Multiple Contingency Analysis of Power Systems

By

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Abstract

Power system security and reliability has a higher priority in power system operations. Power systems are exposed to any failures due to their structures. Preventing any unscheduled outage from happening within the power system is impossible, but analyzing possible outages in order to predict their consequences is essential. Contingency analysis is an important tool in evaluating power system security. It models any single or multiple outages to predict power system state variables after them. By analyzing and preparing for outages, their consequences can be contained.

The N-1 contingency which models any single outages of a power system is studied. A DC power flow is used to identify critical single line outages, and the selected critical contingencies are evaluated in detail by an AC power flow. A DC power flow performance in estimating line active power flow is evaluated by an appropriate index. It is shown that a DC power flow has an acceptable performance in contingency analysis.

The main goal of this study is to identify critical double line outages whose outage will lead to line flow violations in a power system. This is defined as N-2 contingency analysis. Evaluating all possible N-2 contingencies is a huge burden computationally. Identifying important double line outages without evaluating all N-2 contingencies by either an AC power flow or DC power flow is possible. Screening algorithms are used to identify critical outages based on line outage distribution factors and N-1 contingency analysis. The results are compared to the ones obtained from full AC power flow. It is shown that these algorithms are able to identify a very high percentage of the double line outages that result in line flow violations.

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Chapter 1

Introduction

1.1 Background of the Research

An electric power system consists of generation, transmission and distribution subsystems that connects power providers and customers. It is a large and critical infrastructure, and it has an essential influence on functioning of society and economy. A big interruption in power system, called blackout, affects a large portion of society and creates a lot of problems for a huge number of customers that may extend over significant time periods. Such disruptions result in direct and indirect losses.

The complexity and dynamic of power system have been increasing due to the increase in renewable resources' penetration and the maximum loading of the systems to fulfill the economic expectations. The security of electrical power system is the first priority in both power system planning and operation, and contingency analysis is an important tool used to assess security under both topological changes and component failures. Power system operators extensively use contingency analysis to decide preventive and corrective control actions in power system operation.

Contingency analysis is an essential tool to evaluate system security under component failures and topological changes. The preventive and corrective control decisions are taken based on contingency analysis. To ensure secure operation of the power system, large number of contingencies must be considered and analyzed during the power system planning and operation [1, 2].

The N-1 security criterion is a common standard for assessing the security of power systems. According to this criterion, planned power system should withstand against any single component failure without any violation in other component constraints while supporting all loads in the system. Indeed, N-1 contingency criterion refers to the ability of system to move from one stable operation to another without any violation after the contingency (the loss of a transmission line or a generator) occurs.

The N-1 contingency criterion may not be sufficient when multiple component failures take place simultaneously. The N-K contingency analysis seems to be inevitable considering serious blackouts due to multiple component failures. The N-K contingency criterion means that a power system should be able to withstand K component failures simultaneously [3, 4].

1.2 Objectives of the Research

The purpose of this thesis is to study the contingency analysis of power system considering multiple line outages (N-2 contingencies). The first goal of this research is to study and implement existing methodologies for N-1 contingency analysis. An AC power flow and various DC power flow models and their applications in power system steady state analysis in both normal mode and contingent mode of operations are studied. Active and Reactive

Power Performance Indices will be investigated through DC and AC power flow analysis. The N-2 contingency analysis and screening methods are investigated next.

The number of multiple contingencies, even in moderate network, is high. This makes a technical challenge to process all possible contingencies in a power system using an AC power flow analysis, although it is the most accurate method to analyze a power system in steady state operation mode. High speed computers with parallel implementation could be a solution to overcome computational constraints. The other way is using a DC power flow analysis, a linear model of the power system, in contrast with a nonlinear AC power flow analysis in power system contingency analysis. This method is fast but not as accurate as the AC power flow method.

Linear sensitivity factors calculated by a DC power flow are used to estimate power flow change in transmission lines due to the change in a power system operation. Power Transfer Distribution Factors (PTDFs) estimate line flow changes for a power shift between two buses of the system. Line Outage Distribution Factors (LODFs) estimate line flow changes for any line outage in the system. These factors are used to evaluate a power system operation after any outage in the system. These are fast but their accuracy depends on the system topology and load.

Contingency screening is an important step in contingency analysis. Through this step, contingencies are listed in descending order based on their importance. A transmission line whose outage causes severe outages in the system will appear in top of the list. Different Performance Indices are used to classify contingencies. Important contingencies are identified by a DC power flow analysis. All possible contingencies in the system are analyzed using a DC power flow and classified by different performance indices. A few highly ranked contingencies are selected based on their performance indices for further analysis using an AC power flow.

In this research, a DC power flow performance is evaluated in different power operating conditions. Distribution Factors and Performance Indices capabilities in contingency screening are discussed for both N-1 and N-2 transmission line outages. Different IEEE benchmark systems are used to evaluate the performance of the mentioned methods. PowerWorld and MATLAB software are used in modeling and simulation of the systems.

1.3 Organization of the Thesis

In chapter 2, blackout history of various power systems is discussed. Most important blackouts in different continents are explained. Main reasons, corrective actions and severity of each contingency are classified.

Power system steady state is modeled in chapter 3. An AC power flow is modeled and analyzed. Various DC power flow models are investigated. Various DC power flow model performances in estimating line active power flows are evaluated. Root mean square error is used to evaluate various DC power flow models. A DC power flow performance is evaluated in comparison to an AC power flow.

Chapter 4 discusses N-1 contingency for power system. The importance of power system security is explained. Sensitivity factors and their application in contingency analysis are formulated. Contingency selection and performance indices are explained. Case studies are done to evaluate N-1 contingency using different methods.

Chapter 5 explains N-2 contingency comprehensively. Different contingency selection methods for N-2 contingencies are discussed completely. A small system is simulated to explain strengths and weakness of the discussed methods. In chapter 6, N-2 contingency is explained further using a case study.

The key contributions of the research and suggestions for possible future work are highlighted and summarized in chapter 7.

Chapter 2

History of Electrical Power System Blackouts

2.1 Introduction

The electrical energy is the most dominant form of energy that is used in all part of the world for different kinds of purposes. It has been used in industrial, commercial, transportation and domestic sectors. Imagining the world without electrical energy is unbelievable. It has been used in all aspect of human life because of its outstanding characteristics. It is produced in generation centers and transferred economically over a long distance. It is easy to control electrical energy in comparison to different other forms of energy. It has less environmental side effects.

Safety, reliability and efficiency are three major objectives in power system operations. Power system operation is an important task since it can affect people's life dramatically. Figure 2.1 demonstrates the basic structure of a power system[5]. Electrical energy is produced in generating units, stepped up to higher voltage by transformers, transferred through transmission systems, and supplied to costumers by distribution systems. It is better to have generating units close to load centers, but the locations for generating units are defined by primary energy resources and environmental concerns. Practically, integrated transmission systems connect load centers to the bulk generating units within the country or even within the bigger region. Figure 2.2 shows the time trend for transmission system development, and Fig. 2.3 shows the North America interconnected system[5]. Interconnected systems have economic, security and reliability benefits[5, 6].

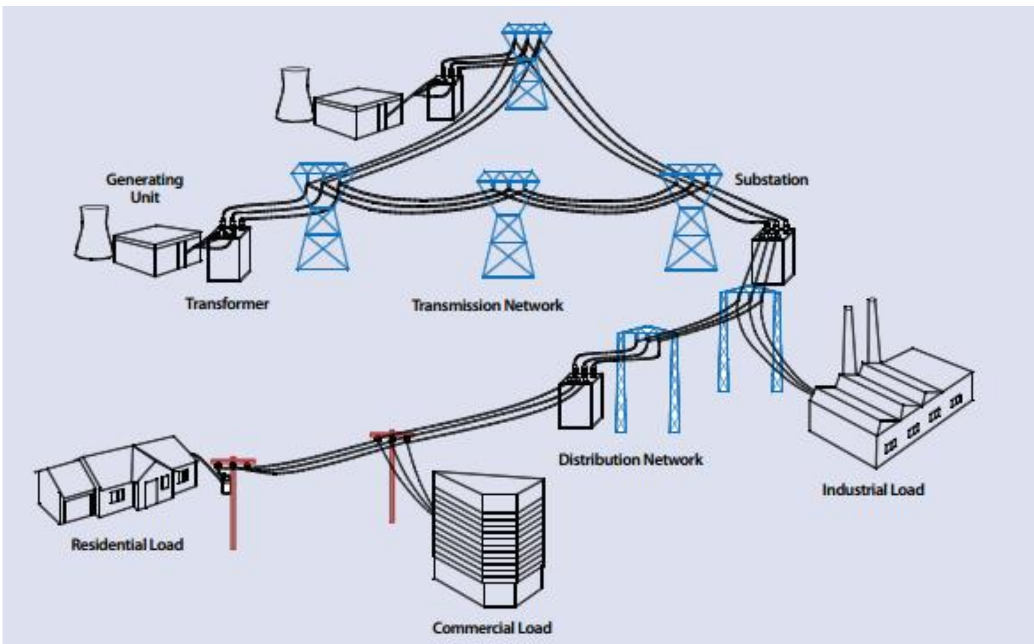


Figure 2.1 Basic structure of an electrical power system

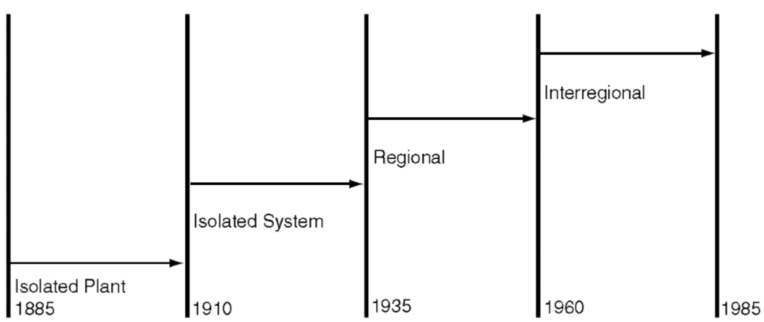


Figure 2.2 Stages of transmission system development

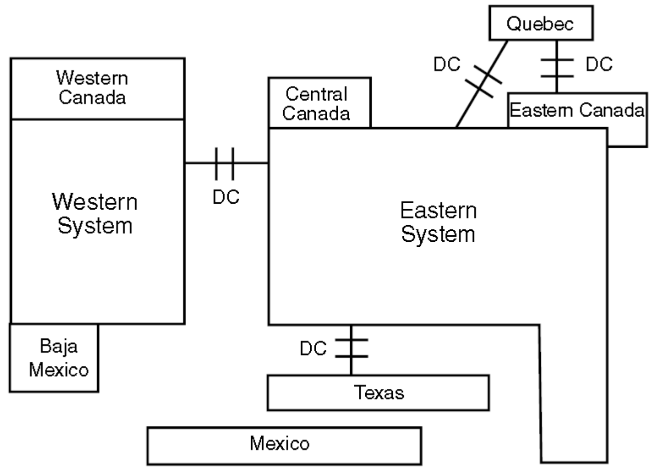


Figure 2.3 North America integrated transmission system

Having a big interconnected transmission system with huge number of generating units and transmission lines presents problems due to the natural structure of power systems. The loss of any generating or transmitting element can affect other elements' operation in the system. Although nearby elements are affected mostly, an element many hundreds miles away can be affected as well. Failure in elements' operation may lead to a malfunction in the whole system operation. The severity of some failures may lead to shut-down in the whole system, called blackout. A few catastrophic blackouts have recently occurred in different part of the world. Blackout brings important economic, social and political consequences. The insufficient investment in power systems and more complex operation regulations of the new deregulated power systems may lead to more blackouts in future [7, 8].

