control adjustments to the base or pre-contingency operation to prevent violations in the post-contingency conditions are called “security-constrained optimal power flows”. These programs can take account of many contingencies and calculate adjustments to generator MW, generator voltages, transformer taps etc. Together with the function of system monitoring, contingency analysis and the corrective actions the analysis procedure forms a set of complex tools that can lead to the secure operation of a power system.

1.2 LITERATURE REVIEW

The importance of power system security assessment for prediction of line flows and bus voltages following a contingency has been presented in [1-2]. The paper also summarized the challenges faced for the practical implementation of security analysis algorithms. The approximate changes in the line flow due to an outage in generator or transmission line is predicted based on distribution factors [3-4]. The use of AC power flow solution in outage studies has been dealt in [5].

Contingency screening or contingency selection is an essential task in contingency analysis. This helps to reduce the numerous computations, the bounding method [6] reduces the number of branch flow computation by using a bounding criterion that helps in reducing the number of buses for analysis and is based on incremental angle criterion. The 1P-1Q method for contingency selection has been presented in [7]. In this method the solution procedure is interrupted after an iteration of fast decoupled load flow. Zaborzky *et* *al.* introduced the concentric relaxation method for contingency evaluation [8] utilizing the benefit of the fact that an outage occurring on the power system has a limited geographical effect. The use of fast decoupled load flow [9] proves to be very suitable for contingency analysis. Contingency selection criterion based on the calculation of performance indices has been first introduced by Ejebe and Wollenberg [10] where the contingencies are sorted in descending order of the values of performance index (PI) reflecting their severity.

The potential of Artificial Neural networks for non linear adaptive filtering and control, its ability to predict solutions from the past trends, its enormous data processing capability and its ability to provide fast response in mapping data makes them as a very promising tool for its application to power systems [11]. The first work towards the power system security analysis by pattern recognition technique has been reported by Pang *et al.* [12]. The Artificial Neural Network has been used for various power system applications such as load forecasting [13], transient stability analysis [14]. The potential of ANN for static assessment further improved with the introduction of powerful computers [15-16].

The learning ability of Multi Layer Perceptron with error back propagation algorithm has been used by researchers various problems [17, 20]. The application of ANN for determining the voltage stability margin under contingency situation has been discussed in [18-19]. The learning of the network has been done using error back propagation algorithm for minimising the error function and for determining the weights. A review from [20] illustrates the types of neural networks that have been used by various researchers for static security assessment in power systems. Power system security assessment has been performed using Kohenen neural network [21] where the securities regions have been identified using a self organizing feature map and learns in an unsupervised process. Combined use of supervised and unsupervised learning for power system security assessment [22], has been used to overcome the slow rate of convergence and local minima problem faced in multilayer perceptron neural network using back propagation training. A counter propagation network employing a combination of Kohenen self organising map and a supervised Grossberg outstar layer, which is doing the correct mapping of input and reducing the dimensionality of input pattern by having feature selection technique have been studied in [23]. The counter propagation network presented in [23] is employed [24] to identify the coherency existing between load buses. The Fast Fourier Transform (FFT) as a pre processing tool for the ANN inputs has been studied in [25], to speed up the ANN training and performance. The use of Hopfield neural network for contingency analysis has been shown in [26].

The use of Radial Basis Function (RBF) neural network for function approximation proves to be highly efficient, as it employs a hybrid two stage learning scheme. The RBF neural networks have several advantages like fast training, structural simplicity and no local minima problem [27-28]. The non linear mapping capability of the RBF network for estimating the line loading and bus voltage following a contingency in bulk power systems has been done in [29]. Chicco *et al.* [30] presented a detailed comparison for estimating the performance of self organising network, progressive learning network and RBF. The author [31] suggested the parallel operation of RBF neural network for contingency analysis to yield fast training and higher accuracy.

Contingency analysis problem has been solved by using fuzzy logic in [32]. The post contingency cases have been first studied using fast decoupled load flow. These quantities have been assigned a degree of severity. Fuzzy logic is applied to contingency selection problem in [33] for voltage ranking where the post contingent voltages are used to rank the contingencies. The application of Genetic algorithm for contingency ranking has been studied in [34] where the problem of contingency ranking problem is formulated as an optimization problem with an objective of finding the critical cases, this approach reduces the computational burden for contingency analysis. The authors [35] attempted post voltage calculations for a transmission line and transformer outages using Genetic algorithm.

1.3 OBJECTIVE OF THE WORK

The objective of the present work is selection of power system contingencies by calculating the performance indices for transmission line outages using the Fast decoupled load flow analysis and radial basis function (RBF) neural network. The objective is also to compare the performance of the method employing RBF and FDLF for various power system networks.

1.4 ORGANIZATION OF THESIS

The work carried out in this thesis has been summarized in four chapters, **Chapter 1** deliberates on the overview of the problem, brief literature review, objectives of work and organization of the thesis. **Chapter 2** discusses the various methods for contingency analysis, the contingency selection by calculating the active and reactive power performance indices using the Fast decoupled load flow and the results for various systems. In **Chapter 3** the contingency analysis has been modelled using Radial basis function neural network and corresponding results for various test bus systems. The conclusions and the scope of further work are detailed in **Chapter 4**.

CHAPTER-2

CONTINGENCY ANALYSIS USING LOAD FLOW SOLUTION

2.1 INTRODUCTION

During a transmission line contingency both the active power flow limit and the reactive power limit which in particular affects the bus voltage gets altered, hence it is essential to predict these power flow and the bus voltages following a contingency. This chapter mainly discusses on the various methods of modelling contingency analysis. The contingency analysis by the use of sensitivity factors has been discussed. Further the use of AC power flow for contingency analysis has been presented in detail. The algorithm for contingency analysis using Fast Decoupled Load Flow has been developed with the main focus on performing the contingency selection for line contingencies for various test bus systems have been discussed thoroughly.

2.2 MODELLING CONTINGENCY ANALYSIS

Since contingency analysis involves the simulation of each contingency on the base case model of the power system, three major difficulties are involved in this analysis. First is the difficulty to develop the appropriate power system model. Second is the choice of which contingency case to consider and third is the difficulty in computing the power flow and bus voltages which leads to enormous time consumption in the Energy Management System.

It is therefore apt to separate the on-line contingency analysis into three different stages namely contingency definition, selection and evaluation. Contingency definition comprises of the set of possible contingencies that might occur in a power system, it involves the process of creating the contingency list. Contingency selection is a process of identifying the most severe contingencies from the contingency list that leads to limit violations in the power flow and bus voltage magnitude, thus this process eliminates the least severe contingencies and shortens the contingency list. It uses some sort of index calculations which indicates the severity of contingencies. On the basis of the results of these index calculations the contingency cases are ranked. Contingency evaluation is then done which involves the necessary security actions or necessary control to function in order to mitigate the effect of contingency.

2.2.1Contingency Analysis using Sensitivity Factors

The problem of studying thousands of possible outages becomes very difficult to solve if it is desired to present the results quickly. One of the easiest ways to provide a quick calculation of possible overloads is to use sensitivity factors [1]. These factors show the approximate change in line flows for changes in generation on the network configuration and are derived from the DC load flow**.** These factors can be derived in a variety of ways and basically come down to two types:

- **Generation Shift Factors** [1]
- **Line Outage Distribution Factors** [1]

The **generation shift factors** are designated a_{li} and have the following definition:

$$a_{li} = \frac{\Delta f_l}{\Delta P_i} \tag{2.1}$$

where

l= line index

i=bus index

Δf_l = change in megawatt power flow on line l when a change in generation ΔP_i occurs at bus i

ΔP_i = change in generation at bus i

It is assumed that the change in generation ΔP_i is exactly compensated by an opposite change in generation at the reference bus, and that all other generators remain fixed. The a_{li} factor then represents the sensitivity of the flow on line l due to a change in generation at bus i. If the generator was generating P_i^o MW and it was lost, it is represented by ΔP_i, as the new

$$\Delta P_i = - P_i^o \tag{2.2}$$

power flow on each line in the network could be calculated using a pre calculated set of ***"a"*** factors as follows:

$$f_l = f_l^0 + a_{li} \Delta P_i \text{ for } l = 1 \ldots L \tag{2.3}$$

where,

f_l = flow on line l after the generator on bus i fails

f_l^0 = flow before the failure

The outage flow f_l on each line can be compared to its limit and those exceeding their limit are flagged for alarming. This would tell the operations personal that the loss of the generator on bus *i* would result in an overload on line *l.* The generation shift sensitivity factors are linear estimates of the change in flow with a change in power at a bus. Therefore, the effects of simultaneous changes on several generating buses can be calculated using superposition.

The **line outage distribution factors** are used in a similar manner, only they apply to the testing for overloads when transmission circuits are lost. By definition, the line outage distribution factor has the following meaning:

$$d_{l,k} = \frac{\Delta f_l}{f_k^0} \tag{2.4}$$

where

$d_{l,k}$ = line outage distribution factor when monitoring line *l* after an outage on line *k*

Δf_l = change in MW flow on line *l*

f_k^0 = original flow on line *k* before it was outaged i.e., opened

If one knows the power on line *l* and line ***k*,** the flow on line *l* with line *k* out can be determined using ***"d"*** factors.

$$f_l = f_l^0 + d_{l,k} f_k^0 \tag{2.5}$$

where

f_l^0 and f_k^0= pre outage flows on lines *l* and *k*, respectively

f_l = flow on line *l* with line *k* out

By pre calculating the line outage distribution factors, a very fast procedure can be set up to test all lines in the network for overload for the outage of a particular line. Furthermore, this procedure can be repeated for the outage of each line in turn, with overloads reported to the operations personnel in the form of alarm messages. The generator and line outage procedures can be used to program a digital computer to execute a contingency analysis study of the power system. It is to be noted that a line flow can be positive or negative so that we must check f_l against $-f_l^{max}$ as well as f_l^{max}. It is assumed that the generator output for each of the generators in the system is available and that the line flow for each transmission line in the network is also available and the sensitivity factors have been calculated and stored.

2.2.2 Contingency Analysis using AC Power Flow

The calculations made with the help of network sensitivity factors for contingency analysis are faster, but there are many power systems where voltage magnitudes are the critical factor in assessing contingencies. The method gives rapid analysis of the MW flows in the system, but cannot give information about MVAR flows and bus voltages. In systems where VAR flows predominate, such as underground cables, an analysis of only the MW flows will not be adequate to indicate overloads. Hence the method of contingency analysis using AC power flow is preferred as it gives the information about MVAR flows and bus voltages in the system. When AC power flow is to be used to study each contingency case, the speed of solution for estimating the MW and MVAR flows for the contingency cases are important, if the solution of post contingency state comes late, the purpose of contingency analysis fails. The method using AC power flow will determine the overloads and voltage limit violations accurately. It does suffer a drawback, that the time such a program takes to execute might be too long. If the list of outages has several thousand entries, then the total time to test for all of the outages can be too long. However, the AC power flow program for contingency analysis by the Fast Decoupled Power Flow (FDLF) [9] provides a fast solution to the contingency analysis since it has the advantage of matrix alteration formula that can be incorporated and can be used to simulate the problem of contingencies involving transmission line outages without re inverting the system Jacobian matrix for all iterations. Hence to model the contingency analysis problem the AC power flow method, using FDLF method has been extensively chosen.

2.3 CONTINGENCY SELECTION

Since contingency analysis process involves the prediction of the effect of individual contingency cases, the above process becomes very tedious and time consuming when the power system network is large. In order to alleviate the above problem contingency screening or contingency selection process is used. Practically it is found that all the possible outages does not cause the overloads or under voltage in the other power system equipments. The process of identifying the contingencies that actually leads to the violation of the operational limits is known as contingency selection. The contingencies are selected by calculating a kind of severity indices known as Performance

Indices (PI) [1]. These indices are calculated using the conventional power flow algorithms for individual contingencies in an off line mode. Based on the values obtained the contingencies are ranked in a manner where the highest value of PI is ranked first. The analysis is then done starting from the contingency that is ranked one and is continued till no severe contingencies are found.

There are two kind of performance index which are of great use, these are **active power performance index (PI_P)** and **reactive power performance index (PI_V)**. PI_P reflects the violation of line active power flow and is given by eq.2.6.

$$PI_P = \sum_{i=1}^{L} \left(\frac{P_i}{P_{imax}}\right)^{2n} \qquad (2.6)$$

where,

P_i = Active Power flow in line *i*,

P_i^{max} = Maximum active power flow in line *i*,

n is the specified exponent,

L is the total number of transmission lines in the system.

If *n* is a large number, the PI will be a small number if all flows are within limit, and it will be large if one or more lines are overloaded. Here the value of n has been kept unity. The value of maximum power flow in each line is calculated using the formula

$$P_i^{max} = \frac{V_i * V_j}{X} \qquad (2.7)$$

where, V_i= Voltage at bus i obtained from FDLF solution

V_j= Voltage at bus j obtained from FDLF solution

X = Reactance of the line connecting bus ‘i’ and bus ‘j’

Another performance index parameter which is used is reactive power performance index corresponding to bus voltage magnitude violations. It mathematically given by eq.2.8

$$PI_V = \sum_{i=1}^{Npq} \left[\frac{2(Vi - Vinom)}{Vimax - Vimin}\right]^2 \qquad (2.8)$$

where, V_i= Voltage of bus i

V_{imax} and V_{imin} are maximum and minimum voltage limits

V_{inom} is average of V_{imax} and V_{imin}

N_{pq} is total number of load buses in the system

A flow chart for contingency selection technique is shown in Fig. 2.1

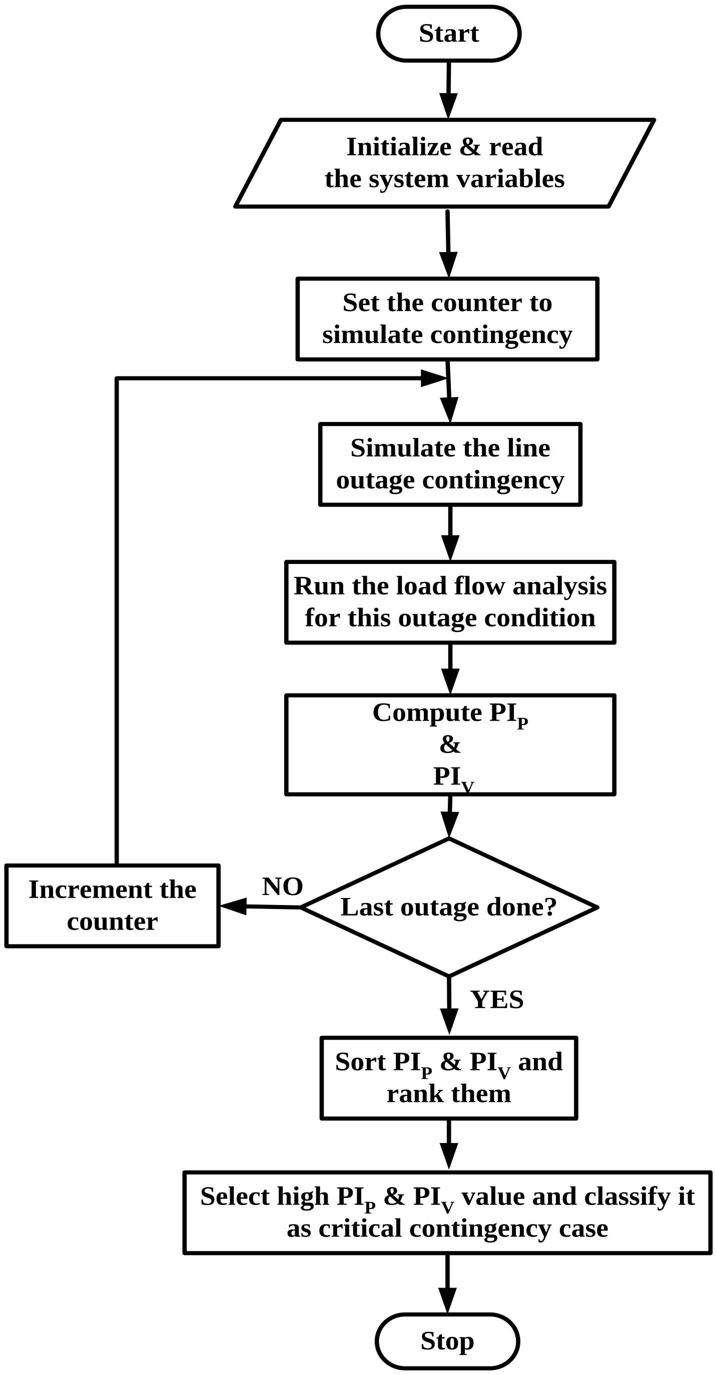


Fig. 2.1 Flow Chart for Contingency Selection

For calculation of PI_V it is required to know the maximum and minimum voltage limits, generally a margin of $\pm$ 5% is kept for assigning the limits i.e, 1.05 P.U. for maximum and 0.95 P.U. for minimum. It is to be noted that the above performance indices is useful for performing the contingency selection for line contingencies only. To obtain the value of PI for each contingency the lines in the bus system are being numbered as per convenience, then a particular transmission line at a time is simulated for outage condition and the individual power flows and the bus voltages are being calculated with the help of fast decoupled load flow solution.

2.4 FAST DECOUPLED LOAD FLOW SOLUTION

The development of Fast Decoupled Load Flow (FLDF) method was developed by Stott [9] and this has been proposed based on the certain assumptions in the N-R method, hence to understand the FLDF method it is required to consider the study of N-R method.