Studying power systems' blackout history helps the power system operators and designers to understand reasons and consequences of various critical contingencies in electrical power systems. Improvements have been made in designing and operating of power systems based on the learnt lessons from various blackouts around the world. In this chapter a few of the most important blackouts in different parts of the world are documented. The primary reasons for each blackout, the sequence of events leading to blackout, and suggested solution to prevent similar kinds of blackouts for each of the blackouts are explained.

2.2 Blackout History in America

1) The Northeast power failure on 9th November 1965 in the United States

This blackout left 30 million people in darkness. This was a major failure in 85 years of electrical industries in the United States leaving New York City in darkness for 13 hours [9, 10].

A) Sequence of the events

- A backup protection tripped one line out of five in heavy loading condition due to relay setting for low load level.
- The other four lines were disconnected following the first line outage.
- Several lines were overloaded by 1700 MW due to the outages.

B) The primary causes of the blackout

- The main cause was the weak transmission line between northeast and southwest.
- It was also identified that there was not enough spinning reserve kept at the time the blackout was initiated.

C) Proposed solutions

- Extra High Voltage transmission lines were proposed to be built.
- Less essential load shedding was introduced for emergency cases.

- Keeping distributed spinning reserve was put into practice.

2) The collapse of the Con Edison system on 13th July 1977

This blackout affected 8 million people for 5 to 25 hours [9].

A) Sequence of the events

- Severe thunderstorm and lightning strikes hit lines.
- Outage of three transmission lines tripped by failed operation of protective equipment.
- Transmission ties were disconnected due to the overloads caused by forced contingencies.

B) The primary causes of the blackout

- Equipment malfunction.
- Questionable system design features.
- Operating errors as lack of preparation for major emergencies.

C) Failed actions

This might have been easily prevented by a timely increase of generation or manual load shedding.

D) Proposed solutions

- The reliability criteria were designed to identify the extreme sensitivity of the city network.

- The system was also instructed to operate well within the cautious interpretation of such severities. This was mainly achieved using a stopwatch criterion on reducing tie line power during thunderstorm periods.

3) The Western North American power system blackout on 2nd July 1996

This blackout caused 2 GW power outages leaving cities in darkness [11].

A) Sequence of the events

- A short circuit on a 345 KV transmission line, the series compensated line by a capacitor with a 1300 km length.
- Voltage depression due to power transfer loss.
- Few hydro generator outages due to over load caused by voltage depression.
- An outage of a 230 kV line tripped by zone 3 relay operation due to the voltage drop in load center situated at a distance of 500 km.
- A small 164 MW peak-to-peak oscillation caused by generator acceleration due to the voltage drop.

B) The primary causes of the blackout

- Voltage collapse while the generators were operated with exciter limits.

C) Proposed solutions

- To prevent this in the future, the defence in depth approach was used. In other words, outage detection based stability controls were changed to respond faster, and operating limits were investigated and changed.

- The zone 3 protection analysis resulted with proposed modern digital controlled protection system at power plants to minimize unit tripping for voltage and frequency excursions.

4) The US - Canadian blackout on 14th August 2003

This blackout covered a wide geographic area and affected about 50 million people. By tripping 400 transmission lines and 531 generating units at 261 power plants, 63 GW load of the network was interrupted [9, 12].

A) Sequence of the events

- Tripping voltage regulator due to over excitation.
- The generators with high reactive power productions went out when the operators tried to restore the regulators.
- Two 345 KV transmission lines tripped because of a tree contact.
- A major tie line was tripped by line by zone 3 relay tripping. This outage led to a reversed power flow in the system and hence a cascading blackout of the entire region.

B) The primary causes of the blackout

- The major reason was voltage instability due to insufficient reactive power.
- Inadequate understanding of the system.
- Inadequate level of situation awareness.
- Inadequate level of vegetation management.
- Inadequate level of support from the Reliability Coordinator.

C) Failed actions

- The load shedding might prevent the major tie line tripping if the system monitoring software did not fail.
- If modern excitation was employed it might have saved the generator tripping by automatically returning to voltage control mode.

5) The Brazil blackout on 10th November 2009

The blackout affected 40 million people, with interrupting 24.436 GW loads[13].

A) Sequence of the events

- Phase to ground fault on phase B of a 765 KV transmission line between large generating centers in southwestern to the load centers in Rio de Janeiro and Sao Paulo.
- Another single-phase fault on the parallel 765 KV transmission line right after the first fault was cleared.
- Third single-phase fault right after the second single phase fault.
- High harmonic and dc component due to these single-phase faults disconnected three phase shunt reactors.
- Few 500 KV transmission lines disconnected following the 765 KV transmission lines.
- Several power plants went out due to voltage collapse.
- The two HVDC bipoles related to generations with 50 Hz were blocked by under-voltage protection.

2.3 Blackout History in Europe

1) The Italy System on 28th September 2003

This blackout was a nationwide blackout, left all Italy in darkness, affected 57 million people, and interrupted 24 GW loads [14].

A) Sequence of the events

- A heavily loaded Italy-Switzerland tie line was tripped by a tree flashover.
- Auto re-closer failed to reconnect the line due to a large phase difference across the line.
- The loss of synchronism, caused by a power deficit in Italy, started with the rest of Europe.
- Distance relay disconnected the interface line between Italy and France.
- The line between Italy and Austria went out by distance relay operation.
- The transmission corridor between Italy and Slovenia went out due to overload.

B) Failed actions

The frequency decay was not controlled sufficiently to stop generating units from tripping.

2) The Swedish/Danish system on 23rd September 2003

This blackout affected 4 million people (in Sweden, 1.6 million people affected and in Denmark, 2.4 million people affected) and interrupted 6.55 GW loads. Two 400-kV lines and HVDC links connecting the Nordel system with continental Europe and several components were out of service due to maintenance. The Swedish failure is a good example of unexpected outage when the system was under N-l contingency operation [7, 9].

A) Sequence of the events

- A 1200 MW nuclear unit in the southern part of Sweden was disconnected.
- Another 1800 MW power plant was tripped due to fault in the substation because of an equipment failure.
- Voltage collapse due to a high power flow from north to south because of generator outages.
- The system was separated into islanded systems.
- The islanded systems collapsed in both voltage and frequency.

3) The Europe system on 4th November 2006

This was the most sever disturbance in the history of UCTE (Union for the Coordination of the Transmission of Electricity) leading to 14.5 GW load interruption and affecting 15 million people in Europe. The main reason was a planned disconnection of a 380 KV transmission line for transportation purpose. This line switching did not happen based on analysis. The system was not compatible with N-1 criterion. Different regional transmission system operators (TSOs) did not coordinate appropriately during this event [15, 16].

4) The Turkey system on 31st March 2015

This blackout was a nationwide blackout leaving 70 million Turkish people in darkness with 32.2 GW unsupplied load. There was no awareness of angular stress of the system in control center. The control center was not equipped with a reliable on line contingency analysis and off line angular stability tools [17].

A) Sequence of the events

- A 400 KV transmission line went out due to the overload.
- Angular instability was initiated by the line outage.

B) The primary causes of the blackout

- The system was not operating under N-1 criterion.
- Three 400 KV transmission lines were out of service for construction works and another 400 KV transmission line was out for maintenance.
- These planned outages weaken the East to West transmission coordinator.
- High generation in the east and high load in the west made it hard to keep the system's balance.

2.4 Blackout History in Asia

1) The Iran System on 20th May 2001

The most important blackouts in the history of the Iranian national grid was experienced in May 2001 [8, 18].

A) Sequence of the events

- A 400 kV transmission, one of two major lines connecting north part, generation center, to the central part of Iran, load center, was disconnected due to short circuit fault while the other line was out of service due to annual routine protection tests.
- Other transmission lines between north and center of the country got overloaded.
- Two of these lines tripped due to overload leading to an isolation between generation center in the north and load center in the capital.
- The system voltage and frequency dropped due to shortage of energy supply.
- Some of the transmission lines were disconnected due to operation of protection relays.

2) The Tokyo System, Japan on 23rd July 1987

This blackout left 2.8 million customers in darkness with the outage of 3.4 GW power out of the maximum power demand of 38.5 GW. The reserve was kept at 1.52 GW and it was sufficient to manage the usual demand increase[18].

A) Sequence of the events

- Increase in demand (400 MW/minute), unexpected level.
- High voltage drop due to high demand of power.
- System collapse due to voltage drop.

B) The primary causes of the blackout

- There was an unusual power demand on that day due to extreme hot weather.
- The rising demand for power was very fast.
- Air conditioners, constant power characteristic loads, caused a voltage drop and high current in the system due to their load characteristics.

C) Proposed solutions

- The operators increased the trunk line voltage by 5% of its normal operation during summer time. A 1 GW power plant was proposed to be built closer to the load centre.
- Shunt capacitors together with SVC of 1,550 MVAR were installed.
- The power transmission route was changed through sub transmission network to minimize tie line power.

3) The Indian System on 30th and 31st July 2012

This blackout was the largest one in the world affecting 620 million people. Three of Indian grids failed to supply their customers on 30th and 31st. Nine states of Northern India went dark on 30th July with approximately 3.6 GW of load. Another disturbance hit Indian network on 31st July leading to a blackout, which covered almost the entire system. 4.8 GW load were disconnected affecting more than 700 million people life.

Relay malfunction and incorrect setting, high reactive power consumption and high load demand due to high temperatures were possible reasons for the disturbances. Transmission system was weak due to few outages, and the tie line between western and northern region was overloaded due to high demand in northern region. Zone 3 of distance relay separated these regions without any fault in the system. Indian electrical system suffers from high power losses in its transmission and distribution systems [19, 20].

A) The primary causes of the blackout

- Weak transmission system due to multiple outages.
- Tie line overload between north and west because of high demand in western region.
- Separation of north and west reason due to zone 3 relay operation.

4) The Pakistan System on 24th September 2006

This blackout left 160 million people in darkness. The whole system was affected by the disturbance and 11.11 GW load was disconnected. Small signal instability and voltage instability were the main reasons for the blackout. A 500 KV transmission line was out for maintenance, the other two parallel 500 KV transmission lines were uncompensated and loaded close to their stability limits. The system was operating to its stability limit, and there was no stability margin in the system for any contingency condition [21].

2.5 Summary of Global Blackouts

Table 2.1 shows blackout data for different countries. The number of affected people, the amount of interrupted loads and the date for studied cases are summarized in the table. The Indian blackout was the worst one affecting 620 million people. The North America blackout in 2003 was the biggest based on the interrupted loads, affecting 50 million people.

Table 2.1 Blackout data for different countries, affected people and interrupted load

Country	Date	Affected people in million	Intruppted loads in GW
United States, Canada	August 14, 2003	50	57.669
United States	July 13, 1977	8	
United States, Canada	November 9, 1965	30	
Turkey	March 31, 2015	70	32.2
India	July 31, 2012	620	8.4
Brazil	November 10, 2009	40	24.436
Europe	November 4, 2006	45	14.5
Pakistan	September 24, 2006	160	11.116
Italy	September 28, 2003	57	24
Denmark and Sweden	September 23, 2003	4	6.55
Iran	March 31, 2003	22	7.063
Japan	July 23, 1987	2.8	3.4

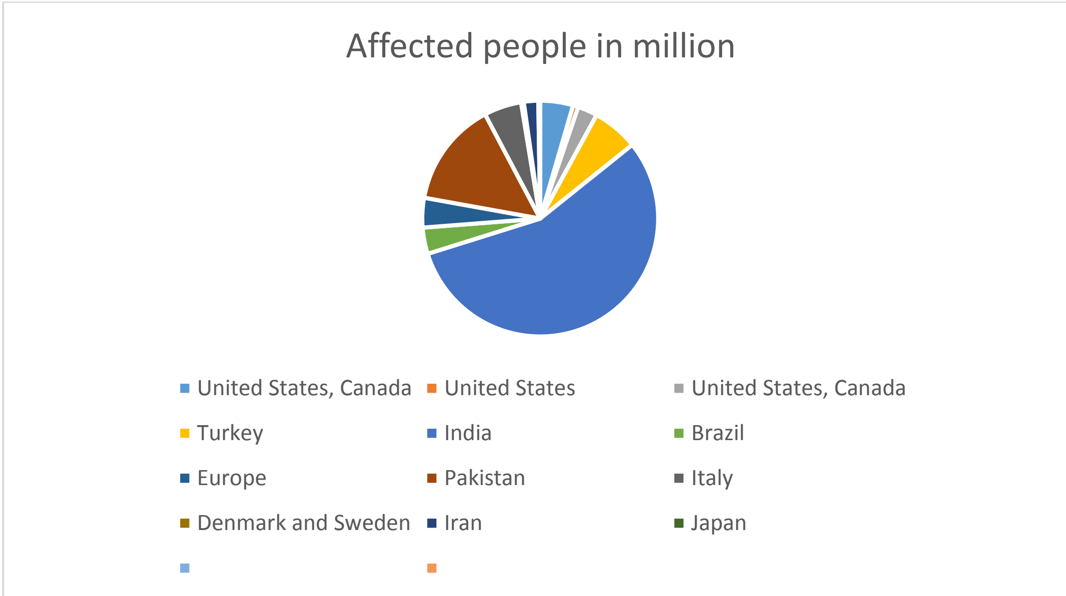


Figure 2.4 Affected people by blackouts in different part of the world

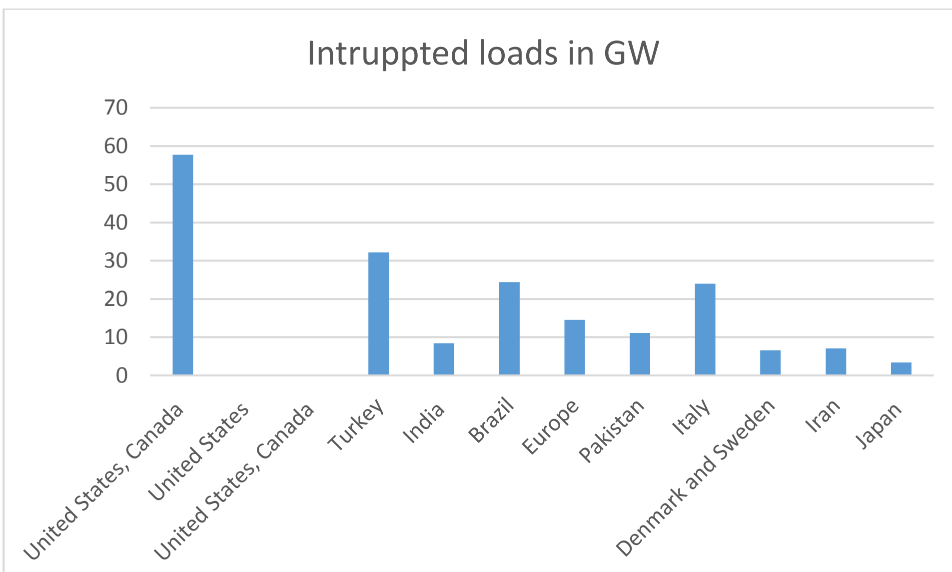


Figure 2.5 Interrupted loads by blackouts in different part of the world

2.6 Summary

Designing and operating a power system without any failure are impossible. Operator mistakes, component failures, and natural incidents make power systems vulnerable. This chapter has reviewed a few important blackouts around the world indicating that power system blackouts are a part of these systems, and while they cannot be avoided, they should be managed to control their frequency and severity. Investment in power system infrastructures, implementation of new and advanced technologies to monitor and control a power system, detail analysis of a power system steady state and dynamics in different mode of operation, and consideration of new rules regarding system security in planning and operating of a power system can prevent future power system blackouts.

Chapter 3

Study of DC Power Flow Analysis Methods for Power Systems

3.1 Introduction

The long and short-term operation planning of power systems, in a way that systems could be able to provide efficient, economical as well as reliable energy to customers, is a difficult task for power system operators and researchers. The power flow study is both an important and a necessary tool for power system's planning and operating evaluation. The power flow is a steady state analysis of balanced three phase power systems. It gives voltage amplitude and angle as an output at each bus of the system, and hence active and reactive power flows in the transmission lines. Moreover, it gives valuable information about power system conditions. The results of the power flow analysis are used to evaluate and control a power system both technically and commercially. Some practical applications of the power flow analysis are [2, 22-24]:

- Transmission planning: to check system voltage and overloads, and to find the network reinforcement's location.

- Contingency analysis: to test how transmission line or generator outages may influence system operation.
- Reactive power (VAR) compensation and voltage profile: to determine the value and location of compensators, and to evaluate their effectiveness.
- Transfer capability analysis: to test for inter utility power transfer limits.
- Online control and security enhancement: to analyze the effectiveness of corrective measures to alleviate emergencies.

Nonlinear power flow equations, known as AC power flow, in contrast with linear power flow equations, known as DC power flow, are the accurate models for power systems in steady state mode of operation. Although the AC power flow is accurate, convergence difficulty and convergence speed limit make it nonfunctional in some applications. A power system operating condition changes constantly, so its estimator should be fast enough to estimate its condition in short time with satisfactory accuracy. A power system operation under forced outages should be evaluated fast. A contingency analysis evaluates system states under outages, which can be done by using either an AC or a DC power flow; it also can be done with a linear sensitive analysis. A contingency analysis by AC power flow evaluates system states correctly but slowly. The result is nonfunctional since the power system operating condition changes rapidly. A contingency analysis by DC power flow, which is fast but not as accurate as the AC power flow, is the solution [2, 22-26].

A DC power flow is used in online contingency analysis, meanwhile inaccurate results may cause serious problems like blackout and voltage collapse, in the worst case [27]. A DC power flow, or a MW only power flow, is a popular method in power system analysis with an application in a contingency screening, transmission loading relief, transfer analysis and long term transmission planning. The linear, non-complex, and often state-independent features of the DC power flow make it interesting from analytical and computational point of view. Compared to the AC power flow, its advantages are [26]:

- Non-iterative, reliable and unique solutions.
- Simplicity of models and software.
- Can be solved and optimized efficiently, especially in contingency analysis.
- Minimum network data requirement.
- Conformity with economic theory because of its linearity.
- Acceptable accurate line active power flow approximation.

In summary, this chapter explains power system steady state modeling and analysis using both the AC and DC power flow methods. Section 3.2 presents a general overview of an AC power flow modeling and analysis procedure. Section 3.3 demonstrates a DC power flow analysis comprehensively. A classical DC power flow and its other forms are formulated in this section. Case studies are done in section 3.4 to evaluate a DC power flow performance in three different networks. Section 3.5 gives a summary of the chapter.

3.2 AC Power Flow Analysis

A four-bus system is considered, as shown in Figure 3.1, to demonstrate and formulate a power flow problem. Each bus has both a generator and a load, and the transmission lines are considered as medium length lines with a π model. The node-voltage analysis can be written as Equation (3.1) based on Figure 3.1. The goal of a node-voltage analysis method is to calculate the voltage of nodes provided the injected currents are known.

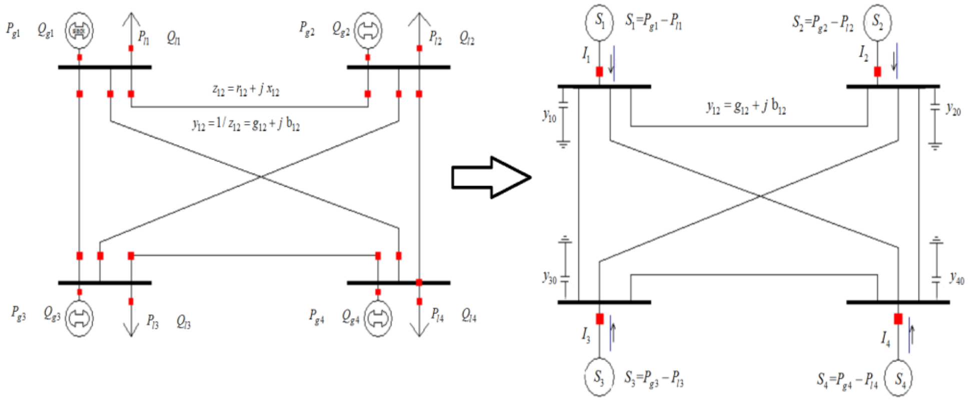


Figure 3.1 Four bus system single line diagram and its equivalent model

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} = \begin{bmatrix} y_{10}+y_{12}+y_{13}+y_{14} & -y_{12} & -y_{13} & -y_{14} \\ -y_{12} & y_{20}+y_{21}+y_{23}+y_{24} & -y_{23} & -y_{24} \\ -y_{31} & -y_{32} & y_{30}+y_{31}+y_{32}+y_{34} & -y_{34} \\ -y_{41} & -y_{42} & -y_{34} & y_{40}+y_{41}+y_{42}+y_{44} \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \end{bmatrix} \Rightarrow I = Y_{bus}\ V \tag{3.1}$$

where:

I: line injected current vector.

Y_{bus}: Admittance matrix of the system.

V: Bus voltage vector.