For a typical bus of a power system [38] is shown in Fig. 2.2, the current entering the bus *i* is given by eq.2.9 which is written in terms of bus admittance matrix as

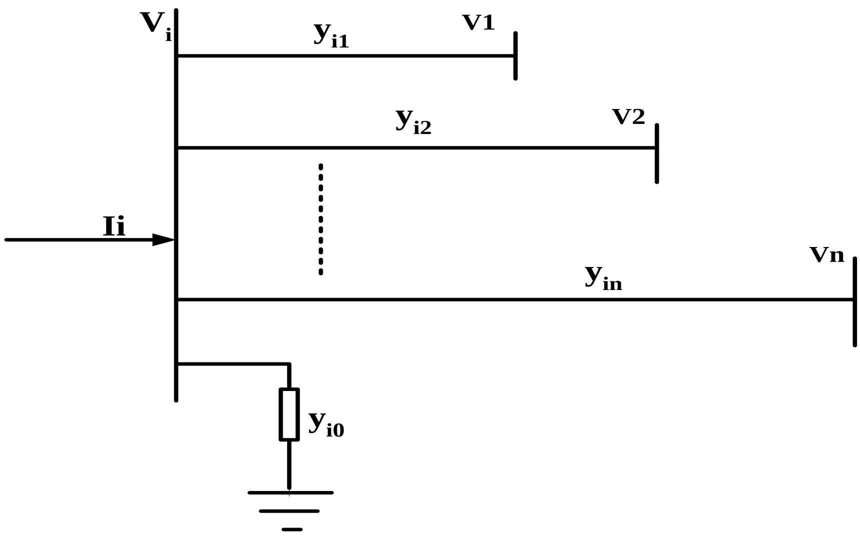


Fig. 2.2 Typical bus of a power system

$$I_i = \sum_{j=1}^{n} Y_{ij}\ V_j \tag{2.9}$$

The above equation is expressed in polar form as

$$I_i = \sum_{j=1}^{n} |Y_{ij}||V_j| \angle\theta_{ij} + \delta_j \tag{2.10}$$

The complex power at bus *i* is given by eq.2.11

$$P_i - jQ_i = V_i^* I_i \tag{2.11}$$

Substituting the value of (2.10) to (2.11) we get,

$$P_i\text{-}jQ_i=|V_i|\angle-\delta_i \sum_{j=1}^{n}|Y_{ij}||V_j|\angle\theta_{ij}+\delta_j \tag{2.12}$$

Separating the real and real parts we get,

$$P_i=\sum_{j=1}^{n}|Y_{ij}||V_i||V_j|\cos(\theta_{ij}-\delta_i+\delta_j) \tag{2.13}$$

$$Q_i=-\sum_{j=1}^{n}|Y_{ij}||V_i||V_j|\sin(\theta_{ij}-\delta_i+\delta_j) \tag{2.14}$$

Equations 2.13 and 2.14 are the non linear algebraic equations in terms of independent variables, voltage and phase angle, we have two equations for load bus given by eq.2.13 and eq.2.14 and one equation for voltage controlled bus given by eq.2.14. Expanding eq.2.13 and eq.2.14 in Taylor's series about the initial estimates we get the following set of linear equations.

$$\begin{bmatrix} \Delta P_2^{(k)} \\ \cdot \\ \cdot \\ \cdot \\ \Delta P_n^{(k)} \\ \hline \Delta Q_2^{(k)} \\ \cdot \\ \cdot \\ \cdot \\ \Delta Q_n^{(k)} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_2^{(k)}}{\partial \delta_2^k} & \cdots & \frac{\partial P_2^{(k)}}{\partial \delta_n^k} & \frac{\partial P_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_2^{(k)}}{\partial |V_n|} \\ \vdots & & \vdots & \vdots & & \vdots \\ \frac{\partial P_n^{(k)}}{\partial \delta_2^k} & \cdots & \frac{\partial P_n^{(k)}}{\partial \delta_n^k} & \frac{\partial P_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_2^{(k)}}{\partial |V_n|} \\ \frac{\partial Q_2^{(k)}}{\partial \delta_2^k} & \cdots & \frac{\partial Q_2^{(k)}}{\partial \delta_n^k} & \frac{\partial Q_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_2^{(k)}}{\partial |V_2|} \\ \vdots & & \vdots & \vdots & & \vdots \\ \frac{\partial Q_2^{(k)}}{\partial \delta_n^k} & \cdots & \frac{\partial Q_n^{(k)}}{\partial \delta_n^k} & \frac{\partial Q_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_n^{(k)}}{\partial |V_n|} \end{bmatrix} \begin{bmatrix} \Delta\delta_2^{(k)} \\ \cdot \\ \cdot \\ \cdot \\ \Delta\delta_n^{(k)} \\ \hline \Delta\left|V_2^{(k)}\right| \\ \cdot \\ \cdot \\ \cdot \\ \Delta\left|V_n^{(k)}\right| \end{bmatrix} \tag{2.15}$$

From eq.2.15 the Jacobian matrix gives the linearized relationship between small changes in voltage angle $\Delta\,\delta_i^{(k)}$ and voltage magnitude $\Delta\left|V_i^{(k)}\right|$ with the small changes in real and reactive power $\Delta P_i^{(k)}$ and $\Delta Q_i^{(k)}$. The elements of Jacobian matrix are the partial derivatives of equations 2.13 and 2.14 evaluated at $\Delta\,\delta_i^{(k)}$ and $\Delta\left|V_i^{(k)}\right|$. In short the eq.2.15 can be expressed as;

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} \tag{2.16}$$

The diagonal and the off diagonal elements of J_1 are

$$\frac{\partial P_i}{\partial \delta_i} = \sum_{j\neq i}^{n}|Y_{ij}||V_i||V_j|\sin(\theta_{ij}-\delta_i+\delta_j) \tag{2.17}$$

$$\frac{\partial P_i}{\partial \delta_j} = -\,|Y_{ij}||V_i||V_j|\sin(\theta_{ij}-\delta_i+\delta_j) \qquad j\neq i \tag{2.18}$$

The diagonal and the off-diagonal elements of J_2 are

$$\frac{\partial P_i^{(k)}}{\partial |V_i|} = 2|Y_{ii}||V_i|\cos(\theta_{ii}) + \sum_{j\neq i}^{n}|Y_{ij}||V_j| \cos(\theta_{ij} - \delta_i + \delta_j) \qquad (2.19)$$

$$\frac{\partial P_i^{(k)}}{\partial |V_j|} = |Y_{ij}||V_i| \cos(\theta_{ij} - \delta_i + \delta_j) \qquad j \neq i \qquad (2.20)$$

The diagonal and the off-diagonal elements of J_3 are

$$\frac{\partial Q_i}{\partial \delta_i} = \sum_{j\neq i}^{n}|Y_{ij}||V_i||V_j| \cos(\theta_{ij} - \delta_i + \delta_j) \qquad (2.21)$$

$$\frac{\partial Q_i}{\partial \delta_j} = - |Y_{ij}||V_i||V_j| \cos(\theta_{ij} - \delta_i + \delta_j) \qquad j \neq i \qquad (2.22)$$

The diagonal and off-diagonal elements of J_4 are

$$\frac{\partial Q_i^{(k)}}{\partial |V_i|} = -2|Y_{ii}||V_i|\cos(\theta_{ii}) - \sum_{j\neq i}^{n}|Y_{ij}||V_j| \sin(\theta_{ij} - \delta_i + \delta_j) \qquad (2.23)$$

$$\frac{\partial Q_i^{(k)}}{\partial |V_j|} = -|Y_{ij}||V_i| \cos(\theta_{ij} - \delta_i + \delta_j) \qquad j \neq i \qquad (2.24)$$

The terms $\Delta P_i^{(k)}$ and $\Delta Q_i^{(k)}$ are the difference between the scheduled and calculated values, known as power residuals given by,

$$\Delta P_i^{(k)} = P_i^{(sch)} - P_i^{(k)} \qquad (2.25)$$

$$\Delta Q_i^{(k)} = Q_i^{(sch)} - Q_i^{(k)} \qquad (2.26)$$

The new estimates for phase angles and bus voltages are

$$\delta_i^{(k+1)} = \delta_i^{(k)} + \Delta\delta_i^{(k)} \qquad (2.27)$$

$$\left|V_i^{(k+1)}\right| = \left|V_i^{(k+1)}\right| + \Delta\left|V_i^{(k)}\right| \qquad (2.28)$$

Using these, the new values of active and reactive power are being found using equations 2.13 and 2.14, simultaneously the new values of the elements of Jacobian matrix are being obtained using equations 2.17 – 2.24 and again the new values of phase angles and bus voltages are obtained and the process is continued until the residuals $\Delta P_i^{(k)}$ and $\Delta Q_i^{(k)}$ are less than he specified accuracy, i.e.,

$$\left|\Delta P_i^{(k)}\right| \leq \varepsilon \qquad (2.29)$$

$$\left|\Delta Q_i^{(k)}\right| \leq \varepsilon \qquad (2.30)$$

In the above process the calculation of new values of phase angles and bus voltages are obtained only after the inversion of the Jacobian matrix which is very complex and requires rigorous computational effort so as to avoid this the concept of FLDF is used.

It has been found that for transmission lines have high values of X/R ratio, so for such system the real power changes ΔP are less sensitive to changes in the voltage magnitude and are most sensitive to change in phase angles $\Delta\boldsymbol{\delta}$. Similarly the reactive power is less sensitive to change in angles and is mainly dependent on changes in voltage magnitude; this concept is used to formulate the FDLF solution. Thus the element J_2 and J_3 of the Jacobian matrix is set to zero. Thus eq.2.16 can be written as

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix}J_1 & 0\\ 0 & J_4\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \Delta|V|\end{bmatrix} \tag{2.31}$$

or

$$\Delta P = J_1\,\Delta\delta = \frac{\partial P_i}{\partial \delta_j}\,\Delta\delta \tag{2.32}$$

$$\Delta Q = J_4\,\Delta|V| = \frac{\partial P_i}{\partial |V|}\,\Delta|V| \tag{2.33}$$

Hence we can say that the matrix equations 2.32 and 2.33 have separated into two decoupled equations requiring considerably less amount of time as compared to eq.2.16, further the recomputing of J_1 and J_4 per iteration gets eliminated. The diagonal elements of J_1 described by eq.2.17 can be written as

$$\frac{\partial P_i}{\partial \delta_i} = \sum_{j=i}^{n}\left|Y_{ij}\right||V_i|\left|V_j\right|\ \sin\left(\theta_{ij}-\delta_i+\delta_j\right) - \left|V_i^2\right||Y_{ii}|\sin(\theta_{ii}) \tag{2.34}$$

Replacing the first term of the above equation with $-Q_i$ as given by (2.14) results in

$$\frac{\partial P_i}{\partial \delta_i} = -\,Q_i - \left|V_i^2\right||Y_{ii}|\sin(\theta_{ii}) \tag{2.35}$$

$$= -\,Q_i - \left|V_i^2\right|B_{ii} \tag{2.36}$$

Where $B_{ii}= |Y_{ii}|\ \sin(\theta_{ii})$ is the imaginary part of the diagonal elements of the bus admittance matrix. B_{ii} is the sum of susceptance of all the elements incident to bus *i* . In a typical power system the self susceptance $B_{ii} >> Q_i$ and assuming $\left|V_i^2\right| \approx |V_i|$, which yields,

$$\frac{\partial P_i}{\partial \delta_i} = -\,|V_i|B_{ii} \tag{2.37}$$

Under normal operating conditions, $\delta_i-\delta_j$ is quite small, thus assuming $\theta_{ii}-\delta_i+\delta_j \approx \theta_{ii}$ the off diagonal elements of J_1 in eq.2.18 becomes,

$$\frac{\partial P_i}{\partial \delta_j} = -\,|V_i|\left|V_j\right|B_{ij} \tag{2.38}$$

Further simplification is obtained by assuming $\left|V_j\right| \approx 1$

$$\frac{\partial P_i}{\partial \delta_j} = - |V_i|\, B_{ij} \qquad (2.39)$$

Similarly, the diagonal elements of J_4 described by eq.2.23 may be written as

$$\frac{\partial Q_i^{(k)}}{\partial |V_i|} = -|Y_{ii}||V_i| \sin(\theta_{ii}) - \sum_{j=i}^{n} |Y_{ij}| |V_i| |V_j| \sin(\theta_{ij} - \delta_i + \delta_j) \qquad (2.40)$$

Replacing the second term of the above term of the above equation with $-Q_i$ as given by eq.2.14 results in

$$\frac{\partial Q_i^{(k)}}{\partial |V_i|} = -|Y_{ii}||V_i| \sin(\theta_{ii}) + Q_i \qquad (2.41)$$

Again, since $B_{ii} = |Y_{ii}| \sin(\theta_{ii}) >> Q_i$, Q_i may be neglected and eq.2.23 reduces to

$$\frac{\partial Q_i^{(k)}}{\partial |V_i|} = - |V_i| B_{ii} \qquad (2.42)$$

Likewise in eq.2.24, assuming $\theta_{ii} - \delta_i + \delta_j \approx \theta_{ij}$ results in,

$$\frac{\partial Q_i^{(k)}}{\partial |V_j|} = - |V_i| B_{ij} \qquad (2.43)$$

With these assumptions, equations 2.32 and 2.33 becomes,

$$\frac{\Delta P}{|V_i|} = -B' \Delta\delta \qquad (2.44)$$

$$\frac{\Delta Q}{|V_i|} = -B'' \Delta|V_i| \qquad (2.45)$$

Here, B' and B'' are the imaginary part of the bus admittance matrix Y_{BUS}, therefore in fast decoupled load flow power algorithm, the successive voltage magnitude and phase angle changes are given by,

$$\Delta\delta = -[B']^{-1} \frac{\Delta P}{|V|} \qquad (2.46)$$

$$\Delta|V| = -[B'']^{-1} \frac{\Delta Q}{|V|} \qquad (2.47)$$

Thus it can be concluded that fast decoupled power flow solution requires the least time per iteration among all load flow techniques available, hence the power flow solution is obtained very rapidly. Thus this technique is very useful in contingency analysis where numerous outages are to be simulated in a very rapid manner.

The flow chart for Fast Decoupled Load Flow solution has been shown in Fig. 2.3.

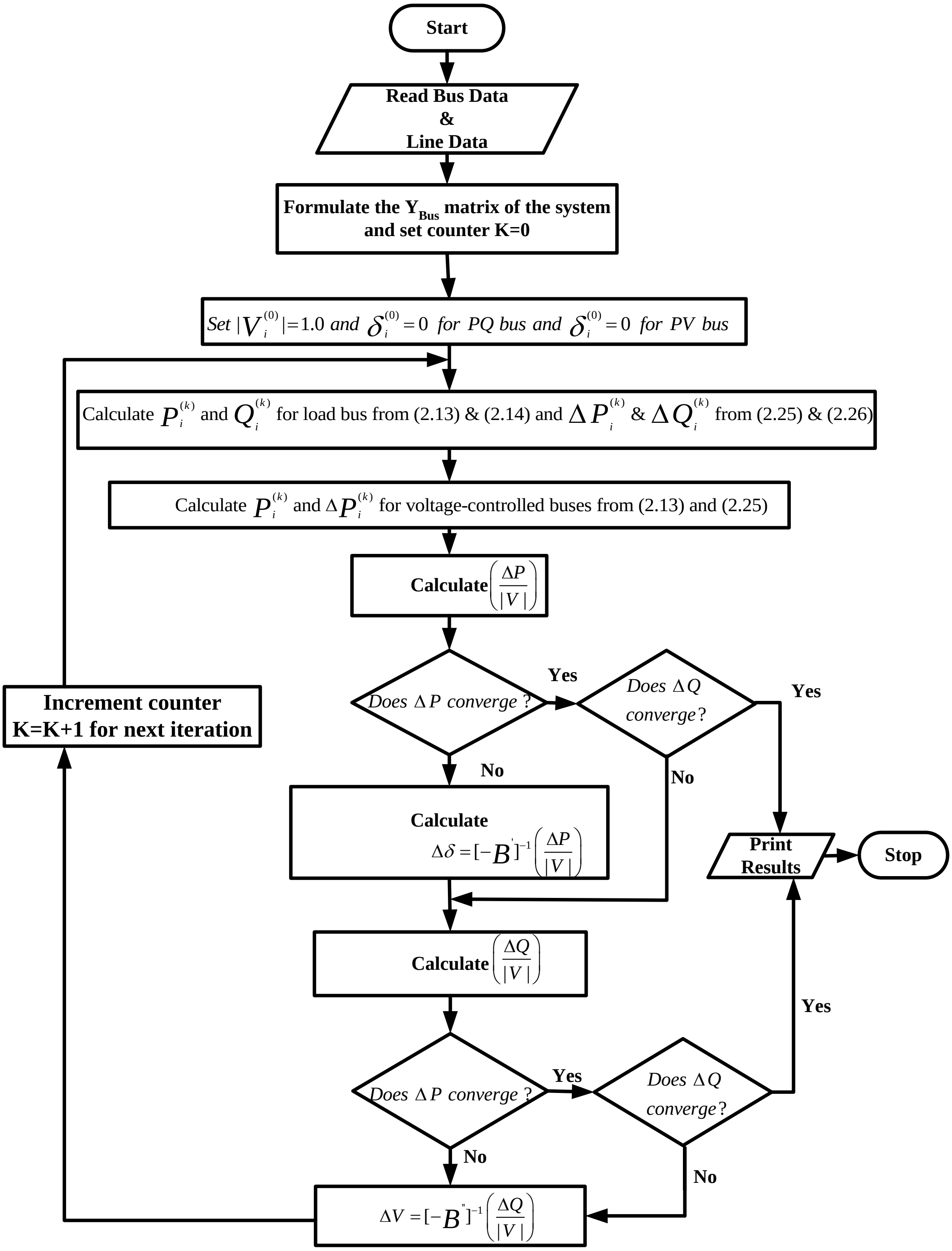


Fig. 2.3 Flow Chart for FDLF algorithm

2.5 ALGORITHM FOR CONTINGENCY ANALYSIS USING FAST DECOUPLED LOAD FLOW

The algorithm steps for contingency analysis using fast decoupled load flow solution are given as follows:

***Step 1*:** Read the given system line data and bus data.

***Step 2*:** Set the counter to zero before simulating a line contingency.

***Step 3*:** Simulate a line contingency.

***Step 4*:** Calculate the active power flow for in the remaining lines and the maximum power flow P^{Max} using eq.2.7.

***Step 5*:** Calculate the active power performance index PI_P which give the indication of active power limit violation using eq.2.6.

***Step 6*:** Calculate the voltages at all the load buses following the line contingency.

***Step 7*:** Calculate the reactive power performance index PI_V which gives the voltage limit violation at all the load buses due to a line contingency using eq.2.8.

***Step 8*:** Check if this is the last line outage to be simulated; if not the step (3) to (7) is computed till last line of the bus system is reached.

***Step 9*:** The contingencies are ranked once the whole above process is computed as per the values of the performance indices obtained.

***Step 10*:** Do the power flow analysis of the most severe contingency case and print the results

The flow chart of the algorithm is shown in Fig. 2.4.

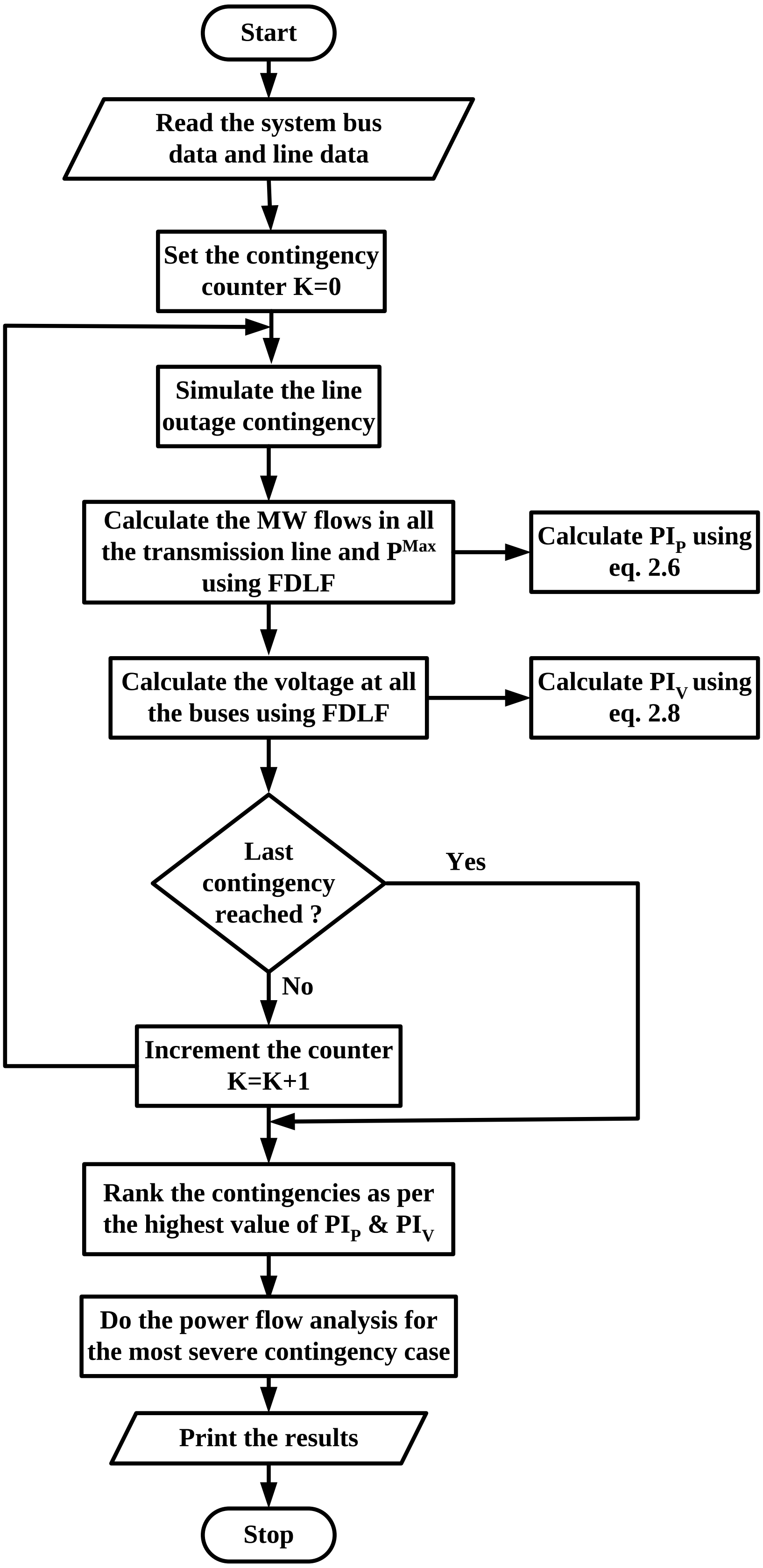


Fig. 2.4 Flow chart for Contingency Analysis using FDLF

2.6 RESULTS AND DISCUSSION

The main focus here is to perform the contingency selection process, by calculating the active and reactive power performance indices i.e. PI_P and PI_V respectively. The contingencies are then ranked where the most severe contingency is the one which is having the highest performance index value. The computation of these indices has been done based on load flow analysis carried out using fast decoupled load flow (FDLF) under MATLAB environment. The most severe contingency is then chosen from the contingency list and the corresponding power flows and bus voltages are analysed for the entire system. The study has been carried out for the following standard systems:

- ***5-Bus System*** [36].
- ***14- Bus System*** [37].
- ***30- Bus System*** [38].

2.6.1 5-Bus System

The bus data and line data of 5-Bus System are detailed in Appendix-A. The system as shown in Fig. 2.5 consists a slack bus numbered **1** and 4 load buses numbered **2**, **3**, **4** and **5**. It has total seven transmission lines and the active power flow in each transmission lines that has been obtained using FDLF corresponding to the base case loading condition is shown in Fig. 2.5, this base case analysis is also referred a Pre-contingency state.

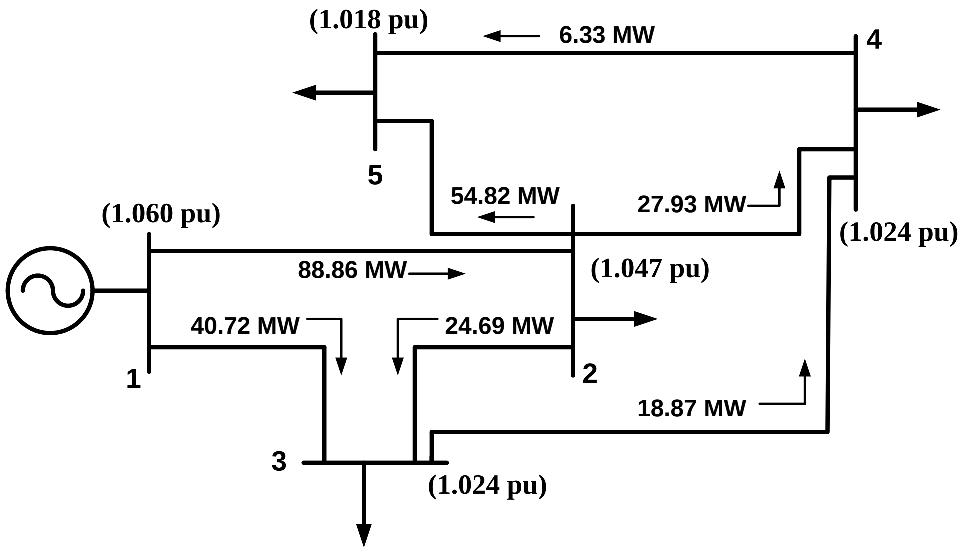


Fig. 2.5 Pre-Contingency State of 5-Bus system

The load flow analysis is then carried out by considering the one line outage contingency at a time. The active and reactive power performance indices (PI_P & PI_V) are also calculated considering the outage of only one line sequentially and the calculated indices are summarized in Table 2.1. The ranking of the line outage contingency has been decided on the basis of PI_V value. The higher the PI_V value indicates higher rank and higher level of severity. From Table 2.1 it can be inferred that outage of line number 1 is the most vulnerable one and its outage will result a great impact on the whole system, the highest value of PI_V for this outage suggests that the highest attention be given for this line during the operation. Fig. 2.6 and Fig. 2.7 shows the graphical representation of these performance indices for each outage cases and contingency ranking for this bus system based on PI_V values has been shown in Fig. 2.8.

Table 2.1

Performance Indices & Contingency Ranking using FDLF for 5-Bus System

Outage Line No)	PI_P	PI_V	Ranking
1	**0.2800**	**3.1916**	**1**
2	0.3619	0.2699	6
3	0.3377	0.6557	4
4	0.3790	0.6173	5
5	0.4221	0.2653	7
6	0.2995	0.8599	3
7	0.3036	0.8799	2

It is seen that the contingency in the **line connected between buses (1-2)** results in highest value of the reactive power performance index and thus it is ranked first for the contingency selection, hence the post contingency state of the system corresponding to this contingency has been analysed. Since, the value of PI_V indicates the severity that is occurring in the system due to violation in the voltage limits, the pre contingency and the post contingency voltages at the buses of the entire system have been detailed in Table 2.2. The MW flows corresponding to the pre contingency state and the post contingency state have been detailed in Table 2.3.

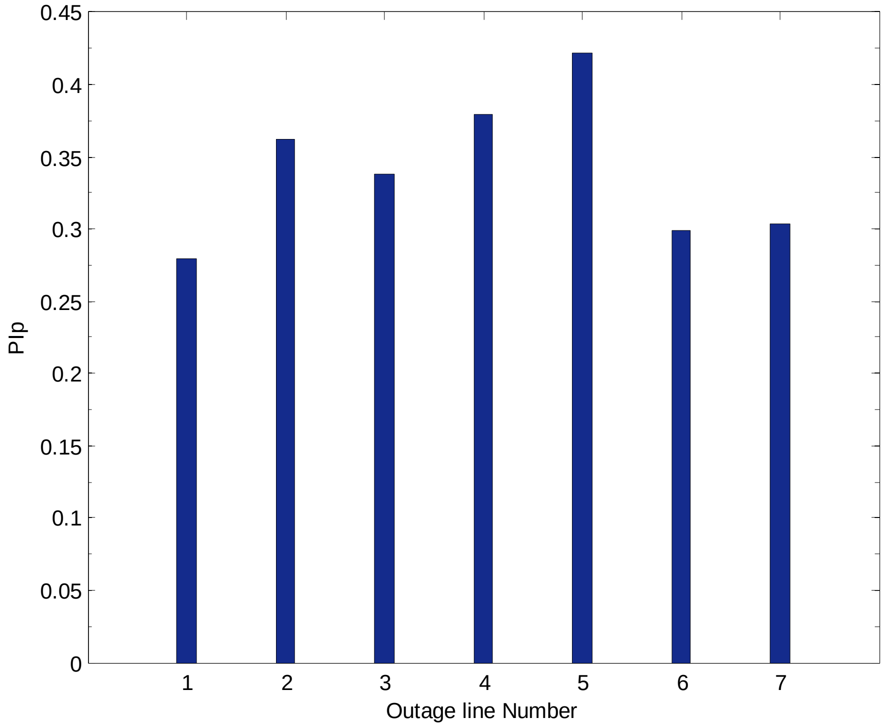


Fig. 2.6 Values of PI_P for 5-Bus system

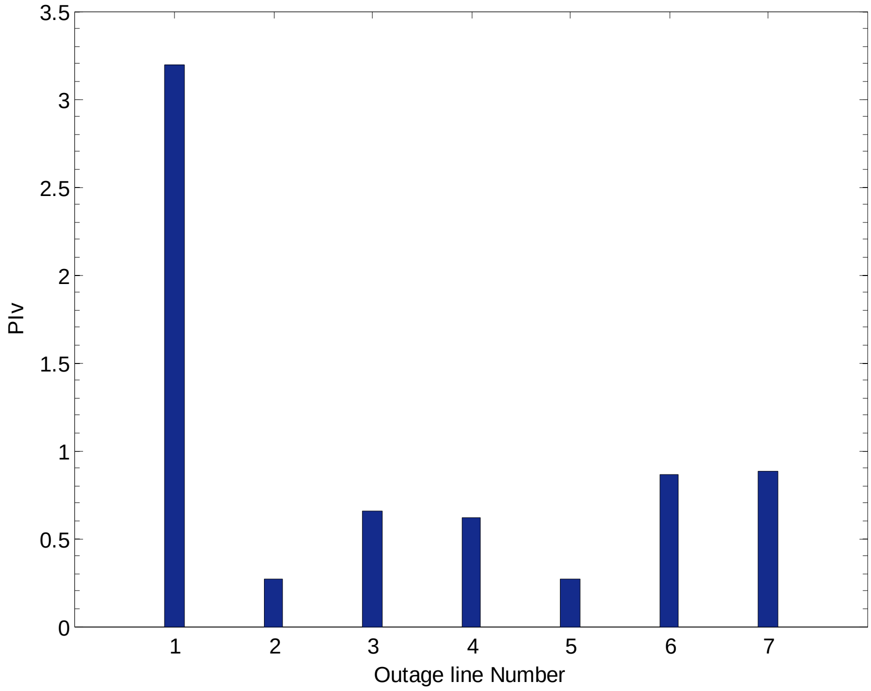


Fig. 2.7 Values of PI_V for 5-Bus system

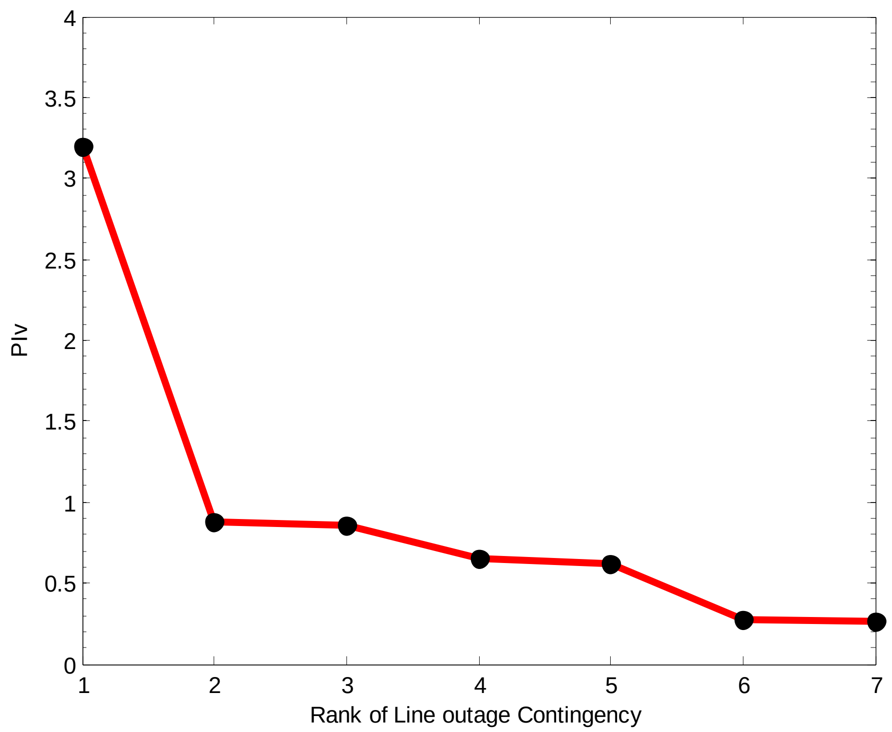


Fig. 2.8 Contingency Ranking and PI_V of 5-Bus system

Table 2.2

Bus Voltages in the Pre and Post Contingency State

Bus Number	Pre-contingency voltage (pu)	Post-contingency voltage (pu)
1	1.060	1.060
2	1.047	0.891
3	1.024	0.886
4	1.024	0.880
5	1.018	0.861

Table 2.3

Active Power Flow in the Pre and Post Contingency State

Line No	Start Bus	End Bus	Pre contingency MW flow	Post contingency MW flow
1	**1**	**2**	**88.86 MW**	**0 MW**
2	1	3	40.72 MW	143.63 MW
3	2	3	24.69 MW	15.33 MW
4	2	4	27.93 MW	4.00 MW
5	2	5	54.82 MW	39.07 MW
6	3	4	18.87 MW	66.80 MW
7	4	5	6.33 MW	22.23 MW

Fig. 2.9 shows the power flows and bus voltages in the system following the most severe contingency, which is the outage of the transmission line connecting buses (1-2).

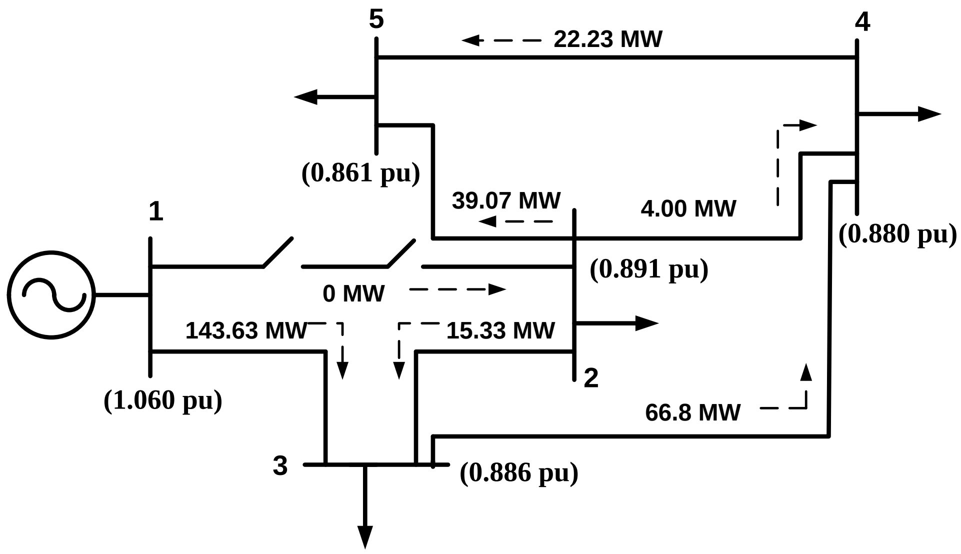


Fig. 2.9 Post Contingency state of 5-Bus system

2.6.2 14-Bus System

The bus data and line data of the IEEE-14 bus test system are detailed in Appendix B. The system as shown in Fig. 2.10 consists of 1 slack bus, 9 load buses and 4 generator buses. There are three synchronous compensators used only for reactive power support. The active power flow in each transmission lines that has been obtained using FDLF corresponding to the base case loading condition is also shown in Fig. 2.10. This state of the system corresponds to the pre contingency state. The system has a total 20 number of transmission lines, hence we evaluate for 20 line contingency scenarios by considering the one line outage contingency at a time. The performance indices are summarized in the Table 2.4. From Table 2.4 it can be inferred that outage in **line number 16** is the most vulnerable one and its outage will result a great impact on the whole system. The high value of PI_V for this outage also suggests that the highest attention be given for this line during the operation. Fig. 2.11 and Fig. 2.12 shows the graphical representation of the performance indices for all the line contingencies with the value of PI on the y-axis and the outage line number labelled on the x-axis.