Y_{bus} Matrix is ‘n’ by ‘n’ matrix, ‘n’ is the number of system buses, and equals:

$$Y_{pq} = \begin{cases} \text{sum of connected admitances to bus p} & \text{p=q} \\ \text{negative sum of admitances connected between buses p and q} & \text{p} \neq \text{q} \end{cases}$$

In the power system analysis, because the injected current vector is a phasor parameter, and the angle of the currents is not available, therefore a complex power vector is used as an input vector.

$$S_p = P_p + j\ Q_p = (P_{gp} - P_{lp}) + j\ (Q_{gp} - Q_{lp}) \tag{3.2}$$

$$I = \frac{S^*}{V^*} \ \Rightarrow \ \left[\frac{P - jQ}{V^*}\right] = \left[Y_{bus}\right]\ \left[V\right] \tag{3.3}$$

S: Complex power injected vector.

$$\frac{P_p - jQ_p}{v_p^*} = \sum_{q=1}^{n} Y_{pq}\ v_q \ \ \Rightarrow\ P_p - jQ_p = \sum_{q=1}^{n} v_p^*\ Y_{pq}\ v_q \tag{3.4}$$

$$P_p = \text{real}(\sum_{q=1}^{n} v_p^*\ Y_{pq}\ v_q) \tag{3.5}$$

$$\text{Q}_p = -\text{image}(\sum_{q=1}^{n} v_p^*\ Y_{pq}\ v_q) \tag{3.6}$$

Power flow equations (3.4-3.6) are nonlinear, and should be solved using iteration techniques. The Gauss Seidel and Newton-Raphson (NR) methods are two well-known methods, used in power flow analysis.

- The Gauss Seidel method: simple and easy to compute, has long convergence time, and used as an initial solution for the Newton-Raphson method.
- The Newton Raphson method: used in large power systems, and has fast convergence time. This method is divided into two Cartesian and polar categories. The speed of convergence is limited in the Cartesian method; however, the polar method leads to a faster method named the Fast Decoupled Newtown Raphson (FDNR). The NR and FDNR techniques are widely used in commercial power flow software packages [24,

25]. Using the polar NR method, the calculated active and reactive injected power are presented in Equations (3.7-3.9).

$$\begin{aligned} v &= |v|\angle\delta = e + j\,f \\ Y_{pq} &= |Y_{pq}|\angle -\theta = G_{pq} - j\,B_{pq} \end{aligned} \tag{3.7}$$

$$P_p^{cal} = \sum_{q=}^{n} |v_p||v_q||Y_{pq}|\cos(\delta_p - \delta_q + \theta_{pq}) \tag{3.8}$$

$$Q_p^{cal} = \sum_{q=}^{n} |v_p||v_q||Y_{pq}|\sin(\delta_p - \delta_q + \theta_{pq}) \tag{3.9}$$

Every bus has two equations, but four unknown variables. Therefore, buses are divided into three groups based on their known and unknown parameters:

- Slack bus: The voltage magnitude and angle are known while the active and reactive powers are determined by power flow equations. Any system has just one slack bus, and it is responsible for system losses in regulated networks. It is a fast power plant, which is responsible for power conservation of the power system in order to prevent frequency variation in the power system.
- PQ bus: The active and reactive powers are known, and the voltage magnitude and angle are calculated. Most of the power system buses are PQ buses.
- PV bus: This is a generator-connected bus. The generator keeps the bus voltage amplitude constant. The active power of the bus is known, and the reactive power and voltage angle are calculated by power flow equations.

3.2.1 AC Power Flow Equations

1) Slack bus: The voltage magnitude and angle are known, and the injected active and reactive power are calculated using Equations (3.10-3.11).

$$P_1^{cal} = \sum_{q=}^{n} |v_1||v_q||Y_{pq}|\cos(\delta_1 - \delta_q + \theta_{pq}) \qquad (3.10)$$

$$Q_1^{cal} = \sum_{q=}^{n} |v_1||v_q||Y_{pq}|\sin(\delta_1 - \delta_q + \theta_{pq}) \qquad (3.11)$$

2) PV bus: The injected active power and voltage magnitude are known, and the voltage angle and injected reactive power are calculated using Equations (3.12).

$$m-1 \begin{Bmatrix} P_2^{sch} - P_2^{cal} = 0 \\ P_3^{sch} - P_3^{cal} = 0 \\ . \\ . \\ P_m^{sch} - P_m^{cal} = 0 \end{Bmatrix}$$

(3.12a)

$$m-1 \begin{Bmatrix} |v_2^{spec}| - |v_2^{cal}| = 0 \\ |v_3^{spec}| - |v_3^{cal}| = 0 \\ . \\ . \\ |v_m^{spec}| - |v_m^{cal}| = 0 \end{Bmatrix}$$

(3.12b)

3) PQ bus: The injected active and reactive power are known, and the voltage amplitude and angle are calculated through Equations (3.13).

$$n-m \begin{Bmatrix} P_{m+1}^{sch} - P_{m+1}^{cal} = 0 \\ P_{m+2}^{sch} - P_{m+2}^{cal} = 0 \\ . \\ . \\ P_n^{sch} - P_n^{cal} = 0 \end{Bmatrix}$$

(3.13a)

$$n-m \begin{Bmatrix} Q_{m+1}^{sch} - Q_{m+1}^{cal} = 0 \\ Q_{m+2}^{sch} - Q_{m+2}^{cal} = 0 \\ . \\ . \\ Q_{m+2}^{sch} - Q_{m+2}^{cal} = 0 \end{Bmatrix}$$

(3.13b)

Where:

$$S_p^{sch} = P_p^{sch} + j\ Q_p^{sch} = (P_{gp}^{sch} - P_{lp}^{sch}) + j\ (Q_{gp}^{sch} - Q_{lp}^{sch}) \tag{3.14}$$

$$S_p^{cal} = P_p^{cal} + j\ Q_p^{cal} = (P_{gp}^{cal} - P_{lp}^{cal}) + j\ (Q_{gp}^{cal} - Q_{lp}^{cal}) \tag{3.15}$$

Table 3.1 Power flow analysis summary

Bus Type	Number of Bus	Determined Quantities	Number of Equations	Number of State
Slack Bus	1	$\lvert v \rvert$ δ	0	0
PV Bus	2 … m	P $\lvert v \rvert$	2 (m-1)	2 (m-1)
PQ Bus	m+1 … n	P Q	2 (n-m)	2 (n-m)
Total	n	2 n	2 n- 2	2 n –2

3.2.2 AC Power Flow Solution Procedure

As explained in the previous section, the voltage magnitude and angle are determined for a slack bus, and its active and reactive power can be calculated using Equations (3.10-3.11), right after power flow analysis of the system is done. The voltage magnitude of the PV buses is determined as well, and the equations in (3.12b) are true while the reactive powers are within the defined constraints. The PV bus should be considered as a PQ bus when its reactive power violates the constraints defined by the generator capability and system stability concerns. Therefore, the reactive power of each PV bus should be checked against its constraints in any iteration of the power flow analysis. To accomplish the power flow analysis of the system, Equations (3.12a, 3.13a, and 3.13b) should be executed using iterative methods. The state variables are the voltage angle for all buses except the slack bus, and the voltage amplitude for the PQ buses. Equations (3.16-3.18) explain how to calculate the state variables of the system using the Newton Raphson polar method.

$$\begin{bmatrix} \begin{bmatrix} \frac{\partial P_2^{cal}}{\partial \delta_2} & \cdots & \frac{\partial P_2^{cal}}{\partial \delta_n} \\ \cdot & J_{11} & \cdot \\ \cdot & & \cdot \\ \frac{\partial P_n^{cal}}{\partial \delta_2} & \cdots & \frac{\partial P_n^{cal}}{\partial \delta_n} \end{bmatrix} & \begin{bmatrix} |V_{m+1}| \frac{\partial P_2^{cal}}{\partial |V_{m+1}|} & \cdots & |V_n| \frac{\partial P_2^{cal}}{\partial |V_n|} \\ \cdot & J_{12} & \cdot \\ \cdot & & \cdot \\ |V_{m+1}| \frac{\partial P_n^{cal}}{\partial |V_{m+1}|} & \cdots & |V_n| \frac{\partial P_n^{cal}}{\partial |V_n|} \end{bmatrix} \\ \begin{bmatrix} \frac{\partial Q_{m+1}^{cal}}{\partial \delta_2} & \cdots & \frac{\partial Q_{m+1}^{cal}}{\partial \delta_n} \\ \cdot & J_{21} & \cdot \\ \cdot & & \cdot \\ \frac{\partial Q_n^{cal}}{\partial \delta_2} & \cdots & \frac{\partial Q_n^{cal}}{\partial \delta_n} \end{bmatrix} & \begin{bmatrix} |V_{m+1}| \frac{\partial Q_{m+1}^{cal}}{\partial |V_{m+1}|} & \cdots & |V_n| \frac{\partial Q_{m+1}^{cal}}{\partial |V_n|} \\ \cdot & J_{22} & \cdot \\ \cdot & & \cdot \\ |V_{m+1}| \frac{\partial Q_n^{cal}}{\partial |V_{m+1}|} & \cdots & |V_n| \frac{\partial Q_n^{cal}}{\partial |V_n|} \end{bmatrix} \end{bmatrix}^k \begin{bmatrix} \begin{bmatrix} \Delta\delta_2 \\ \cdot \\ \cdot \\ \cdot \\ \Delta\delta_n \end{bmatrix} \\ \begin{bmatrix} \frac{\Delta|V_{m+1}|}{|V_{m+1}|} \\ \cdot \\ \cdot \\ \cdot \\ \frac{\Delta|V_n|}{|V_n|} \end{bmatrix} \end{bmatrix}^k = \begin{bmatrix} \begin{bmatrix} \Delta P_2 \\ \cdot \\ \cdot \\ \cdot \\ \Delta P_n \end{bmatrix} \\ \begin{bmatrix} \Delta Q_{m+1} \\ \cdot \\ \cdot \\ \cdot \\ \Delta Q_n \end{bmatrix} \end{bmatrix}^k \tag{3.16}$$

$$\delta_i^{k+1} = \delta_i^k + \Delta\delta_i^k \tag{3.17}$$

$$|V_i|^{k+1} = |V_i|^k + \Delta|V_i|^k = |V_i|^k \left(1 + \frac{\Delta|V_i|^k}{|V_i|^k}\right) \tag{3.18}$$

Where: $$\delta_i^0 = 0 \quad \& \quad |V_i|^0 = 1 \text{ pu} \tag{3.19}$$

3.3 DC Power Flow Analysis

A power system analysis using DC power flow determines generators' dispatch and lines' active power flow, which are important variables in some applications such as electricity market and contingency analysis [27].

Classical DC power flow equations are derived from AC power flow formulations based on the following assumptions:

- Reactive power conservation is not considered.