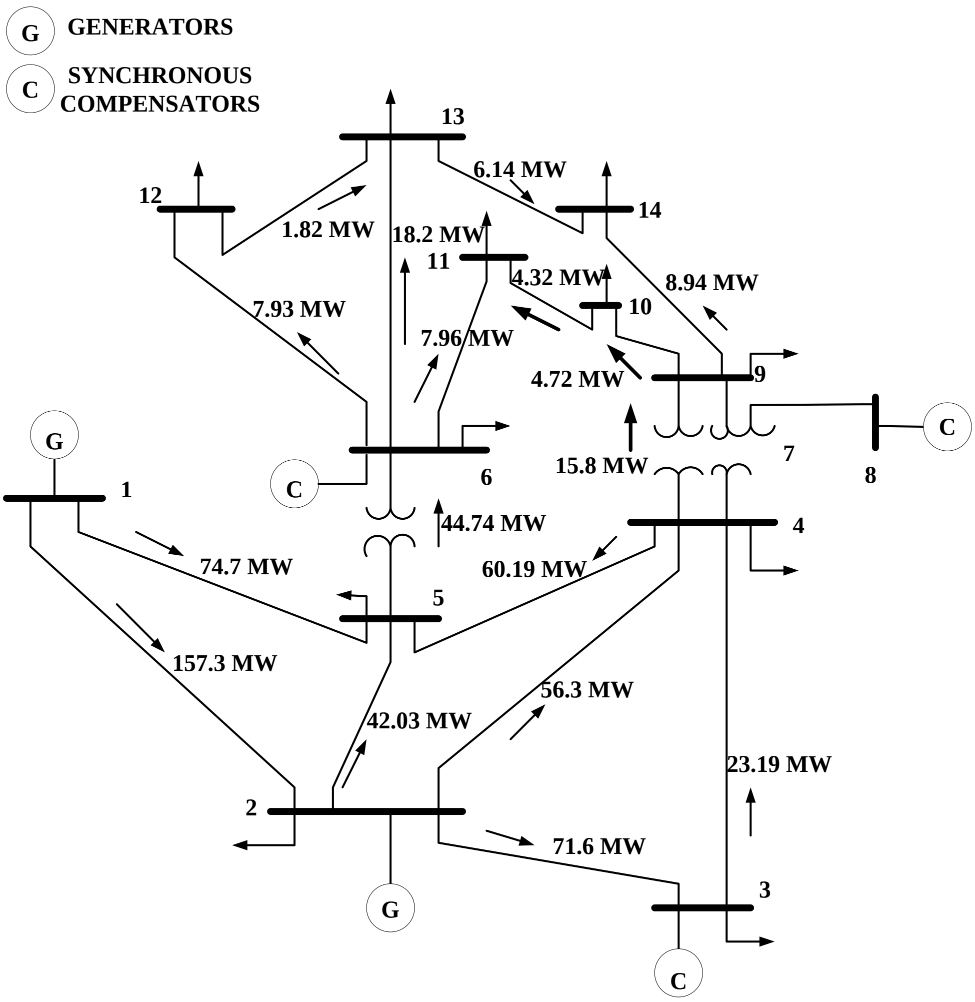


Fig. 2.10 Pre-Contingency State of 14-Bus System

Table 2.4

Performance Indices & Contingency Ranking using FDLF for 14-Bus System

Contingency number	PI_P	PI_V	Ranking
1	1.1693	7.3032	10
2	0.9807	7.6696	11
3	1.1654	10.0014	7
4	0.9999	7.3213	12
5	0.9820	8.8759	9
6	0.9640	13.2572	2
7	0.9915	0.3566	19
8	1.0747	1.1753	17
9	0.9807	10.5776	4
10	1.2396	1.6047	16
11	1.0142	9.5907	8
12	1.0127	1.8089	15
13	1.0569	1.3669	18
14	1.0072	10.4518	6
15	1.0759	0.0844	20
16	**1.0114**	**13.3464**	**1**
17	1.0164	2.3482	13
18	1.0030	10.5217	5
19	1.0008	12.5538	3
20	1.0076	2.2891	14

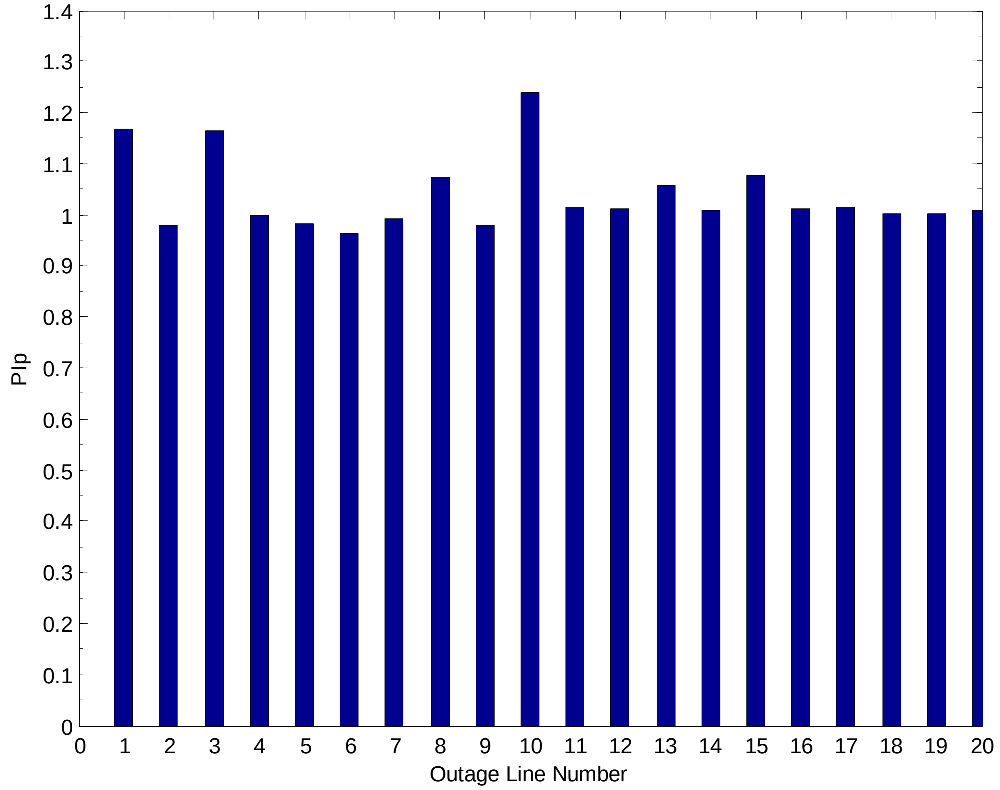


Fig. 2.11 Values of PI_P for 14-Bus system

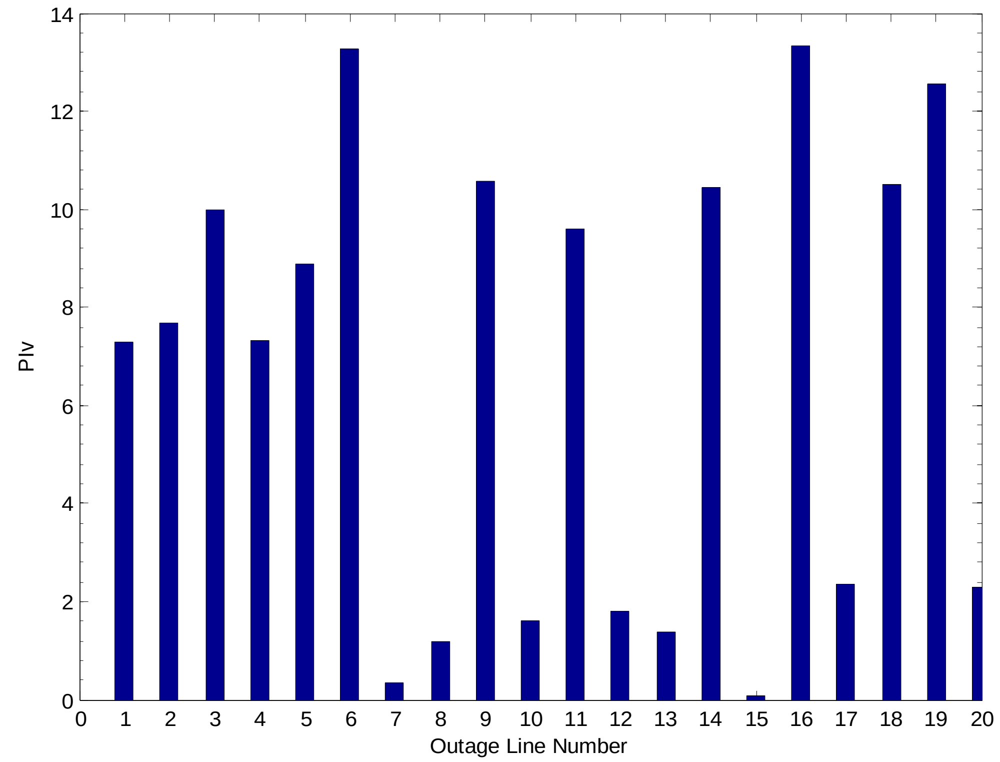


Fig. 2.12 Values of PI_V for 14-Bus system

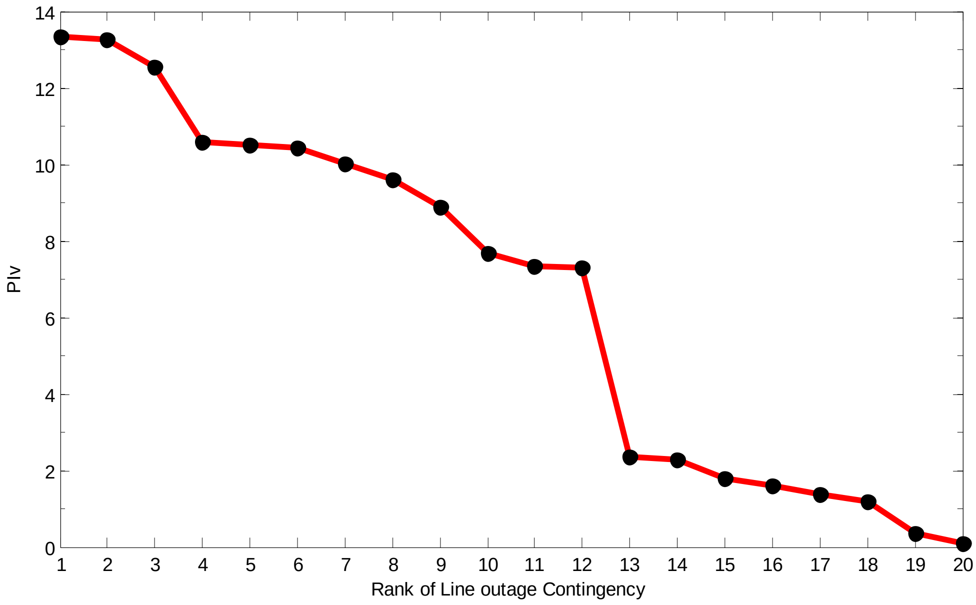


Fig. 2.13 Contingency Ranking and PI_V of 14-Bus system

The contingencies have been ordered by their ranking where the most severe contingency is being ranked 1 and the least has been ranked 20. The variation of reactive performance index with their ranking has been shown in the Fig. 2.13. It is clear from the result of different PI_V that the contingency number 16 which the line outage contingency corresponding to the **line connected between buses (9-10)** is the most severe contingency. Hence the post contingency analysis corresponding to this line outage has been performed. The voltage of the system corresponding to the pre contingency state and the post contingency state has been detailed in Table 2.5. The MW flows corresponding to the pre contingency state and the post contingency state has been detailed in Table 2.6. The state of the system after the outage in the line connected between buses (9-10) has been represented in Fig. 2.14.

Table 2.5

Bus Voltages in the Pre and Post Contingency State

Bus Number	Pre-contingency voltage (pu)	Post-contingency voltage (pu)
1	1.075	1.075
2	1.050	1.050
3	1.000	1.000
4	1.002	1.000
5	1.009	1.009
6	1.025	1.025
7	1.007	1.008
8	1.016	1.016
9	0.993	0.996
10	0.991	0.978
11	1.004	0.997
12	1.007	1.008
13	1.001	1.002
14	0.978	0.980

Table 2.6

Active Power Flow in the Pre and Post Contingency State

Line No	Start Bus	End Bus	Pre contingency MW flow	Post contingency MW flow
1	1	2	157.3 MW	156.8 MW
2	1	5	74.7 MW	75 MW
3	2	3	71.6 MW	71.5 MW
4	2	4	56.3 MW	56 MW
5	2	5	42.03 MW	42.3 MW
6	3	4	23.19 MW	23 MW
7	4	5	60.19 MW	57.6 MW
8	4	7	27.38 MW	25.5 MW
9	4	9	15.8 MW	14.9 MW
10	5	6	44.74 MW	48.2 MW
11	6	11	7.96 MW	12.79 MW
12	6	12	7.93 MW	7.58 MW
13	6	13	18.21 MW	16.67 MW
14	7	8	0.0 MW	0.0 MW
15	7	9	27.39 MW	25.5 MW
16	**9**	**10**	**4.72 MW**	**0 MW**
17	9	14	8.94 MW	10.7 MW
18	10	11	4.32 MW	9.09 MW
19	12	13	1.82 MW	1.4 MW
20	13	14	6.14 MW	4.33 MW

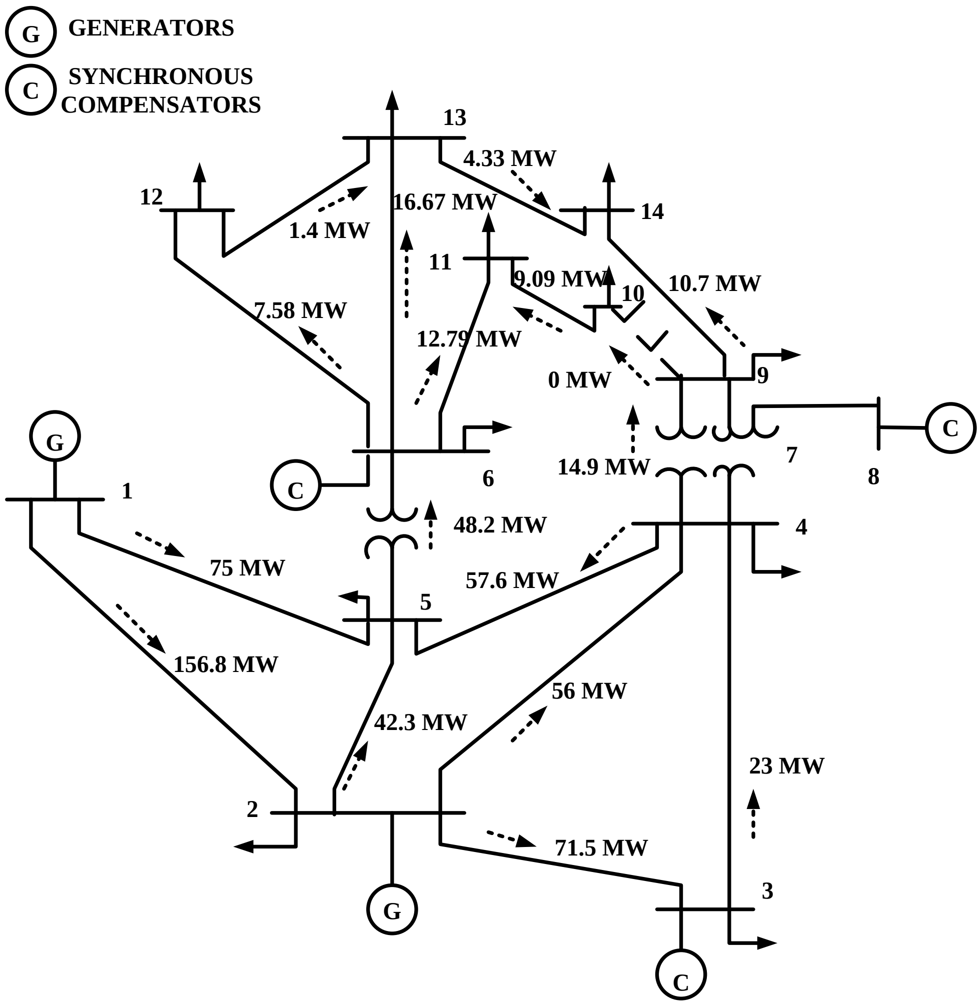


Fig. 2.14 Post-Contingency State of 14-Bus system

2.6.3 30-Bus System

The bus data and line data for the IEEE-30 bus system are detailed in Appendix C. The IEEE-30 bus system has 6 PV buses, 24 PQ buses and 41 lines [38], hence for the PI_P and PI_V calculation a total number of 41 line contingency cases are performed. The active power flow in each transmission lines that has been obtained using FDLF corresponding to the base case loading condition is shown in Fig. 2.15. This base case analysis is also referred as pre-contingency state. Since the system consists of 41 transmission lines, the load flow analysis is carried out for 41 line contingency case considering one line outage at a time.