- Line power loss is neglected.
- Voltage magnitude is considered one per unit.
- Small voltage angle difference between buses is considered.

$$\left.\begin{array}{l}\left.\begin{array}{l}|v|=1\\ r=0\end{array}\right\}\Rightarrow P_p^{cal}=\sum_{q=1}^{n}B_{pq}\cos(\delta_p-\delta_q+90)\\ \delta\rightarrow 0\Rightarrow\left\{\begin{array}{l}\sin(\delta)\rightarrow\delta\\ \cos(\delta)=1\end{array}\right.\end{array}\right\}\Rightarrow P_p^{cal}=-\sum_{q=1}^{n}B_{pq}(\delta_p-\delta_q)$$
$$[P]=[B][\delta]\Rightarrow[\delta]=[B]^{-1}[P]$$
$$[B]=-\mathrm{Im}([Y_{bus}]) \tag{3.20}$$

Based on the first assumption, the voltage angle is determined by an active power conservation ignoring the reactive power influence on the voltage angle which may lead to a considerable error. Ignoring the active power losses of transmission lines may lead to a substantial error, especially in a power system with high resistance to reactance ratio and with high loads. Therefore, the classical DC power flow is a good estimator for line active power flow if its assumptions are accurate. Overall, there is an accuracy concern for the DC power flow method. Several DC power flow methods have been investigated in order to modify the inaccuracy of the classical method. These methods are classified into two general categories [26-29]:

- Hot start models.
- Cold start models.

The hot start, or state-dependent model, is based on the initial operating point obtained from the AC power flow analysis. The DC power flow formulation is a linear approximation around the initial operating point. Line active power losses are calculated using an initial operating point, and they remain constant as a load in the DC power flow analysis. The new reactance of transmission lines reflect the effect of voltage magnitudes in DC power flow. The satisfactory accuracy of this model in estimating the line power flow has been proved [26]. It should be mentioned that an error in this model depends on the initial operating point, so it grows when the operation point goes away from the initial operating point.

The cold start, or state-independence method, considers a one per unit voltage magnitude for all buses, and either ignores or approximates line power losses since there is no available initial operating point in this method. Indeed, the loss approximation method is more accurate than lossless method, but still there is a big concern of inaccuracy. The classical DC power flow is classified in the cold start category. Furthermore, ignoring the reactive power conservation and the flat voltage assumption are two important deficiencies for both hot and cold start methods. A new approach of cold start DC power flow has been proposed in [27] which considers both the reactive power conservation and the voltage profile effect on the voltage angle.

3.4 DC Power Flow Equations

a) Hot Start model

This method is useful when the initial operating point of the system is available either by the AC power flow analysis or by phasor measurement units (PMU). A single AC line between two buses and its DC equivalent model are shown in Figure 3.2. A line loss obtained from AC analysis is modeled as constant loads in the buses, and the effects of voltage profile are considered in the line reactance in the DC model.

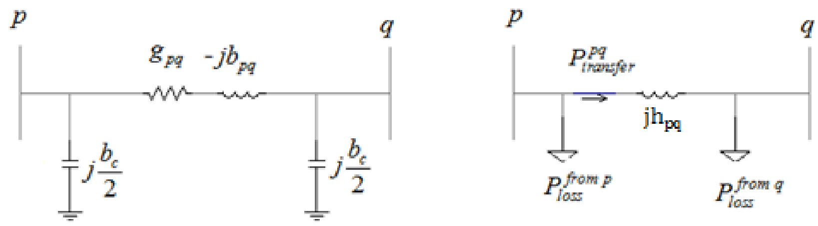


Figure 3.2 Line model and its DC equivalent

It should be noted that in a hot start model, the line power losses and the voltage magnitude of buses are dependent on the initial operating point; therefore, their effects should be updated to consider the change of operating point. It takes time to consider the change of operating point.

$$S_{pq} = P_{pq} + j\ Q_{pq} = v_p^* i_{pq} = |v_p| \angle -\delta_p \left[(v_p - v_q)) y_{pq} + j\frac{b_c}{2} v_p \right] \tag{3.21}$$

$$S_{qp} = P_{qp} + j\ Q_{qp} = v_q^* i_{qp} = |v_q| \angle -\delta_q \left[(v_q - v_p)) y_{pq} + j\frac{b_c}{2} v_q \right] \tag{3.22}$$

$$P_{pq} = g_{pq} |v_p| \left(|v_p| - |v_q| \cos(\delta_p - \delta_q) \right) + b_{pq} |v_p| |v_q| \sin(\delta_p - \delta_q) \tag{3.23}$$

$$P_{qp} = g_{pq} |v_q| \left(|v_q| - |v_p| \cos(\delta_q - \delta_p) \right) + b_{pq} |v_p| |v_q| \sin(\delta_q - \delta_p) \tag{3.24}$$

$$\Rightarrow \begin{cases} P^{pq}_{transfor} = b_{pq} |v_p| |v_q| \sin(\delta_p - \delta_q) = -b_{pq} |v_p| |v_q| \sin(\delta_q - \delta_p) \\ P^{from\ p}_{loss} = g_{pq} |v_p| \left(|v_p| - |v_q| \cos(\delta_p - \delta_q) \right) \\ P^{from\ q}_{loss} = g_{pq} |v_q| \left(|v_q| - |v_p| \cos(\delta_q - \delta_p) \right) \end{cases} \tag{3.25}$$

$$\begin{cases} P^{pq}_{transfor} = b_{pq}\left|v_p\right|\left|v_q\right|\sin\left(\delta_p-\delta_q\right) = b_{pq}\left|v_p\right|^o\left|v_q\right|^o\cos\left(\delta_p^o-\delta_q^o\right)\left(\delta_p-\delta_q\right) = h_{pq}\left(\delta_p-\delta_q\right) \\ P_{loss}^{from\ p} = g_{pq}\left|v_p\right|^o\left(\left|v_p\right|^o-\left|v_q\right|^o\cos\left(\delta_p^o-\delta_q^o\right)\right) = \alpha_p \\ P_{loss}^{from\ q} = g_{pq}\left|v_q\right|^o\left(\left|v_q\right|^o-\left|v_p\right|^o\cos\left(\delta_q^o-\delta_p^o\right)\right) = \alpha_q \end{cases} \tag{3.26}$$

$$\begin{aligned} &[P]=[P_G]-[P_L]-[P_{loss}]=[H][\delta] \\ &P:\text{injected power vector} \\ &P_G:\text{generation power vector} \\ &P_L:\text{load power vector} \\ &P_{loss}:\text{line equivalent loss power vector} \end{aligned} \tag{3.27}$$

Another approximation for h_{pq} is:

$$h_{pq} \approx b_{pq}\left|v_p^o\right|\left|v_q^o\right|\frac{\sin(\delta_p^o-\delta_q^o)}{\delta_p^o-\delta_q^o} \tag{3.28}$$

b) Cold Start model

The cold start, or state independence, is used since there is no reliable operating point in some applications such as long term planning studies. The cold start model is categorized in two groups:

- Classical DC power flow: A well-known DC model based on four assumptions: ignoring the reactive power conservation, considering a flat voltage for buses, ignoring line power losses, considering a small difference in voltage angles between buses. Equation (3.20) explains this model.
- DC power flow model with loss compensation: the only difference between this model and the classical one is the compensation of the line active power losses by modifying the loads. The loads are modified by multiplying them with a constant. A single

multiplier is equal to a ratio of the active power generated in the system to the active power consumed by the loads in the system. Line active power losses are distributed between loads arbitrarily. This method shows a better performance compared to the classical method.

3.4.1 Different DC Power Flow Methods Execution Procedures

This section gives a detailed analysis procedure for six different DC power flow methods. Each method and its assumptions are discussed. The differences between the models are explained through case studies in the next section.

a) Classical DC power flow used in MatPower software (MP) [30]

The MP DC power flow analysis is based on Equation 3.16. The MP result is used as a base to evaluate the accuracy of the other DC power flow methods studied in this chapter.

b) Classical DC power flow with zero line resistance (DC, r=0)

This method uses Equation 3.16 to accomplish the power flow analysis. The resistance of each line is considered zero.

$$\left.\begin{array}{l} z_{pq} = r_{pq} + jx_{pq} \\ r_{pq} = 0 \end{array}\right\} \Rightarrow z_{pq} = jx_{pq} \Rightarrow y_{pq} = \frac{1}{z_{pq}} = -j\frac{1}{x_{pq}} = -jb_{pq} \qquad (3.29)$$

c) Classical DC power flow with a zero line conductance (DC, g=0)

This method is a classical DC power flow with line conductance equals to zero instead of line impedance. Equations (3.30-3.31) demonstrates the difference between the method and the previous one.

$$\left.\begin{aligned} z_{pq} &= r_{pq} + jx_{pq} \\ y_{pq} &= 1/z_{pq} \end{aligned}\right\} \Rightarrow y_{pq} = \frac{r_{pq}}{r_{pq}^2 + x_{pq}^2} - j\frac{x_{pq}}{r_{pq}^2 + x_{pq}^2} = g_{pq} - jb_{pq} \tag{3.30}$$

$$g_{pq} = 0 \Rightarrow y_{pq} = -jb_{pq} = -j\frac{x_{pq}}{r_{pq}^2 + x_{pq}^2} \tag{3.31}$$

d) Single multiplier DC power flow with zero line resistance (DC, SM r=0)

The loss of the transmission line is not considered in the three mentioned methods. However, this method tries to compensate for the power loss of the transmission lines by distributing the losses between buses as loads arbitrarily. The single multiplier (SM) is equal to the ratio of the active generated power in the system to the active consumed power, as shown in Equation (3.32).

$$SM = \frac{P_{Gen}}{P_{Load}} \tag{3.32}$$

Table 3.3 shows this factor for three different systems studied in this chapter.

Table 3.2 Single multiplier factor (SM)

	7-bus system	39-bus system	118-bus system
SM	1.01	1.007	1.03

e) ingle multiplier power flow with zero line conductance (DC, SM g=0)

This method is the same as the previous one, except that the conductance of the transmission lines is considered zero.

f) Hot start DC power flow

The hot start DC power flow starts with an initial operating point obtained from AC power flow analysis. This method and its formulation are discussed in section (3.3.1).

3.5 Case Studies

This section compares the accuracy for different DC power flow models by comparing each of them to the AC power flow through the case studies. Three systems with 7, 39 and 118 buses are investigated. A summary of the systems is presented in Table 3.2 and the detailed data for these systems is given in the Appendix A. The simulations are executed in MATLAB and MATPOWER (MP) [31]. The Root Mean Square Error (RMSE) is used as an index to compare various DC power flows with the AC power flow. The RMSE is a frequently used measure of the difference between values. The RMSE of a model with respect to the estimated variable X is defined as the square root of the mean squared error:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} \left(X_{AC,i} - X_{DC,i} \right)^2}{n}} \tag{3.32}$$

where: X_{AC} represents AC values, and X_{DC} represents DC values.