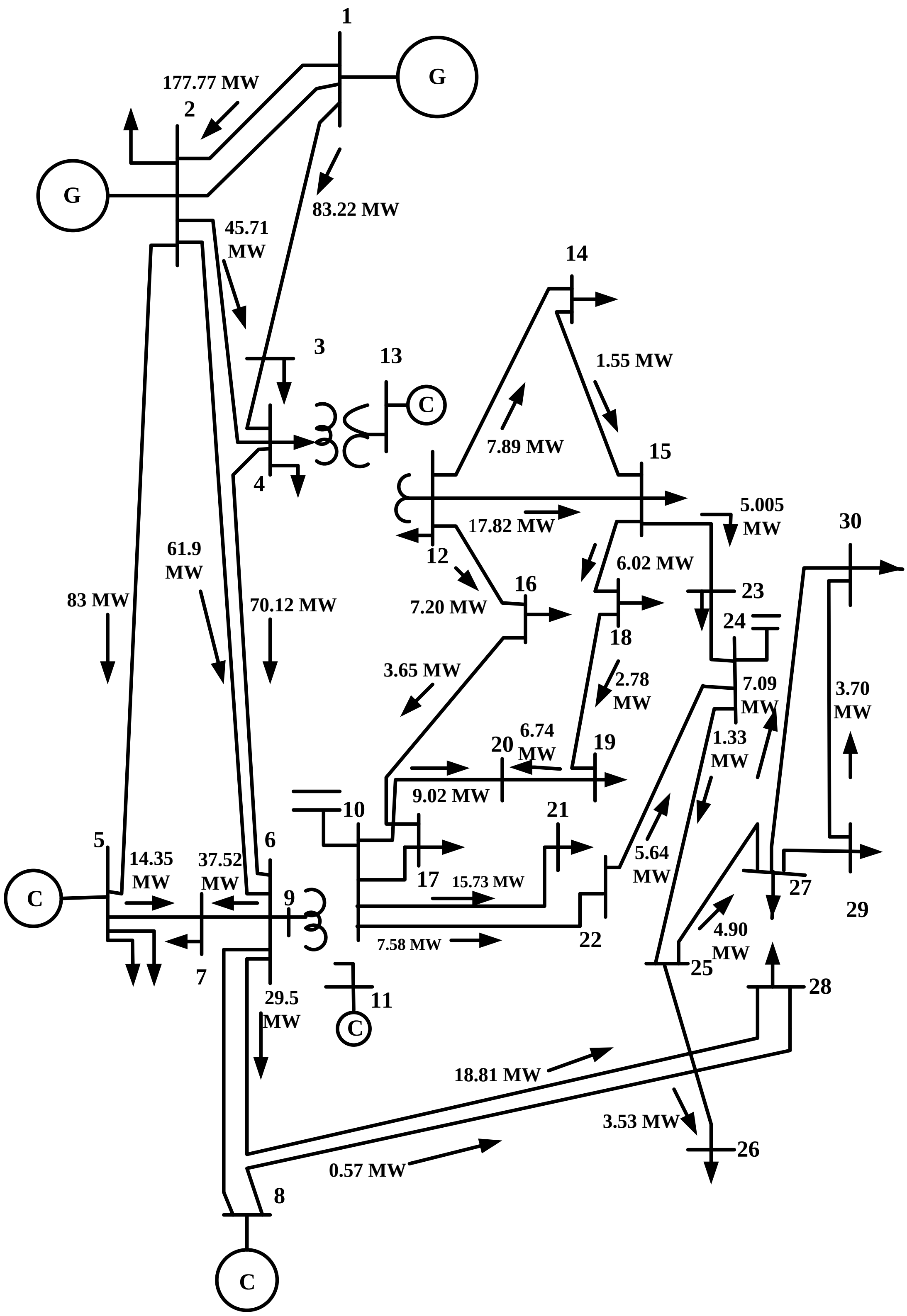


Fig. 2.15 Pre-Contingency State of 30-Bus system

The active and reactive power performance indices are also calculated considering the outage of only one line sequentially and the calculated indices are detailed in Table 2.7. From Table 2.7 it can be inferred that outage of **line number 9** is the most vulnerable one and its outage will result a great impact on the whole system. The highest value of PI_V for his outage suggests that highest attention be given for this line during the operation. The graphical representation of the PI_P and PI_V values for the corresponding line contingencies respectively has been shown in Fig. 2.16 and Fig. 2.17 respectively.

Table 2.7

Performance Indices & Contingency Ranking using FDLF for 30-Bus System

Contingency No.	PI_P	PI_V	Ranking
1	1.5919	3.9995	40
2	1.2754	23.0290	32
3	1.2724	24.5949	26
4	1.2740	26.6730	18
5	1.5029	23.3686	30
6	1.2978	24.1327	28
7	1.2982	23.0787	31
8	1.2692	27.3376	15
9	**1.2803**	**29.5544**	**1**
10	1.3611	29.1055	3
11	1.3691	26.2201	20
12	1.2786	26.3051	19
13	1.2996	18.6875	34
14	1.3727	14.5771	37
15	1.5285	9.6712	39
16	1.2967	14.2764	38
17	2.2972	0.3451	41
18	1.3477	17.2591	35
19	1.3084	24.5808	27
20	1.2928	27.9804	9
21	1.2964	27.6818	13
22	1.3078	24.8931	25
23	1.2983	27.8178	11
24	1.3005	25.2770	24
25	1.3081	20.4257	33
26	1.3000	26.1714	21
27	1.3183	24.0073	29

28	1.2953	27.0173	17
29	1.2954	28.2909	5
30	1.3109	25.7308	23
31	1.3086	27.1708	16
32	1.2960	28.3973	4
33	1.2948	29.1538	2
34	1.9801	27.6726	14
35	1.3111	26.1241	22
36	1.4453	16.6797	36
37	1.3073	27.8202	10
38	1.3211	27.7249	12
39	1.2893	28.0231	8
40	1.2964	28.1952	6
41	1.3282	28.1188	7

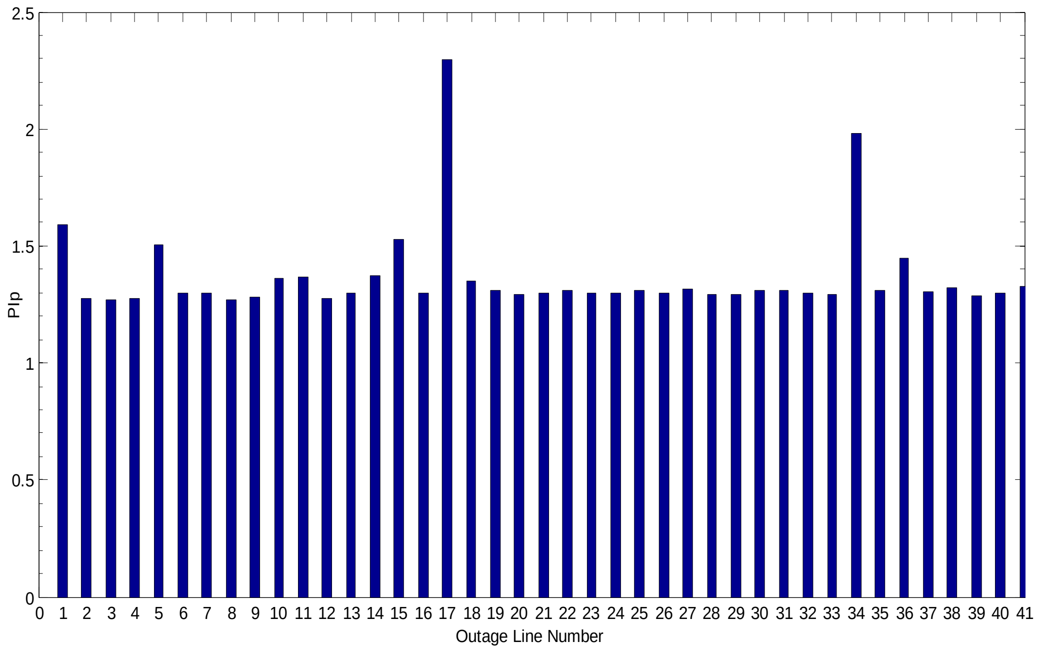


Fig. 2.16 Values of PI_P for 30-Bus system

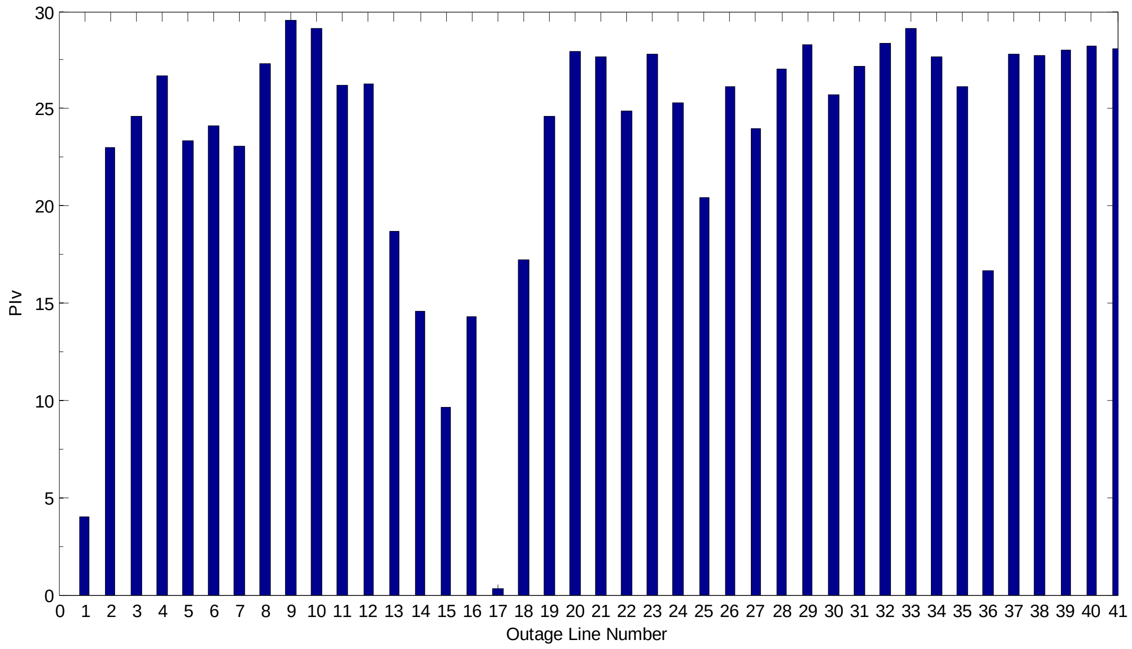


Fig. 2.17 Values of PI_V for 30-Bus system

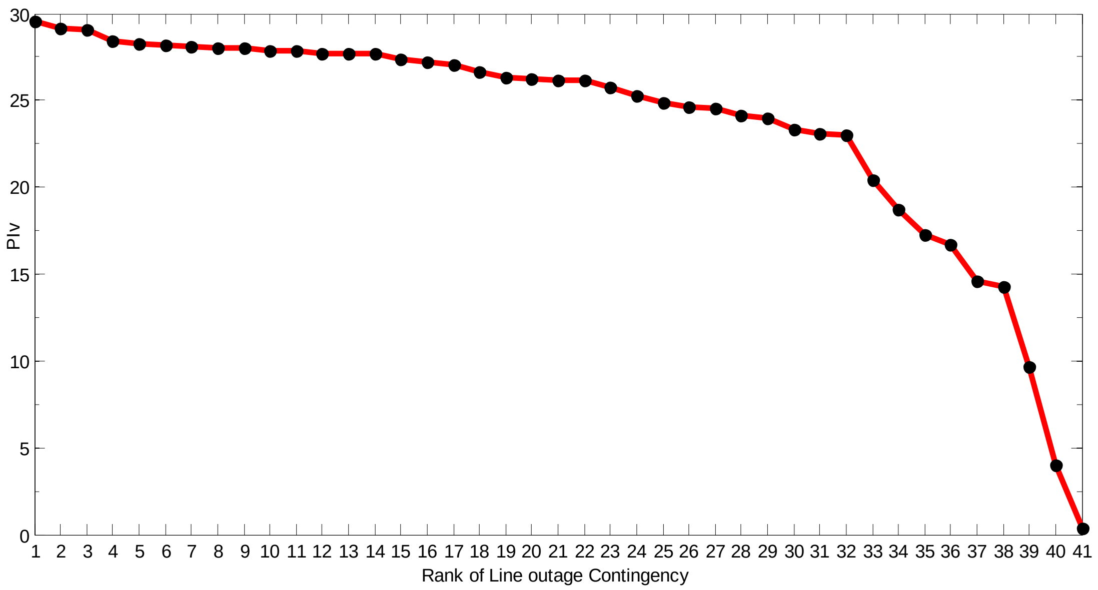


Fig. 2.18 Contingency ranking and PI_V of 30-Bus system

Fig. 2.18 shows the contingency ranking of this system with respect to the PI_V values. Since for the IEEE-30 bus system **contingency number 9** which is the **line connected between buses (6-7)** is the most critical contingency, the post contingency analysis following the outage of this line has been done. Here the system's bus voltages corresponding to the pre contingency and the post contingency state has been obtained. The results are detailed in Table 2.8 and the active power flow in all the lines in the pre contingency and post contingency state has been detailed in Table 2.9.

Table 2.8

Bus Voltages in the Pre and Post Contingency State

Bus Number	Pre-contingency voltage (pu)	Post-contingency voltage (pu)
1	1.060	1.060
2	1.043	1.043
3	1.022	1.024
4	1.013	1.016
5	1.010	1.010
6	1.012	1.015
7	1.003	0.988
8	1.010	1.010
9	1.051	1.053
10	1.044	1.047
11	1.082	1.082
12	1.057	1.059
13	1.071	1.071
14	1.042	1.044
15	1.038	1.039
16	1.045	1.046
17	1.039	1.041
18	1.028	1.030
19	1.025	1.027
20	1.029	1.031

21	1.032	1.034
22	1.033	1.035
23	1.027	1.029
24	1.022	1.024
25	1.019	1.021
26	1.001	1.004
27	1.026	1.028
28	1.011	1.013
29	1.006	1.009
30	0.995	0.997

Table 2.9

Active Power Flow in the Pre and Post Contingency State

Line No	Start Bus	End Bus	Pre contingency MW flow	Post contingency MW flow
1	1	2	177.77 MW	187.77 MW
2	1	3	83.22 MW	74.80 MW
3	2	4	45.71 MW	32.14 MW
4	3	4	78.01 MW	70.13 MW
5	2	5	82.99 MW	123.95 MW
6	2	6	61.91 MW	43.81 MW
7	4	6	70.12 MW	50.83 MW
8	5	7	14.35 MW	23.06 MW
9	**6**	**7**	**37.52 MW**	**0 MW**
10	6	8	29.5 MW	29.55 MW
11	6	9	27.69 MW	28.42 MW
12	6	10	15.82 MW	16.25 MW
13	9	11	0.00 MW	0.00 MW
14	9	10	27.69 MW	28.42 MW
15	4	12	44.12 MW	42.66 MW
16	12	13	0.00 MW	0.00 MW
17	12	14	7.89 MW	7.69 MW

18	12	15	17.82 MW	17.23 MW
19	12	16	7.20 MW	6.53 MW
20	14	15	1.55 MW	1.43 MW
21	16	17	3.65 MW	2.98 MW
22	15	18	6.02 MW	5.65 MW
23	18	19	2.78 MW	2.41 MW
23	19	20	6.74 MW	7.10 MW
25	10	20	9.02 MW	9.39 MW
26	10	17	5.37 MW	6.03 MW
27	10	21	15.73 MW	15.81 MW
28	10	22	7.58 MW	7.63 MW
29	21	22	1.87 MW	1.79 MW
30	15	23	5.00 MW	4.59 MW
31	22	24	5.64 MW	5.71 MW
32	23	24	1.77 MW	1.36 MW
33	24	25	1.33 MW	1.60 MW
34	25	26	3.53 MW	3.54 MW
35	25	27	4.90 MW	5.17 MW
36	28	27	18.18 MW	18.45 MW
37	27	29	6.18 MW	6.18 MW
38	27	30	7.09 MW	7.08 MW
39	29	30	3.70 MW	3.70 MW
40	8	28	0.57 MW	0.55 MW
41	6	28	18.81 MW	19.07 MW

The state of the entire system after the outage in the transmission line connected between **buses (6-7)** has been shown in Fig. 2.19.

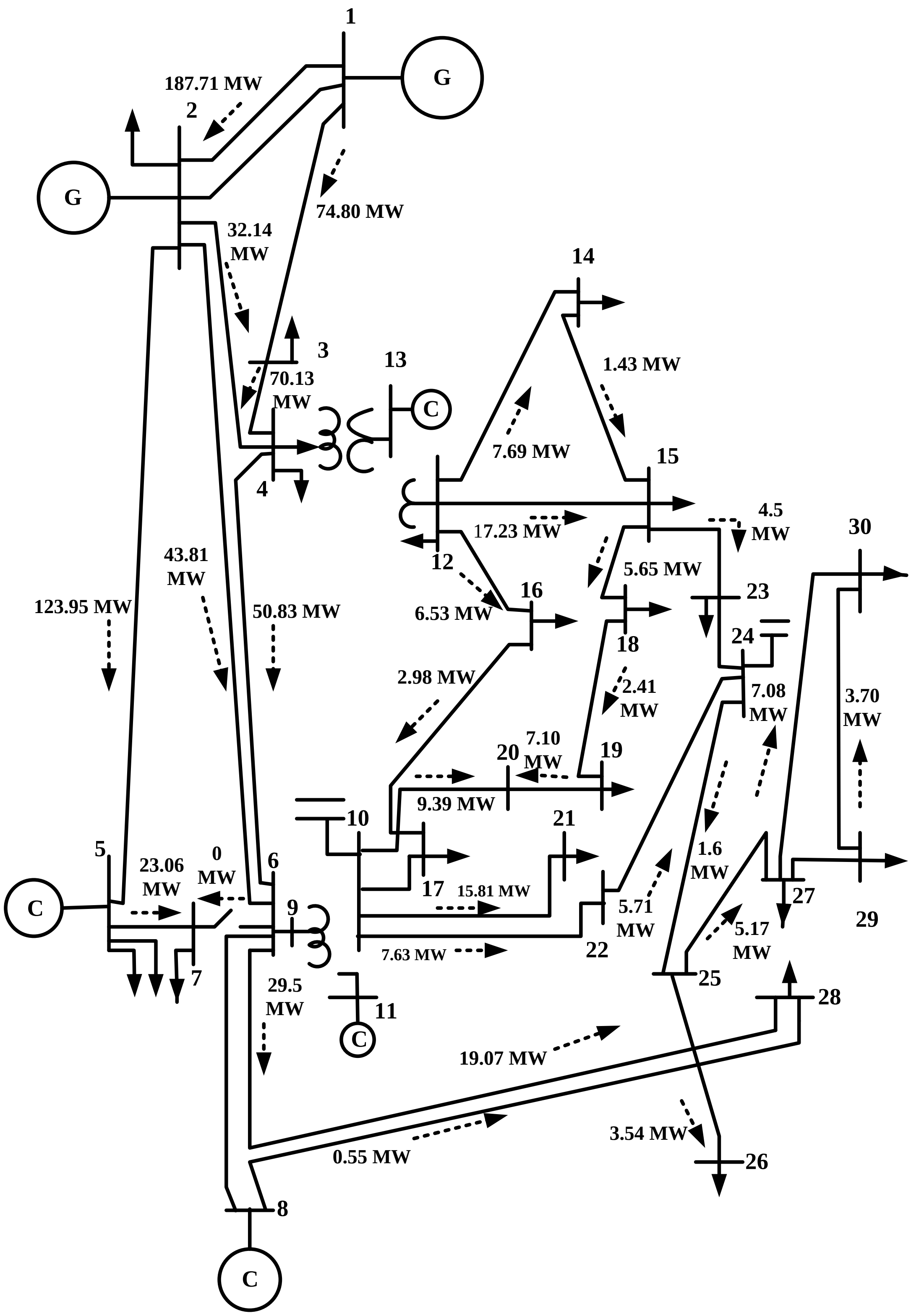


Fig. 2.19 Post-Contingency State of 30-Bus system

2.7 CONCLUDING REMARKS

The methods of contingency analysis using sensitivity factors and AC power flow have been presented, the analysis with AC power flow using FDLF is found most suitable. Since, the list of possible contingency cases is very large for a complex network like power system, hence the approach of contingency selection plays a very important role as it eliminates the large number of contingency cases and focuses on the most severe contingency case. It is highly demanding that the entire process of contingency analysis is done in least time. Hence, to speed up the contingency analysis process as a whole, the computing speed in the selection process must be enhanced.

From the results obtained it can be concluded that the calculation of performance indices gives a good measure about the severity of all the possible line contingencies occurring in the system. The indices with highest value reflect a severe case which has the highest potential to make the system parameters to go beyond their limits. Hence, the most severe contingency case has been chosen from the list of various line contingencies and the post contingency analysis pertaining to this contingency has been done where the most important system parameters like bus voltages and the MW flows have been calculated. The list of severity of contingencies before the power system is put to operation acts as a useful guide to run a reliable system.

CHAPTER-3

CONTINGENCY ANALYSIS USING ARTIFICIAL NEURAL NETWORK

3.1 INTRODUCTION

The contingency analysis process by conventional load flow solution using FDLF can give the solution to the contingency selected only for one loading and generating condition at one go. But practically a power system can have a varying level of operating conditions and to predict the solution of contingency analysis for all the possible and future operating points is an impossible task. In such cases, the use of Artificial Neural Networks (ANN) can be useful. Since ANN has the ability to predict the output for unseen input set once it gets trained with sufficient number of training patterns. It has been used for dynamic nature problems in power system like contingency analysis, load forecasting, component fault detection etc. The ability of Neural Networks to predict the outcome for a new pattern in a fast and accurate manner makes them suitable for online analysis also.

This chapter discusses the brief review of ANN, its application to power system and its ability to solve the contingency analysis problem. The two case studies are used to investigate the solution of contingency selection problem using Radial Basis Function Neural network and the results are discussed thoroughly.

3.2 REVIEW OF ARTIFICIAL NEURAL NETWORKS

The aim of neural network is to mimic the ability of biological neuron or to perform the same kind of processing ability as that of a human brain. It is known that human brain learns by example to which it has experienced in the past and it has the ability to apply this experience for predicting the future situations. The capability of an artificial neural network (ANN) is same as that of a digital computer and it enables parallel processing. The major advantage of using ANN is that once trained the network maps well to any kind of input data and provides an accurate fault tolerant system.

The first model of ANN was proposed by McCulloch & Pitt and following it many researchers proposed various other models of neural net like the Hebbs model, Rossenblatt perceptron model, Hopfield neural network model, Radial Basis Function neural networks and the Vector support machine network model is one of the latest model in the neural net topology [27].

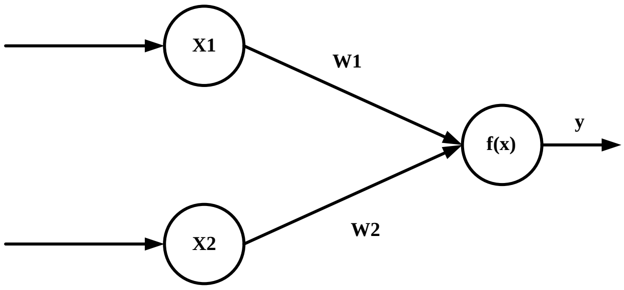


Fig. 3.1 Basic structure of Artificial Neural Network

The basic structure of ANN [27] is shown in Fig. 3.1 where the nodes signify the processing units which are analogous to neurons of a brain, these nodes receives the signals and are transmitted by means of connecting links, these links posses an associated weights which are multiplied by the incoming signal and the output is obtained by applying the activations to the net input.

Out of the various neural network topologies available, the neural networks differed in terms of their ***architecture***, ***learning or training process*** and ***activation functions***. In the following section the characterization of the neural networks based on these parameters have been discussed in brief.

Various types of **architecture** feature are: feed forward network, feed back network, fully recurrent network and competitive network [28].

Feed Forward Net**:** These networks may have single layer of weights where the inputs are directly connected to the outputs or multiple layers with intervening sets of hidden units. Hidden units are used to create internal representations of the input patterns and with adequate number of hidden units, it is possible to approximate arbitrarily any function with a simple feed forward network.

***Competitive Net*:** These networks are similar to single layer feed forward networks except that there are connections, usually negative, between the output nodes, because of these connections the output nodes tend to compete to represent the current input pattern. These outputs can be completely connected and some times the connections are restricted to units that are close to each other. With an appropriate learning algorithm these networks can be made to organize it topologically.

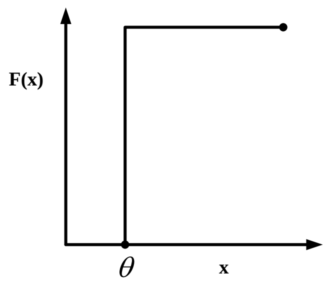
***Recurrent Net*:** In this network architecture all the units are connected to all other units and every unit act as both input and output. Typically, a set of patterns is instantiated on all of the units, one at a time. As each pattern is instantiated the weights are modified, when a degraded version of one of the patterns is presented, the network attempts to reconstruct the pattern.

The process of setting the perfect value of weights between the network layers with an objective to extract an exact output is called training a network. The internal process that takes place during the training is referred to as learning. The common **training methodologies** [28] have been discussed in brief:

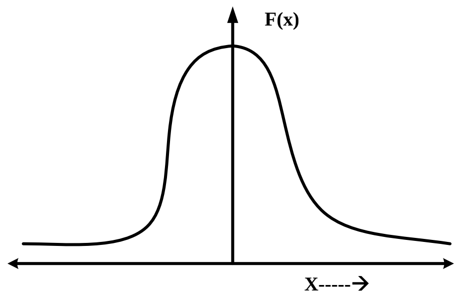
***Supervised Training*:** This kind of training can be considered to as training with the help of a teacher where the new set of inputs are being continuously fed to the network and the output generated from the network is compared with the set of previously generated target data, the error between the actual and the target data is being calculated and based upon this the learning rule is being employed to modify the synaptic weights between the layers. Supervised training is widely used for pattern association; some algorithms employing supervised training are Hebb's rule, delta learning rule, error back propagation etc.

***Unsupervised Training*:** Unsupervised learning rule can be assumed as learning with out a teacher as in this training process the target vectors are not known and this training process is an adaptive one. Here the network modifies its synaptic weights such that the most similar input vector is assigned to the same output unit. This kind of learning is considered to be complex and difficult to implement as it involves looping connections back into feedback layers and iterating through the process until some sort of stable recall can be achieved. Since they have the ability to self learn the networks employing this training paradigm is being referred to as self organizing networks.

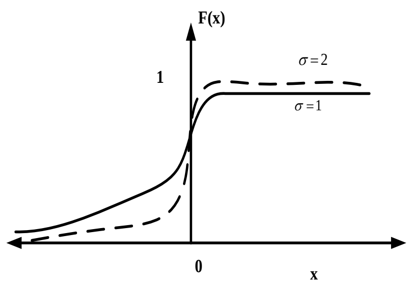
The **Activation functions** [27] are used to calculate the output response of a neuron, the sum of weighted input signal is being applied with an activation to obtain the response, these functions can be linear as well as non linear, where the non linear activation function are used in multilayer networks. Some of the commonly used activation functions are shown in Fig. 3.2, these are detailed in brief.



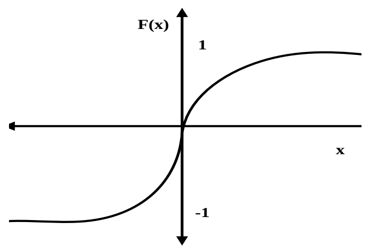
(a) Binary Step Function



(b) Gaussian Activation Function



(c) Binary Sigmoidal Function



(d) Bipolar Sigmoidal Function

Fig. 3.2 Various Activation Function used for ANN

The **Binary Step Function** is given by eq.3.1 here $\boldsymbol{\theta}$ is called the threshold of the activation function the function has been shown in Fig. 3.2(a)

$$\begin{aligned} f(x) &= 1;\ \text{if } f(x) \geq \boldsymbol{\theta} \\ &= 0;\ \text{if } f(x) \leq \boldsymbol{\theta} \end{aligned} \tag{3.1}$$

The **Gaussian Activation Function** gives the exponential measure between an input variable and a bias centre variable; it is given by eq.3.2 this activation function is also known as radial basis function as it is used as an activation function in the hidden neurons of the radial basis neural network. This function is illustrated in Fig. 3.2(b)

$$\boldsymbol{h\|X_i - t_j\| = exp\left(-\frac{||Xi-\mathbf{tj}||^2}{2\sigma^2}\right)} \tag{3.2}$$

where,

X_i is the i^{th} input pattern.

t_j is the j^{th} pattern of the bias centre

$\boldsymbol{\sigma}$ is the spread width

The **Binary Sigmoidal Functions** are usually S-shaped and it is also known as hyperbolic functions or the logistic functions and these are usually used in multilayer networks like the back propagation network. It ranges between 0 and 1 and it is given by;

$$f(x) = \frac{1}{1+\exp(-\sigma x)} \tag{3.3}$$

where, $\boldsymbol{\sigma}$ is called the steepness parameter and if f(x) is differentiated we get,

$f'(x)=\boldsymbol{\sigma} f(x)[1-f(x)]$, the binary sigmoidal function has been illustrated in Fig. 3.2(c)

The **Bipolar Sigmoidal Function** ranges between +1 and -1, and the function is related as hyperbolic tangent function. The bipolar sigmoidal function is given as;

$$f(x) = \frac{1-\exp(-\sigma x)}{1+\exp(-\sigma x)} \tag{3.4}$$

Mostly it is found that bipolar data is generally used hence this activation function is widely used. Fig. 3.2(d) shows the bipolar sigmoidal function.

3.3 CHOICE OF NEURAL NETWORK FOR CONTINGENCY ANALYSIS

Out of several neural network topologies available, it is essential to choose an appropriate neural network which perfectly solves the contingency analysis problem. The use of multi layer perceptron network trained by using error back propagation algorithm is a popular choice for analysis of a complex mapping problem but this suffers from slow rate of convergence and local minima problem. However, the combined use of supervised learning and unsupervised learning can alleviate the problem of local minima. Unsupervised networks can be viewed as a data pre-processing step which reduces the data before learning the data characteristics with supervised learning.

Among the networks like self organising, progressive learning, counter propagation the best non linear mapping capability is provided by the Radial Basis Function Neural Network [30]. It has excellent convergence characteristics on a huge dimensionality and its capability to augment new data with out any retraining makes it a robust tool. Further it has advantages like its structural simplicity, training efficiency and no local minima problem.

3.4 RADIAL BASIS FUNCTION NEURAL NETWORK

The Radial Basis Fuction (RBF) neural networks were first independently proposed by Broomhead *et al.* [22]. This artificial network model is mainly motivated by the "locally tuned" response observed in biological neurons. The RBF architecture has a simple feed forward architecture consisting of three layers, an input layer, one hidden layer and one output layer as shown in Fig. 3.3. The hidden layer activation in RBF is computed using an exponential of a distance measure called the Euclidean distance norm, this layer performs the non linear mapping of the inputs and it commonly uses the Gaussian activation function denoted by Ω(x). Let the RBF network shown in Fig. 3.3 consists an n-dimensional input vector **X** and a total of **J**-neurons in the hidden layer which are fully interconnected to an output layer of **L**-neurons. The outputs of the hidden unit are not calculated using the weighted sum or sigmoidal activation mechanism as used in other networks, rather they are calculated by the exponential measure between the input pattern $\boldsymbol{X_i}$ and the bias centre vector $\mathbf{t_j}$. It is to be noticed that the choice of bias centres are taken randomly from the input training data and the number of bias centres are equal to the number of hidden neurons. The output of the hidden unit $\boldsymbol{h\|X_i - t_j\|}$ is given by eqn.3.5

$$\boldsymbol{h\|X_i - t_j\| = exp\left(-\frac{\|X_i - t_j\|^2}{2\sigma^2}\right)} \tag{3.5}$$

where ,

i takes the value from ***1 to n***,

n signifies the total number of input pattern,

t_j is bias centre vector associated with j^{th} hidden unit,

j takes the value from ***1 to m***,

m signifies the total number of bias centres.

σ is the spread width whose value is being kept greater than 0,

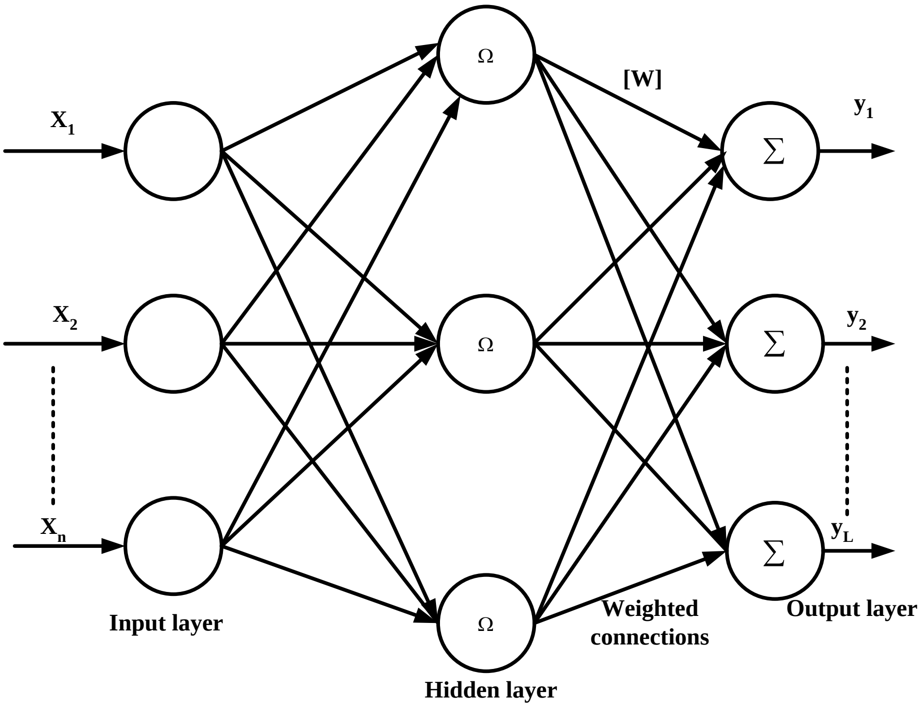


Fig. 3.3 General structure of Radial Basis Function Neural Network

It is to be noted that the input is passed from the input layer to the hidden layer with out any transformation. After computing the signal in accordance to the Gaussian function, the activated output from the hidden neuron is passed on to the linear output neurons through the weighted connected nodes. The size of the weight matrix is **L x J** and the output from the activity vector **y** is given by eqn.3.6

$$\boldsymbol{y_l = \sum_{j=1}^{J} W_{lj} h \left\| X_i - t_j \right\|} \tag{3.6}$$

where, W_{lj} is the synaptic weights connecting hidden neuron j to output neuron l and J is the number of neuron in the hidden layer. There is no formal method for specifying the required number of hidden units in an RBF network. It is to be noted that the weight of the RBF network is determined by a combination of supervised and unsupervised learning, the learning which takes place between the input and hidden layer is unsupervised one and the learning that takes between the hidden and output layer is supervised learning. As the network is required to fit the training data with the desired output $\boldsymbol{d_j}$, where $\boldsymbol{j}$ takes the value from ***1 to n***. It is required to fit the training data as per the eqn.3.7

$$\boldsymbol{y_l = d_j} \tag{3.7}$$

putting the value of eqn.3.7 in eqn.3.6 we obtain the eqn.3.8

$$\boldsymbol{dj = \sum_{j=1}^{J} W_{lj} h \| Xi - tj \|} \tag{3.8}$$

Writing eqn.3.8 in the matrix form we obtain eqn.3.9 given by

$$\mathbf{H.W = d} \tag{3.9}$$

The required weight between the hidden and output unit can be found directly from the above equation. The **H** matrix is not a square matrix, therefore no unique inverse exists for the **H** matrix. Therefore to calculate the weight **W**, the minimum norm solution as explained below is used;

$$\begin{aligned} \mathbf{W} &= \mathbf{H^{+}d} \\ &= \mathbf{(H^{T}H)^{-1}H^{T}d} \end{aligned} \tag{3.10}$$

Here $\mathbf{H^{+}}$ is called the pseudo inverse of matrix **H**

3.5 RBF APPLIED TO CONTINGENCY ANALYSIS

The two performance indices parameters PI_P and PI_V indicating a measure about the severity of the line contingency as discussed in section 2.6, have been evaluated by the use of RBF-ANN. It is clear that when any neural network is applied for a practical problem two modes of operation namely training and testing are performed. In training, sets of training data are used to adjust the weights of the network. Where as, in testing the network response is being seen for the new data which had not been used in training. For the contingency analysis problem the training data has been obtained by using conventional load flow solution for different loading levels and generation scenarios. The training phase has been carried out till the error between the desired and the actual output is small. Where as, testing is done using the data of loading levels that had not been used in the training phase. The RBF-ANN consists of three layers namely input, hidden and output layer, it's the hidden layer which computes the output by an exponential measure between the input data and a sample data. A generalized adopted model for the input, hidden and output layer which has been used for Contingency analysis is shown in Fig. 3.4, the salient features are:

- *The Input layer* should include as many neurons as required for the desired input information. Generally the power injections for generator and load bus are chosen as the raw inputs to the ANN. It is advantageous to choose the power injections as the input data since they are readily available where as the parameters like bus voltages and phase angles cannot be obtained directly. The input layer [x] consists of power injections, P and Q at the generator and load buses, and the value K_i which represents the outage of line *i*, a sample of input pattern has been shown:

$$[x] = [P_{G1}, Q_{G1}, \ldots\ldots\ldots P_{Gg}, Q_{Gg}, \quad P_{L1}, Q_{L1}, \ldots\ldots\ldots P_{Ln}, Q_{Ln}, K_i] \tag{3.11}$$

Where,

G is the generator bus,

g is the number of generators in the power system,

L load bus,

n is the number of load buses

K_i is the number denoting the outaged line.

- *The Middle layer* does not have any criteria for selecting the number of neurons and the choice of the number of neurons in this layer is based on experimentation and simulation, in general the more the number of neurons in the middle layer the better the network can fit the targets while too many neurons in the middle layer can result in over fitting hence the process of experimentation is purely followed for selecting the number of neurons.