Table 3.3 Summary of studied systems

		7 bus system	39 bus system	118 bus system
Generation	MW	767.9	6191.3	4374
	MVAr	103.2	837.3	793.9
Load	MW	760	6149.5	4242
	MVAr	130	1408.9	1438
Shunts	MW	0	0	0
	MVAr	0	-342.7	-84.4
Losses	MW	7.9	41.8	132.5
	MVAr	-26.8	-228.9	-559.7
Number of Generators		5	10	54
Number of Loads		6	31	99
Number of Lines		11	34	177

Table 3.4 Root mean square error of 7-bus system

	DC MP	DC r=0	DC g=0	DC SM r=0	DC SM g=0	DC hot start
Voltage magnitude (V)	0.032	0.032	0.032	0.032	0.032	0.032
Voltage angle (degree)	0.301	0.301	0.517	0.421	0.519	1.74E-09
Line active power flow (MW)	1.934	1.931	4.776	0.872	4.385	7.806

As shown in Table 3.4, the root mean square error (RMSE) of voltage magnitude is the same for different power flow methods since voltage amplitudes of buses are considered one per unit. However, for the voltage angle, the dc hot start, the dc power flow with zero resistance, the dc power flow with single multiplier and zero resistance, the dc power flow with zero conductance, and the dc power flow with single multiplier and zero conductance have small root mean square error respectively. For the line active power flow, the dc power flow with single multiplier and zero resistance has the smallest RMSE while the dc hot start model has the highest error. Figure 3.3 explains these interpretations using bar graphs. Figure 3.4 shows the voltage magnitude and angle for buses and the active power flow of lines for both AC and DC power flows. The dc power flow with a single multiplier and zero resistance is the best estimator of the line active flow based on RMSE index.

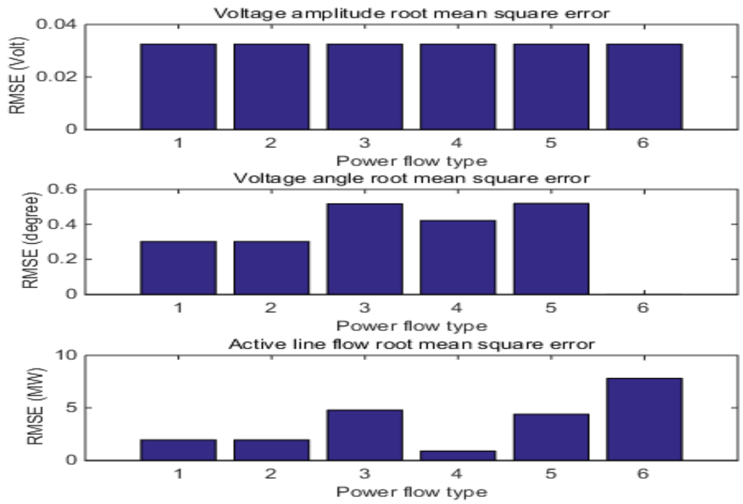


Figure 3.3 Root mean square error of voltage magnitude and angle and line active power flow of a 7-bus system

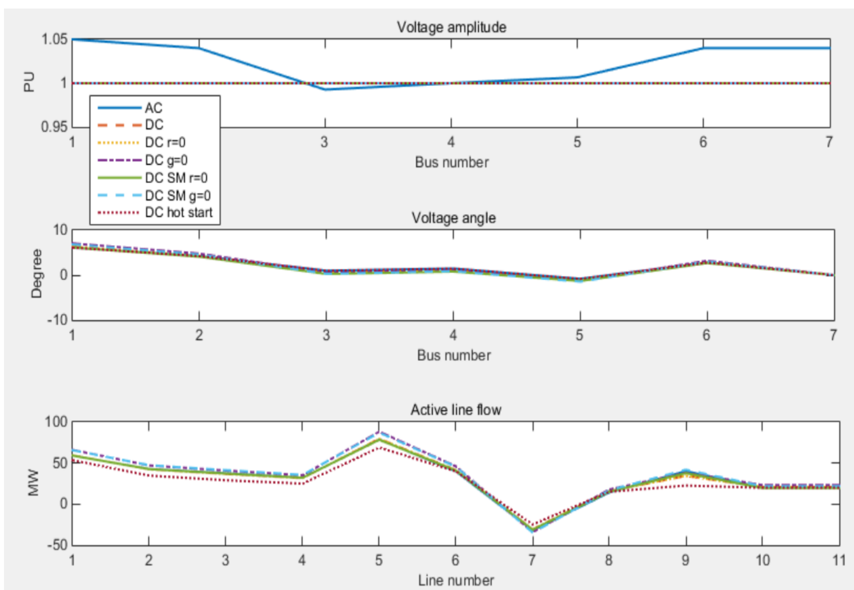


Figure 3.4 Voltage magnitude and angle and line active power flow of a 7-bus system for different kind of power flow analysis

For the 39-bu system the dc hot start has the smallest root mean square error and the classical dc with zero conductance has the biggest for voltage angle, as shown in Table 3.5. The RMSE of the line active power flow is the smallest for the dc with single multiplier and zero resistance and the biggest for the dc hot start model. Figure 3.5 demonstrates

RMSE using bar graphs. Figure 3.6 shows the voltage magnitude and angle of buses and the active power flow of lines for both AC and DC power flows. The dc power flow with single multiplier and zero resistance is the best estimator of the line active flow for a 39-bus system based on RMSE index. Voltage magnitude is considered one per unit for all DC power flow methods.

Table 3.5 Root mean square error of a 39-bus system

	DC MP	DC r=0	DC g=0	DC SM r=0	DC SM g=0	DC hot start
Voltage magnitude	0.034	0.034	0.034	0.034	0.034	0.034
Voltage angle	1.636	2.190	2.327	1.267	1.407	0.599
Line active power flow	10.752	10.926	27.303	3.628	24.203	23.25

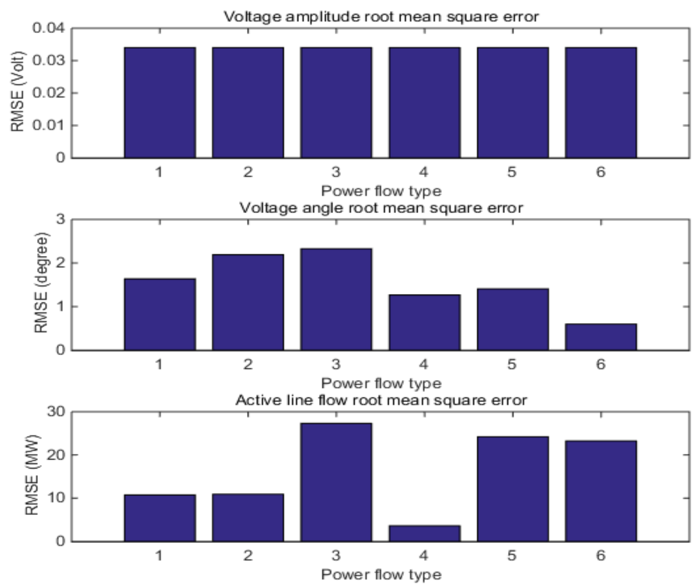


Figure 3.5 Root mean square error of voltage magnitude and angle and line active power flow for a 39-bus system

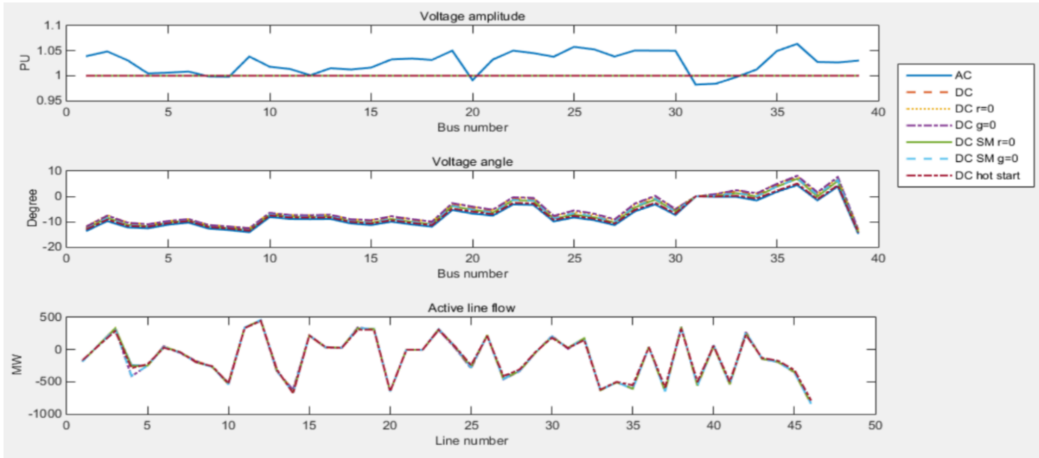


Figure 3.6 Voltage magnitude and angle and line active power flow of a 39-bus system for different kinds of power flow analyses

The RMSE of the voltage angle is the smallest for the dc hot start and the biggest for the classical dc power flow with zero resistance, as shown in Table 3.6 for the 118-bus system. For line active power flow, dc power flow with single multiplier and zero resistance has the smallest RMSE while the dc power flow with zero conductance has the biggest one. The RMSE values for different methods are shown in Figure 3.7. The voltage magnitude and angle of buses and the active power flow of lines for both AC and DC power flows are shown in Figure 3.8. The dc power flow with a single multiplier and zero resistance is the best estimator of the line active flow for 118-bus system considering the RMSE as an indicator.

Table 3.6 Root mean square error of a 118-bus system

	DC MP	DC r=0	DC g=0	DC SM r=0	DC SM g=0	DC hot start
Voltage magnitude	0.027	0.027	0.027	0.027	0.027	0.027
Voltage angle	2.574	2.500	2.155	0.574	0.928	0.128
Line active power flow	7.479	7.559	7.879	2.526	4.832	5.394

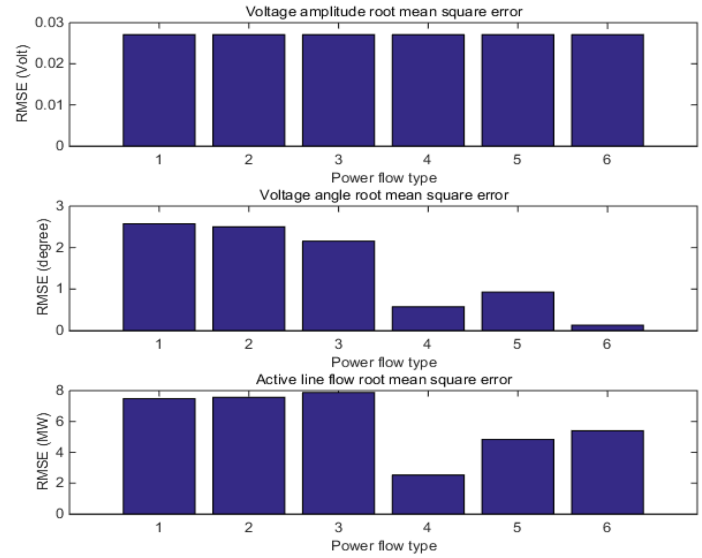


Figure 3.7 Root mean square error of voltage magnitude and angle and line active power flow of a 118-bus system (numbers in X axis stand for different discussed power flow methods)

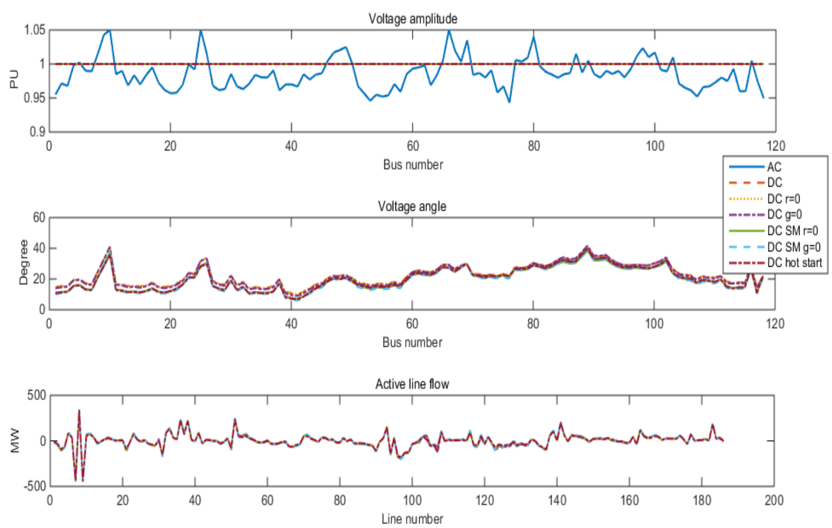


Figure 3.8 Voltage magnitude and angle and line active power flow of a 118-bus system for different kinds of power flow analyses

3.6 Summary

In this chapter, the steady state modeling and analysis of the power system based on both AC and DC power flow are discussed comprehensively. Various DC power flow methods are explained and formulated. The AC power flow is the accurate model of the system in steady state mode of operation, while the DC power flow is a linear approximation of the system in this mode of operation. The DC power flow is fast, and it is useful for online applications such as contingency analysis in power systems. As explained, the DC power flow accuracy varies for various power systems and loading conditions and depends on the considered assumptions for various DC power flow methods. Three systems are simulated to evaluate the different DC power flow methods. The DC power flow with single multiplier and zero line resistance has the best performance in estimating line flows for all three systems. Root mean square error index is used to evaluate the performance of the various methods. Line flows obtained from a DC power flow are compared with those obtained from an AC power flow. Small values of root mean square errors for various systems indicate that the DC power flow could estimate line active power flows. Estimating line flows is an important task in contingency analysis. Therefore, the DC power flow plays an important role in power system contingency analysis.

Chapter 4

N-1 Contingency Analysis for Power Systems

4.1 Introduction

Power system reliability has a higher priority in power system operations, especially in large interconnected modern power systems with the possibility of widespread blackouts. A power system should operate economically and should be designed according to reliability constraints. Power systems should have enough generation systems to meet the loads and adequate transmission lines to deliver the power from the generators to the loads. Power systems should operate reliably if there is no component failure in the system. Furthermore, power systems should be designed so that they are able to operate with no violation in their constraints when there is a component failure on the system, based on the N-1 contingency rule.

Power systems are huge manmade structures, which are exposed to different failures because of either internal or external causes, such as short circuit or bad weather condition. Building a power system with a redundancy that covers all possible failures is impossible, but designing a power system with sufficient redundancy that covers major failures enhances power system security and reduces load-dropping probability. Power system reliability should be checked frequently since operating conditions of the system change constantly. Transmission line and generator unit outages are the most common failures in power systems. Transmission line failures change power flows of the remaining lines and bus voltages.

In order to do preventive and corrective actions when line outages take place, line flows and bus voltages for any specific outage should be estimated. When a generator outage takes place in the power system, not only the transmission lines but also the other generators experience changes in their operating conditions. When the generation unit fails, the balance between loads and generators is violated, and therefore the power system frequency drops. To recover the frequency, the missed generated power should be taken by the remaining generators, provided they are operating within their maximum output constraints. If the remaining generators are not able to compensate the deficiency, load shedding will take place to restore power system frequency. To prevent this, generators should be operated so that the sum of unoccupied capacity, called spinning reserve, to make up the loss is greater than the largest generator's capacity in the power system. A transmission line outage or a transformer outage may lead to a violation in line flows or bus voltages. Any failure may lead to the worst violation in the system operation, therefore evaluation of all failures is desirable but impossible. Overall, operators check possible failures as many times as possible [2, 28].

4.2 Contingency analysis

Outages can influence active and reactive power losses on transmission lines. As shown in Equations (4.1-4.2), the active and reactive power losses depend on line currents (I_l). Therefore, any change in line flow will lead to a change in active and reactive power loss in a power system.

$$P_{loss} = \sum_{all\ \text{lines l}} R_l I_l^2 \tag{4.1}$$

$$Q_{loss} = \sum_{all\ \text{lines l}} x_l I_l^2 \tag{4.2}$$

where R_l and x_l are line l resistance and reactance.

Reactive power losses in transmission lines affect voltages. Transmission lines consume reactive power (Q_l), as shown in Equation (4.2), and produce reactive power (Q_{gen}), as shown in Equation (4.3).

$$Q_{gen} = -\sum_{all\ \text{lines l}} \left(B_{capl} V_{sl}^2 + B_{capl} V_{rl}^2 \right) \tag{4.3}$$

where B_{capl}, V_{sl} and V_{rl} represent line susceptance and sending and receiving end voltages, respectively.

Contingency analysis defines which transmission line outage or generator outage will lead to a violation in the line flows or bus voltages. Contingency analysis models any single outages and multiple outages to predict system states. The line flows and bus voltages are checked against their limits in the contingency analysis. The convergence speed of contingency analysis is important because the number of contingency is extremely high in large power systems, and the power system operating condition changes constantly.

Contingency analysis using a DC power flow estimates line flow accurately and rapidly, since bus voltages are not a big concern in many systems. However, bus voltages are a concern in other systems. That means contingency analysis using an AC power flow is required in order to predict the system states after a specific outage. It should be mentioned that each outage does not lead to a violation in system limitations, and it is impossible to accomplish AC power flow analysis for each outage quickly. Contingency analysis using AC power flow is both unnecessary and impractical. Contingency screening or contingency selection is a procedure by which the important contingencies are selected using a DC power flow, and then the selected contingencies are evaluated by an AC power flow comprehensively [28].

4.3 Linear Sensitivity Factors

Linear sensitivity factors, derived from a DC power flow, are used to calculate line active power flows quickly. These factors show changes in the line active power flows when the system operating condition is changed. These factors are divided into two categories [32-34]:

- Power Transfer Distribution Factors (PTDFs)
- Line Outage Distribution Factors (LODFs)

4.3.1 Power Transfer Distribution Factors

Power transfer distribution factors explain how the active power flow on line l changes when the power is transferred from bus i to j, as shown in Equation (4.4).

$$PTDF_{i,j,l} = \frac{\Delta f_l}{\Delta P} \tag{4.4}$$

where:

$l =$ line index

$i =$ bus where power is injected

$j =$ bus where power is taken out

$\Delta f_l =$ line l active power flow change in MW

$\Delta P =$ power transferred from bus i to bus j

The new active power flow for each of the lines of the system can be calculated by using predetermined PTDFs, as shown in Equation (4.5).

$$f_l^{\wedge} = f_l^{o} + PTDF_{i,j,l}\ \Delta P \tag{4.5}$$

for $l = 1 ... L$

where:

$f_l^{\wedge} =$ flow on the line l after the transfer of the power from bus i to bus j

f_l^{0} = flow before the failure

The new flow ($f_l^{\wedge}$) on each line is compared against its limit ($f_l^{\max}$) and the alarm is announced for a violation. The line flow $f_l^{\wedge}$ should be checked against $-f_l^{\max}$ and $f_l^{\max}$ because a line flow direction is not considered power flow calculation. The line flow may reversed due to an outage in the system. The superposition theory is used in the case of simultaneous generator outages since the PTDF factors are linear.

4.3.2 Line Outage Distribution Factors

Line outage distribution factors (LODFs) calculate the line active power flow changes when the line outages take place in a power system, as shown in Equation (4.6). Figure 4.1 shows LODFs for the line l when the line k goes out.

$$LODF_{l,k} = \frac{\Delta f_l}{f_k^{o}} \tag{4.6}$$

where:

$LODF_{l,k}$ = line outage distribution factor of line l after an outage on line k

Δf_l = change in MW flow on line l

f_k^o = flow on line k before outage

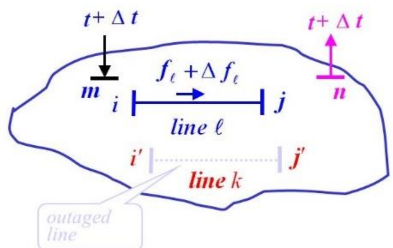


Figure 4.1 Flow change on line *l* due to an outage of line *k*

LODFs, which depend on system parameters and structures, are pre-calculated and stored. Therefore, the post contingency flow in line l is calculated by Equation (4.7), provided the flow of the line is known for pre-contingency, which is either obtained by state estimation techniques or by monitoring the power system.

$$f_l^{\wedge} = f_l^o + LODF_{l,k}\, f_k^o \tag{4.7}$$

where:

f_l^o, f_k^o = flow on line l and line k before outage, respectively

$f_l^{\wedge}$ = flow on line l when the line k fails

The PTDFs and LODFs are independent from a power system operating condition. They are related to transmission line parameters and system topology. Therefore, by pre-calculating these factors, the line active power flows can be quickly checked against their limits in case of line or generator outage. Contingency analysis procedure using sensitivity factors involves the following tasks:

- Calculating PTDFs and LODFs factors based on the transmission line parameters.

- Evaluating the pre-contingency operating condition of the power system.
- Calculating line active power flow using Equation (4.5) for each line of the system when power is transferred from one bus to another bus in the system.
- Calculating line active power flow using Equation (4.7) for each line of the system when any other line fails.
- Initiating an alarm in case of line flow violation due to an outage.