- *The Output layer* consists of an output vector [O] with two elements which are the active and reactive power performance indices PI_P and PI_V respectively, i.e.,

$$[O] = [PI_P, PI_V] \tag{3.12}$$

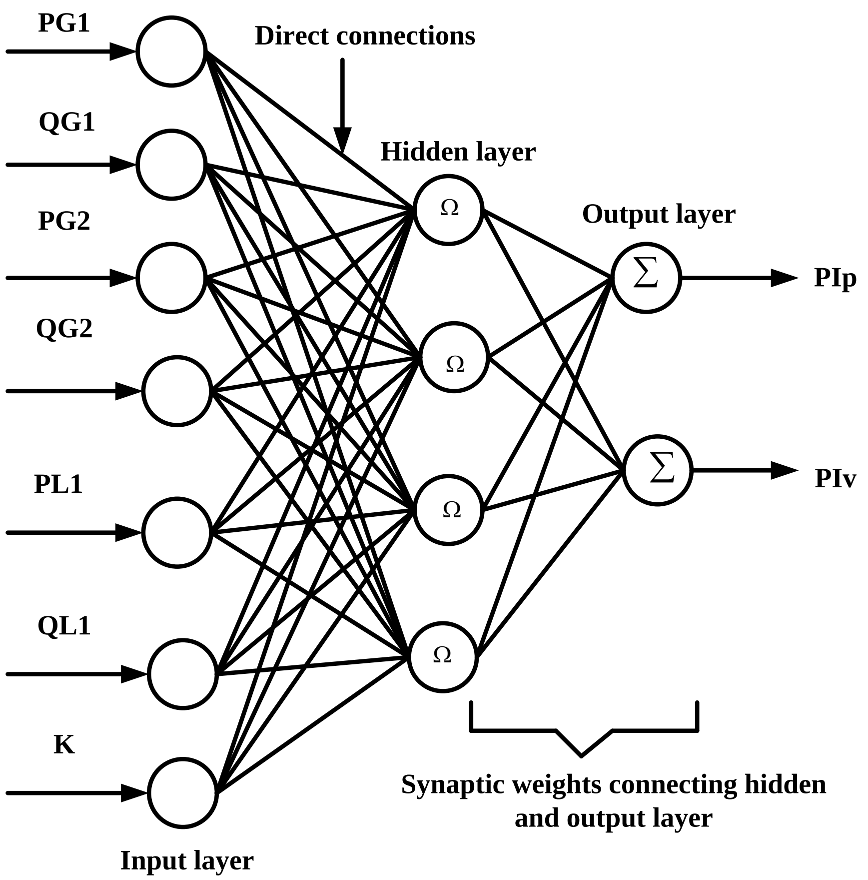


Fig. 3.4 RBF network used for Contingency Analysis

3.5.1 Algorithm for PI_P and PI_V Indices prediction using RBF-ANN

The solution algorithm for the prediction of the active and reactive power performance indices (PI_P & PI_V) is given below:

1. Carry out the fast decouple load flow analysis for all the single line outage cases and calculate the PI_P and PI_V. The indices obtained from this stage are considered as the desired output.
2. Select inputs for the RBFN $[x] = [P_{G1}, Q_{G1}, \ldots\ldots, P_{Gg}, Q_{Gg}, P_{L1}, Q_{L1}, \ldots\ldots\ldots, P_{Ln}, Q_{Ln}, K_i]$
3. Select the number the number of neurons in the middle layer and determine the bias centres $\mathbf{t_j}$ from the input training vector.
4. Select the appropriate value of the spread $\boldsymbol{\sigma}$.
5. Calculate the output of the j^{th} hidden unit using the eq.3.5.
6. Calculate the output of the l^{th} unit of the output neuron y_l using eq.3.6.
7. Calculate the weight matrix that solves the network specification using eq.3.10.
8. Select the test data for the network, these data are chosen different from the data that had been used for the training purpose.
9. Use the weight matrix obtained in step (7) to compute the output from the output layer.
10. Check if the output obtained in step (9) is close to the desired output, if yes then stop, else change the value of number of bias centres and spread and repeat steps (5-9).

The flow chart of the above algorithm has been illustrated in the Fig. 3.5

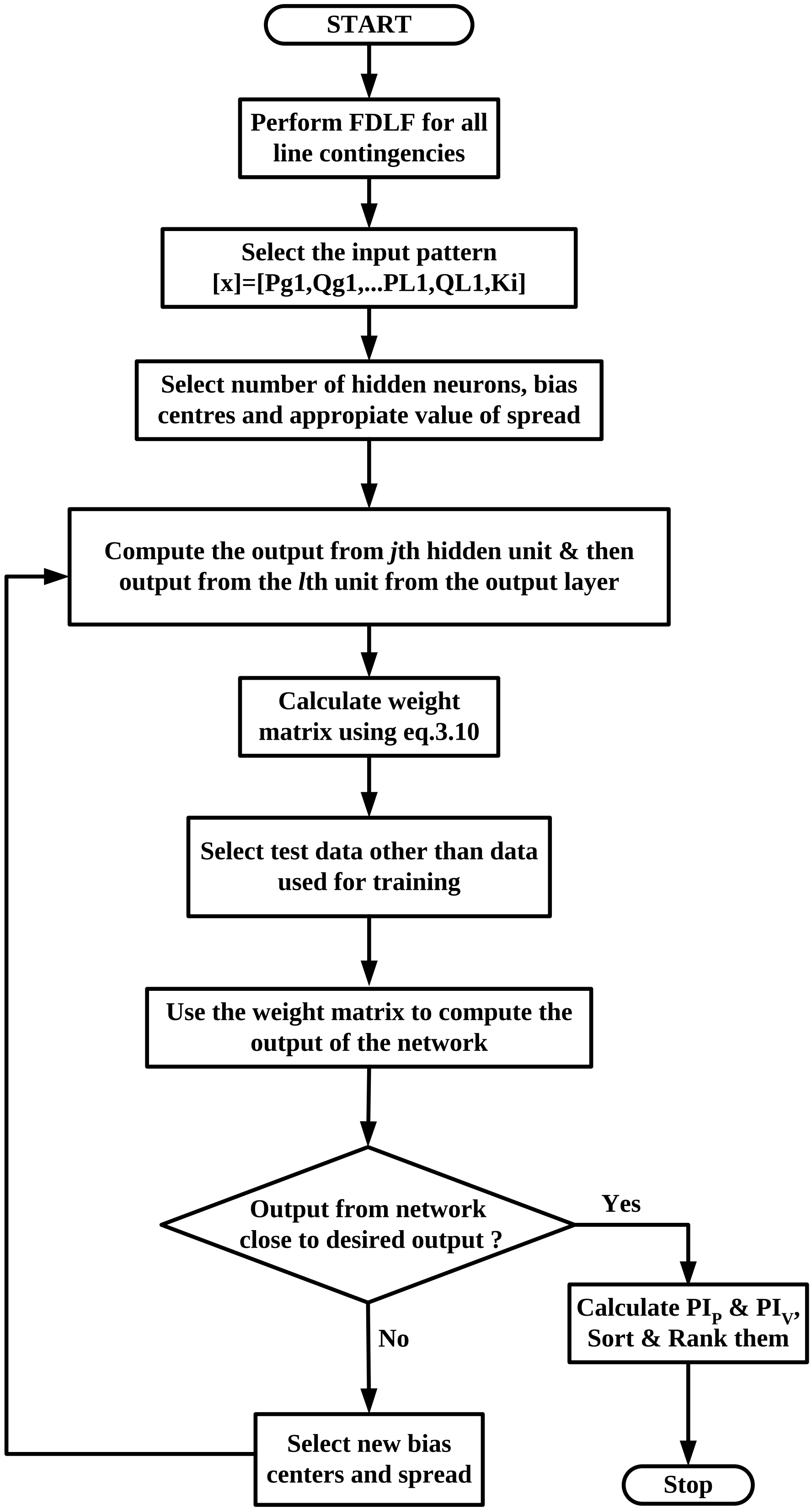


Fig. 3.5 Flowchart for Performance Indices prediction using RBF-ANN

3.6 RESULTS AND DISCUSSION

In this section, the results of contingency analysis problem using RBF neural network have been presented. The algorithms are implemented in MATLAB for the above. The main objective is to determine the active and reactive power performance indices which form an important part of contingency analysis for different bus systems. The algorithms have been evaluated on two set of bus systems which are being referred as Case I and Case II.

Case I: 5 - Bus System [36].

Case II: 14 - Bus Test System [37].

3.6.1 Case I: 5- Bus System

The bus data and line data specifications of the five bus test system have been given in APPENDIX A. The results of active power performance index PI_P and reactive power performance indices PI_V for the base case loading condition of 1650 MW is obtained by using the RBF neural network has been given in Table 3.1.

Table 3.1

Performance Indices and Contingency Ranking using RBF ANN for 5-BUS SYSTEM

Contingency Number (Line Outage No.)	PI_P	PI_V	Ranking
1	**0.2908**	**3.7433**	**1**
2	0.3755	0.2773	7
3	0.3302	0.6739	5
4	0.3926	0.7281	4
5	0.4149	0.3945	6
6	0.3021	0.9203	2
7	0.3047	0.8791	3

Table 3.2 shows the comparative results of the active power performance index PI_P obtained using fast decoupled load flow solution and using RBF neural network. Fig 3.6 shows the graphical representation of the closeness of the results obtained using FLDF and

RBF-ANN. It is found that the network fits the desired data well for seven hidden neuron in the hidden layer and for a spread value of **σ**=2.5.

Table 3.2

Active Power Performance Index using FDLF& RBF ANN for 5-BUS SYSTEM

Contingency Number (Line Outage No.)	**PI_P by FDLF**	**PI_P by RBF ANN**	**Error**
1	0.2800	0.2908	-0.0108
2	0.3619	0.3755	-0.0136
3	0.3377	0.3302	-0.0105
4	0.3790	0.3926	-0.0549
5	0.4221	0.4149	0.0072
6	0.2995	0.3021	-0.0026
7	0.3036	0.3047	-0.0011

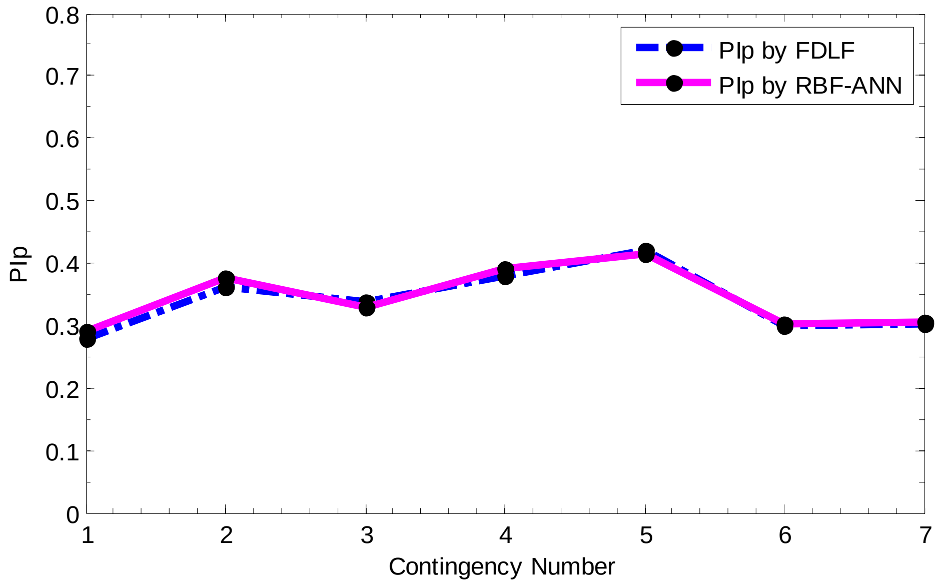


Fig. 3.6 Curves representing PI_P obtained by FDLF & RBFN-ANN

Table 3.3 shows the comparative results of the reactive power performance index PI_V obtained using fast decoupled load flow solution and using RBF neural network. Fig 3.7 shows the graphical representation of the closeness of the results obtained using FLDF and RBF-ANN.

Table 3.3

Reactive Power Performance Index using FDLF& RBF ANN for 5-BUS SYSTEM

Contingency Number (Line Outage No.)	**PI_V by FDLF**	**PI_V by RBF ANN**	**Error**
1	3.1916	3.7433	-0.5517
2	0.2699	0.2773	-0.0074
3	0.6557	0.6739	-0.0182
4	0.6173	0.7281	0.0254
5	0.2653	0.3945	-0.1108
6	0.8599	0.9203	-0.0604
7	0.8799	0.8791	0.0008

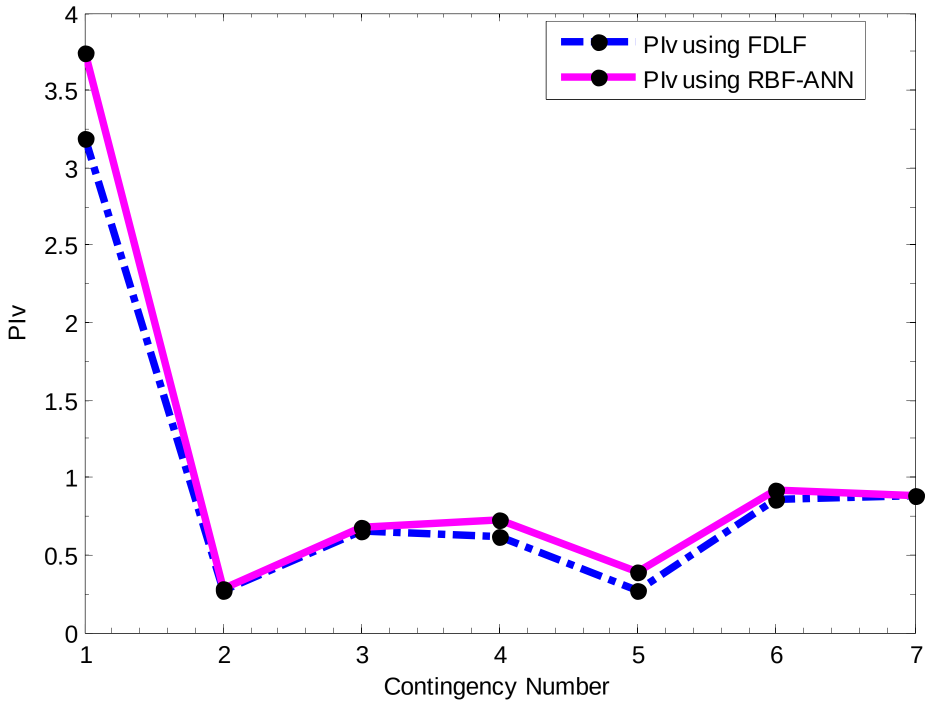


Fig. 3.7 Curves representing PI_V obtained by FDLF & RBFN-ANN

3.6.2 Case II: 14- Bus Test System

The bus data and line data specification for the fourteen bus test system has been given in APPENDIX B. The results of active power performance index PI_P and reactive power performance indices PI_V obtained by using the RBF neural network for a loading level of 10% above the base case i.e. at 2849 MW are given in Table 3.4.

Table 3.4

Performance Indices & Contingency Ranking using RBF-ANN for 14-Bus System

Contingency number	PI_P	PI_V	Ranking
1	1.2028	10.2083	7
2	0.9598	8.6043	9
3	1.1377	9.3682	8
4	1.1606	6.5453	12
5	1.1470	8.2748	10
6	1.1533	11.1543	4
7	1.0093	0.4456	20
8	1.0716	1.0975	19
9	1.0348	12.3597	2
10	1.2497	5.1175	13
11	0.8854	10.8292	5
12	0.9590	2.5526	15
13	1.0512	1.9572	18
14	1.1175	8.1495	11
15	1.0464	3.2304	14
16	**1.0425**	**12.8313**	**1**
17	1.0432	2.4524	16
18	1.1353	10.5126	6
19	0.9874	12.0493	3
20	1.0500	2.2493	17

Table 3.5 shows the comparative results of the active power performance index PI_P obtained using fast decoupled load flow solution and using RBF neural network. Fig 3.8 shows the graphical representation of the closeness of the results obtained using FLDF and RBF-ANN. It is found that the network fits the desired data well for fifteen hidden neuron in the hidden layer and for a spread value of **σ**=10.

Table 3.5

Active Power Performance Index using FDLF& RBF ANN for 14-BUS SYSTEM

Contingency Number (Line Outage No.)	**PI_P by FDLF**	**PI_P by RBF ANN**	**Error**
1	1.1693	1.2028	-0.0335
2	0.9807	0.9598	0.0209
3	1.1654	1.1377	0.0277
4	0.9999	1.1606	-0.1607
5	0.9820	1.1470	-0.1650
6	0.9640	1.1533	-0.1893
7	0.9915	1.0093	-0.0178
8	1.0747	1.0716	0.0031
9	0.9807	1.0348	-0.0541
10	1.2396	1.2497	-0.0101
11	1.0142	0.8854	0.1288
12	1.0127	0.9590	0.0537
13	1.0569	1.0512	0.0057
14	1.0072	1.1175	-0.1103
15	1.0759	1.0464	0.0295
16	1.0114	1.0425	-0.0311
17	1.0164	1.0432	-0.0268
18	1.0030	1.1353	-0.1323
19	1.0008	0.9874	0.0134
20	1.0076	1.0500	-0.0424

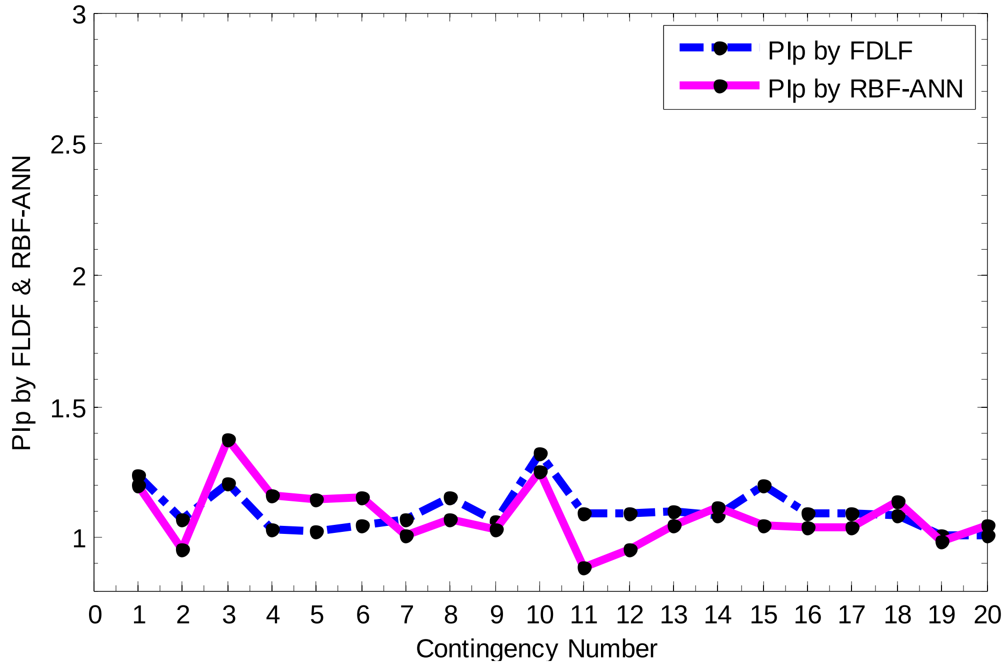


Fig. 3.8 Curves representing PI_P obtained by FDLF & RBFN-ANN

Table 3.6 shows the comparative results of the reactive power performance index PI_V obtained using fast decoupled load flow solution and using RBF neural network. Fig 3.9 shows the graphical representation of the closeness of the results obtained using FLDF and RBF-ANN.

Table 3.6

Reactive Power Performance Index using FDLF& RBF ANN for 14-BUS SYSTEM

Contingency Number (Line Outage No.)	**PI_V by FDLF**	**PI_V by RBF ANN**	**Error**
1	7.2973	10.2083	-2.9110
2	7.6650	8.6043	-0.9393
3	10.0117	9.3682	0.6435
4	7.3190	6.5453	0.7737
5	8.8736	8.2748	0.5988
6	13.2526	11.1543	2.0983
7	0.3520	0.4456	-0.0936
8	1.1707	1.0975	0.0732

9	10.5730	12.3597	-1.7867
10	1.6001	5.1175	-3.5174
11	9.5884	10.8292	-1.2408
12	1.8043	2.5526	-0.7483
13	1.3646	1.9572	-0.5926
14	10.4472	8.1495	2.2977
15	0.0798	3.2304	-3.1506
16	13.3418	12.8313	0.5105
17	2.3436	2.4524	-0.1088
18	10.5171	10.5126	0.0045
19	12.5492	12.0493	0.4999
20	2.2845	2.2493	0.0352

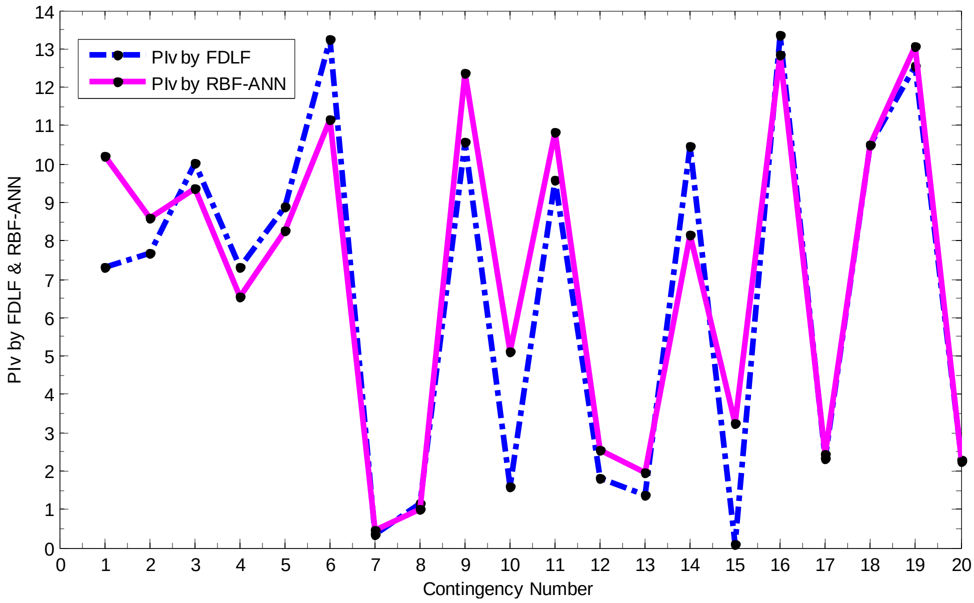


Fig. 3.9 Curves representing PI$_V$ obtained by FDLF & RBFN-ANN

***Comparison of computation time*:** The computation time taken for contingency selection by FDLF and RBF-ANN method for the two bus systems have been detailed in Table 3.7.

Table 3.7

Computation time by FDLF& RBF- ANN

Bus System	By FDLF	By RBF
5-Bus	4.9 Sec	0.007 Sec
14-Bus	17.4 Sec	0.04 Sec

From the above table it can easily inferred that the contingency selection process by the use of RBF-ANN is much faster as compared to the FDLF method. The same inference has been illustrated in Fig. 3.10.

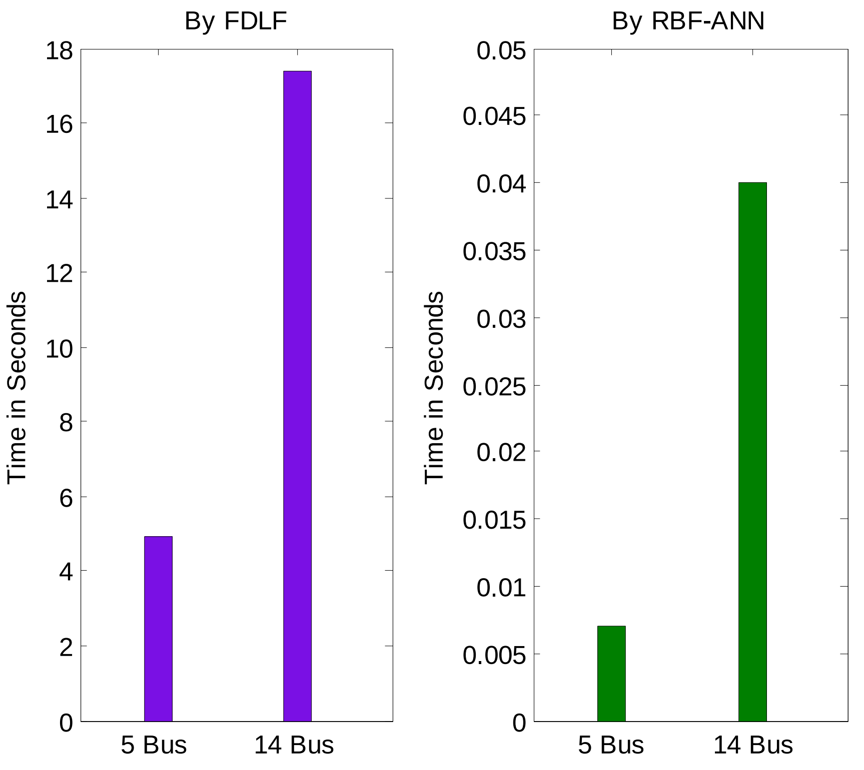


Fig. 3.10 Curves representing computation time by FDLF & RBFN-ANN

3.7 CONCLUDING REMARKS

The algorithm for performing the contingency analysis for five bus and fourteen bus test system have been implemented using Radial Basis Function neural network, the main focus has been to perform the fast contingency selection for the possible line contingencies by calculating the two types of performance indices namely PI_P and PI_V. It has been observed that when correct number of hidden neurons and bias centres are chosen for the network the results obtained using RBF-ANN are very much close to that which has been obtained using FDLF. But the neural network has the ability to perform the contingency selection for any loading and generating conditions once it gets correctly trained. Thus the algorithm provides a much faster and accurate solution for contingency analysis. The prediction of performance indices is instantaneous when calculated though RBF-ANN and hence it can put to use for online applications in power system.

CHAPTER-4

CONCLUSION AND FUTURE SCOPE

4.1 CONCLUSIONS

In this work, the contingency selection and ranking which are important for contingency analysis have been done by evaluating two important performance indices namely; active and reactive power performance index (PI_P & PI_V). These indices were calculated for various test bus systems using the Fast Decoupled Load Flow (FDLF) algorithm and also by using Radial Basis Function (RBF) Neural Network in MATLAB environment. The study has been carried out for the three test systems namely 5-Bus, IEEE-14 Bus and IEEE-30 Bus, the satisfactory performance has been obtained for 5-Bus and 14-Bus system using RBF. The following conclusions are drawn:

- The severity of a single line outage is accurately indicated by the numerical values of PI_P and PI_V respectively.
- The indices are predicted in off line manner for a single loading condition by FDLF. The calculation of these indices using FDLF algorithm proves to be time consuming.
- The contingency selection by RBF-ANN proves to be efficient in terms of accuracy and time. It has the ability to calculate the performance indices following a contingency for any loading case once it is effectively trained.

4.2 SCOPE FOR FURTHUR WORK

The followings can be taken up for further study and analysis:

- The training for large systems like 30-Bus system and the structure of RBF-ANN like, neurons in hidden layer need to be investigated further.
- To perform the contingency analysis and the contingency selection considering a multiple line or equipment failures.
- Implement a hardware model for the neural network so that it can be used for online applications in power system contingency analysis.

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APPENDIX-A

The bus data and line for the 5 bus test system has been given in Table A.1 and A.2 respectively. The following conventions were used for all the test bus systems; Base MVA = 100; Coding used for buses: 0-Load Bus, 1-Slack Bus, 2-PV Bus.

Table A.1

Bus Data of 5-Bus System

Bus No.	Bus code	Voltage Mag.	Angle Degree	Load MW (pu)	Load MVAR (pu)	Gen. MW (pu)	Gen. MVAR (pu)	Gen. Qmin	Gen. Qmax	Injec. MVAR
1	1	1.06	0.0	0.00	0.00	0.0	0.0	0.0	0.0	0.0
2	0	1.0	0.0	0.20	0.10	0.4	0.3	0.0	0.0	0.0
3	0	1.0	0.0	0.45	0.15	0.0	0.0	0.0	0.0	0.0
4	0	1.0	0.0	0.40	0.05	0.0	0.0	0.0	0.0	0.0
5	0	1.0	0.0	0.60	0.15	0.0	0.0	0.0	0.0	0.0

Table A.2

Line Data of 5-Bus System

Start Bus	End Bus	R (pu)	X (pu)	½ B (pu)	Tap Set value
1	2	0.0200	0.0600	0.0300	1
1	3	0.0800	0.2400	0.0250	1
2	3	0.0600	0.1800	0.0200	1
2	4	0.0600	0.1800	0.0200	1
2	5	0.0400	0.1200	0.0150	1
3	4	0.0100	0.0300	0.0100	1
4	5	0.0800	0.2400	0.0250	1

APPENDIX-B

The bus data and line data of IEEE-14 bus system has been given in Table B.1 and B.2 respectively.

Table B.1

Bus Data of IEEE-14 Bus System

Bus No.	Bus code	Voltage Mag.	Angle Degree	Load MW	Load MVAR	Gen. MW	Gen. MVAR	Gen. Qmin.	Gen. Qmax.	Injec. MVAR
1	2	1.06	0.0	0.0	0.0	232.0	0.0	-10.0	10.0	0
2	1	1.05	0.0	21.7	12.7	40.0	-42.4	-0.4	0.5	0
3	2	1.04	0.0	94.0	19.0	0.0	0.0	0.0	0.4	0
4	0	1.0	0.0	47.8	0.00	0.0	0.0	0.0	0.0	0
5	0	1.0	0.0	7.6	1.60	0.0	0.0	0.0	0.0	0
6	2	1.08	0.0	11.2	7.5	0.0	0.0	-0.06	0.24	0
7	0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
8	2	1.071	0.0	0.0	0.0	0.0	0.0	-0.06	0.24	0
9	0	1.0	0.0	29.5	16.6	0.0	0.0	0.0	0.0	0
10	0	1.0	0.0	9.00	5.80	0.0	0.0	0.0	0.0	0
11	0	1.0	0.0	3.50	1.80	0.0	0.0	0.0	0.0	0
12	0	1.0	0.0	6.10	1.60	0.0	0.0	0.0	0.0	0
13	0	1.0	0.0	13.50	5.80	0.0	0.0	0.0	0.0	0
14	0	1.0	0.0	14.90	5.00	0.0	0.0	0.0	0.0	0

Table B.2

Line Data of IEEE-14 Bus System

Start Bus	**End Bus**	**R (pu)**	**X (pu)**	**½ B (pu)**	**Tap Set value**
1	2	0.01938	0.05970	0.05280	1
1	5	0.05403	0.22304	0.0492	1
2	3	0.0125	0.19797	0.0438	1
2	4	0.05811	0.17632	0.0374	1
2	5	0.05695	0.17388	0.034	1
3	4	0.06701	0.17103	0.0346	1
4	5	0.01335	0.04211	0.0128	1
4	7	0.0	0.20912	0.00	0.978
4	9	0.0	0.55618	0.00	0.969
5	6	0.0	0.25202	0.00	0.932
6	11	0.09498	0.1989	0.00	1
6	12	0.12291	0.25581	0.00	1
6	13	0.06615	0.13027	0.00	1
7	8	0.0	0.17615	0.00	1
7	9	0.0	0.11001	0.00	1
9	10	0.03181	0.08450	0.00	1
9	14	0.12711	0.27038	0.00	1
10	11	0.08205	0.19207	0.00	1
12	13	0.22092	0.19988	0.00	1
13	14	0.17093	0.34802	0.00	1

APPENDIX-C

The bus data and line data has been given in Table C.1 and C.2 respectively.

Table C.1

Bus Data of IEEE-30 Bus System

Bus No.	Bus code	Voltage Mag.	Angle Degree	Load MW	Load MVAR	Gen. MW	Gen. MVAR	Gen. Qmin.	Gen. Qmax.	Injec. MVAR
1	1	1.06	0	0.0	0.0	0.0	0.0	0	0	0
2	2	1.043	0	21.70	12.7	40.0	0.0	-40	50	0
3	0	1.0	0	2.4	1.2	0.0	0.0	0	0	0
4	0	1.06	0	7.6	1.6	0.0	0.0	0	0	0
5	2	1.01	0	94.2	19.0	0.0	0.0	-40	40	0
6	0	1.0	0	0.0	0.0	0.0	0.0	0	0	0
7	0	1.0	0	22.8	10.9	0.0	0.0	0	0	0
8	2	1.01	0	30.0	30.0	0.0	0.0	-10	40	0
9	0	1.0	0	0.0	0.0	0.0	0.0	0	0	0
10	0	1.0	0	5.8	2.0	0.0	0.0	0	0	19
11	2	1.082	0	0.0	0.0	0.0	0.0	-6	24	0
12	0	1.0	0	11.2	7.5	0.0	0.0	0	0	0
13	2	1.071	0	0.0	0.0	0.0	0.0	-6	24	0
14	0	1.0	0	6.2	1.6	0.0	0.0	0.0	0.0	0
15	0	1.0	0	8.2	2.5	0.0	0.0	0.0	0.0	0
16	0	1.0	0	3.5	1.8	0.0	0.0	0.0	0.0	0
17	0	1.0	0	9.0	5.8	0.0	0.0	0.0	0.0	0
18	0	1.0	0	3.2	0.9	0.0	0.0	0.0	0.0	0
19	0	1.0	0	9.5	3.4	0.0	0.0	0.0	0.0	0
20	0	1.0	0	2.2	0.7	0.0	0.0	0.0	0.0	0
21	0	1.0	0	17.5	11.2	0.0	0.0	0.0	0.0	0
22	0	1.0	0	0.0	0.0	0.0	0.0	0.0	0.0	0
23	0	1.0	0	3.2	1.6	0.0	0.0	0.0	0.0	0
24	0	1.0	0	8.7	6.7	0.0	0.0	0.0	0.0	4.3
25	0	1.0	0	0.0	0.0	0.0	0.0	0.0	0.0	0
26	0	1.0	0	3.5	2.3	0.0	0.0	0.0	0.0	0

27	0	1.0	0	0.0	0.0	0.0	0.0	0.0	0.0	0
28	0	1.0	0	0.0	0.0	0.0	0.0	0.0	0.0	0
29	0	1.0	0	2.4	0.9	0.0	0.0	0.0	0.0	0
30	0	1.0	0	10.6	1.9	0.0	0.0	0.0	0.0	0

Table C.2

Line Data of IEEE-30 Bus System

Start Bus	End Bus	R (pu)	X (pu)	½ B (pu)	Tap Set value
1	2	0.0192	0.0575	0.02640	1
1	3	0.0452	0.1852	0.02040	1
2	4	0.0570	0.1737	0.01840	1
3	4	0.0132	0.0379	0.00420	1
2	5	0.0472	0.1983	0.02090	1
2	6	0.0581	0.1763	0.01870	1
4	6	0.0119	0.0414	0.00450	1
5	7	0.0460	0.1160	0.01020	1
6	7	0.0267	0.0820	0.00850	1
6	8	0.0120	0.0420	0.00450	1
6	9	0.0	0.2080	0.0	0.978
6	10	0.0	0.5560	0.0	0.969
9	11	0.0	0.2080	0.0	1
9	10	0.0	0.1100	0.0	1
4	12	0.0	0.2560	0.0	0.932
12	13	0.0	0.1400	0.0	1
12	14	0.1231	0.2559	0.0	1
12	15	0.0662	0.1304	0.0	1
12	16	0.0945	0.1987	0.0	1
14	15	0.2210	0.1997	0.0	1
16	17	0.0824	0.1923	0.0	1
15	18	0.1073	0.2185	0.0	1

18	19	0.0639	0.1292	0.0	1
19	20	0.0340	0.0680	0.0	1
10	20	0.0936	0.2090	0.0	1
10	17	0.0324	0.0845	0.0	1
10	21	0.0348	0.0749	0.0	1
10	22	0.0727	0.1499	0.0	1
21	22	0.0116	0.0236	0.0	1
15	23	0.1000	0.2020	0.0	1
22	24	0.1150	0.1790	0.0	1
23	24	0.1320	0.2700	0.0	1
24	25	0.1885	0.3292	0.0	1
25	26	0.2544	0.3800	0.0	1
25	27	0.1093	0.2087	0.0	1
28	27	0.0000	0.3960	0.0	0.968
27	29	0.2198	0.4153	0.0	1
27	30	0.3202	0.6027	0.0	1
29	30	0.2399	0.4533	0.0	1
8	28	0.0636	0.2000	0.0214	1
6	28	0.069	0.0599	0.065	1