4.4 Formulation of PTDFs and LODFs

4.4.1 PTDF Formulation

An active power (ΔP) is transferred from the sending bus (bus s) to the receiving bus (bus r), as shown in Figure 4.2. PTDF gives a fraction of the transferred power flowing on line l, as shown in Equations (4.8-4.10).

$$PTDF_{s,r,l} = \frac{\Delta f_l}{\Delta P_{s\ to\ r}} \Rightarrow f_l^{\wedge} = f_l^{o} + PTDF_{s,r,l}\ \Delta P_{s\ to\ r} \tag{4.8}$$

$$PTDF_{r,s,l} = -PTDF_{s,r,l} \tag{4.9}$$

$$-1 \le PTDF_{s,r,l} \le 1 \tag{4.10}$$

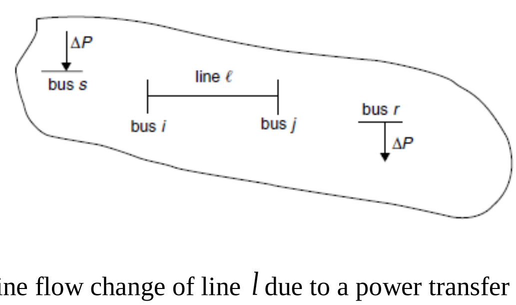


Figure 4.2 Line flow change of line l due to a power transfer from bus r to s

The bus angles are the system states when the system is modeled based on DC power flow. The voltage magnitude is considered one per unit and the voltage angle is calculated by the active power conservation in the system. Equation (4.11) explains the voltage angle changes for a one MW power transferred from bus s to bus r.

$$\Delta\theta = [X]\Delta P_{s\ to\ r} \Rightarrow \begin{bmatrix} \Delta\theta_1 \\ \Delta\theta_2 \\ \dots \\ \Delta\theta_i \\ \dots \\ \Delta\theta_j \\ \dots \\ \Delta\theta_n \end{bmatrix} = \begin{bmatrix} X_{11} & X_{12} & \dots & X_{1n} \\ X_{21} & X_{22} & \dots & X_{2n} \\ \dots & & & \\ X_{i1} & X_{i2} & \dots & X_{in} \\ \dots & & & \\ X_{j1} & X_{j2} & \dots & X_{jn} \\ \dots & & & \\ X_{n1} & X_{n2} & \dots & X_{nn} \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ +1\ (s) \\ \dots \\ -1\ (r) \\ \dots \\ 0 \\ 0 \end{bmatrix} \tag{4.11}$$

$$\begin{cases} \Delta\theta_i = X_{is} - X_{ir} \\ \Delta\theta_j = X_{js} - X_{jr} \end{cases} \tag{4.12}$$

$$\Delta f_l = \frac{1}{x_l}\left(\Delta\theta_i - \Delta\theta_j\right) = \frac{1}{x_l}\left(\left(X_{is} - X_{ir}\right) - \left(X_{js} - X_{jr}\right)\right) \tag{4.13}$$

$$PTDF_{s,r,l} = \frac{1}{x_l}\left(\left(X_{is} - X_{ir}\right) - \left(X_{js} - X_{jr}\right)\right) \tag{4.14}$$

As shown in Equation (4.14), PTDFs depend on the system parameters and they are independent of the system operating condition. The reference bus is not considered in Equation (4.11), so the reactance between the slack bus and the other buses should be considered zero.

4.4.2 LODF Formulation

LODFs formulate a change in line active power flow when a line outage takes place in the system. LODFs estimate the active power of line l when line k fails, as shown in Figure 4.3 [2].

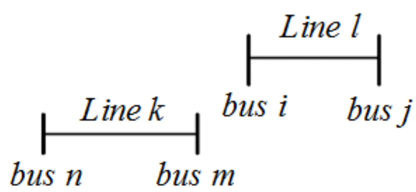


Figure 4.3 Flow change on the line l when the line k out

PTDFs are used to formulate LODFs. The line outage is simulated as a power change in the sending and receiving end of the line, as explained in Figure 4.4 [2]. The original active power flow in line k is P_{nm}, and the flow changes to $P_{nm}^{\sim}$, after ΔP_n and ΔP_m are injected into bus n and bus m respectively. Line k outage can be simulated by Equation (4.15). All of the injected power into bus n flows through line k. The power on line k does not flow through circuit breakers, and the line is open.

$$\Delta P_n = P_{nm}^{\sim} \quad and \quad \Delta P_m = -P_{nm}^{\sim} \tag{4.15}$$

The active power flow of line k due to power injections on bus n and bus m is calculated in Equations (4.16-4.17), based on PTDFs.

$$P_{nm}^{\sim} = P_{nm} + PTDF_{n,m,k}\ \Delta P_n \tag{4.16}$$

$$\Delta P_n = P_{nm}^{\sim} \Rightarrow P_{nm}^{\sim} = \left(\frac{1}{1-PTDF_{n,m,k}}\right) P_{nm} \tag{4.17}$$

The flow change on line l due to line k outage is formulated in Equations (4.18-4.19).

$$\Delta f_l = PTDF_{n,m,l} \tilde{P}_{nm} = PTDF_{n,m,l} \left(\frac{1}{1 - PTDF_{n,m,k}} \right) P_{nm} \tag{4.18}$$

Equation (4.18) relates the flow change on line l to the original flow on line k, so the coefficient in this equation is equal to the LODF of line l.

$$LODF_{l,k} = PTDF_{n,m,l} \left(\frac{1}{1 - PTDF_{n,m,k}} \right) \tag{4.19}$$

$$\hat{f}_l = \mathring{f}_l + LODF_{l,k} \mathring{f}_k \tag{4.20}$$

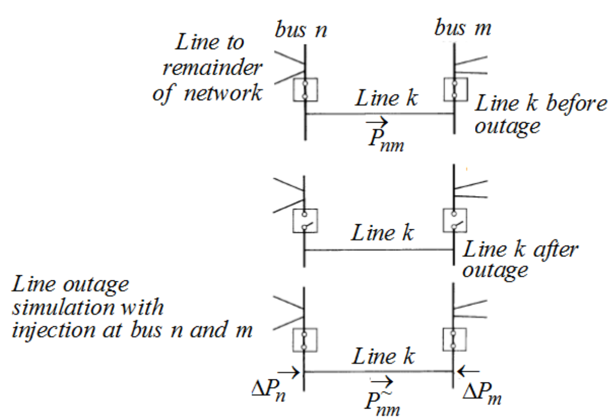


Figure 4.4 Line outage modeled as injections in sending and receiving buses

4.4.3 Compensated PTDF

The compensated PTDFs are defined to consider the power transfer from one bus (bus s) to the other bus (bus r) with simultaneous line outage (line k) on the power system. The flow on line l due to line k outage is defined, as shown in Equation (4.20). The new flow of lines l and k, due to power transfer from bus s to bus r, is calculated by Equations (4.21-4.22).

$$f_l^{\sim} = f_l^{\circ} + PTDF_{s,r,l}\ \Delta P_{s\ to\ r} \tag{4.21}$$

$$f_k^{\sim} = f_k^{\circ} + PTDF_{s,r,\text{k}}\ \Delta P_{s\ to\ r} \tag{4.22}$$

The power flow on line l due to power transfer from bus s to bus r and line k outage is written as Equation (4.23). The superposition theory is used since these factors are linear.

$$f_l^{\wedge} = \left(f_l^{\circ} + LODF_{l,k}\ f_k^{\circ} \right) + \left(PTDF_{s,r,l} + LODF_{l,k}\ PTDF_{s,r,k} \right) \Delta P_{s\ to\ r} \tag{4.23}$$

The compensated PTDFs are expressed as:

$$PTDF_{s,r,l} + LODF_{l,k}\ PTDF_{s,r,k} \tag{4.24}$$

4.5 Contingency Ranking and Selection

PTDFs and LODFs estimate the line active power flows with a satisfactory accuracy when there is a generator or line outage in the system. These factors ignore voltage magnitudes and hence reactive power flows in the system. In some power systems, reactive power flow has a significant effect on the system operating condition, and an active power flow is not a sufficient indicator of line flow overloads. In these cases, distribution factors are not qualified methods to estimate the line overloads, and an AC power flow implementation is inevitable. By using an AC power flow analysis for power system contingency evaluation, the big concerns arise regarding the speed of the solution and hence the number of contingencies which could be considered. Although evaluating each of the outages using an AC power flow analysis gives an accurate solution for line flow and voltage limit violations, it takes too long to be accomplished. The dilemma of choosing between the fast and approximate methods, distributions factor methods, and the accurate and slow method, AC power flow method, can be solved by combination of the various approaches. Contingency analysis procedure by combined methods involves the following tasks:

- Selecting the contingencies with high possibility of causing overloads using distribution factors.
- Evaluating the selected contingencies for an accurate line flow or bus voltage limit violations using AC power flow analysis.

All outages are ranked based on performance indices in a descending order by using sensitivity factors. A few of the outages are evaluated by an AC power flow to estimate not only the line active power flows with higher accuracy but also the line reactive power flows and bus voltages. The performance indices (PI) are important factors in contingency ranking. They should be chosen in a way that the severity of a specific contingency is highlighted correctly. The final list of critical contingencies for the AC power flow analysis is prepared based on performance indices. It is expected that all of the important contingencies are placed in this list by performance indices while unimportant contingencies are excluded by them. In general, the PI can be classified into two groups. A suitable combination of these two groups is considered too.

- Active power based ranking methods: the change in line active power flows is considered.
- Reactive power or voltage security based ranking methods: the change in line reactive power flows or bus voltage variations are considered.

4.5.1 Active Power Based Ranking

The simplest form of PI can be written as Equation (4.27).

$$PI = \sum_{\substack{all\ lines \\ j}} W_j \left(\frac{P_j}{P_{j\ \max}} \right)^n \tag{4.27}$$

$P_j =$ line active power flow
$P_{j\ \max} =$ maximum active power flow on line j
$n =$ a sutible index

This index tends to rank a contingency which leads to many heavily loaded lines and no overloaded lines in the system higher than a contingency which leads to a few overloaded lines and some lightly loaded remaining lines. This problem can be solved by considering only the overloaded lines in Equation (4.27) instead of all lines. The other problem in using Equation (4.27) is that the contingency with many slightly overloaded lines may be ranked higher than a contingency with some heavily overloaded lines, while the second case is severe than the first one. To overcome this problem, a two term PI can be used as explained in Equation (4.28).

$$PI = \left| H_{d1} \right|^{n1} + \sum_{\substack{all\ overloaded \\ lines\ j}} W_j \left(\frac{P_j}{P_{j\ \max}} \right)^{n2} \tag{4.28}$$

$\left| H_{d1} \right| =$ the change in power flow in the highest overloaded line.
$n_1, n_2 =$ suitable indices.

In the contingencies with the same highest overloaded lines, the effect of the second highest overloaded lines should be taken into account in Equation (4.28).

4.5.2 Reactive Power or Voltage Security Based Ranking

There are some PIs used for ranking the contingencies based on a reactive power or a voltage amplitude. Equations (4.29-4.30) explain some of these performance indices.

$$PIv = \sum_{\substack{all\ buses \\ i}} \frac{\alpha_i}{2} \left(\frac{\Delta V_i}{\Delta V_i^{\lim}} \right)^2 \tag{4.29}$$

where: $\Delta \mathrm{V}_i = V_i - V_i^{sp}$; $\Delta V_i^{\lim} = \frac{1}{2}\left(V_i^{\max} - V_i^{\min}\right)$

$V_i =$ post contingency voltage magnitude of bus i

$V_i^{sp} =$ specified voltage at bus i

$V_i^{\max}, V_i^{\min} =$ maximum and minimum limit of voltage magnitude at bus i

$$PIv = \sum_{\substack{violated \\ buses\ i}} W_{vi} \frac{\left|V_i - V_i^{\lim}\right|}{V_i^{\lim}} \tag{4.30}$$

where: $W_{vi} =$ a weighting factor for bus i

$V_i^{\lim} = V_i^{\max}$ if $V_i > V_i^{\max}$

$V_i^{\lim} = V_i^{\min}$ if $V_i < V_i^{\min}$

4.6 Case Studies

In this section, N-1 contingency is evaluated based on performance indices for IEEE 7 and 39 benchmark systems. Table 4.1 shows N-1 contingencies for 7-bus system screened by active power flow performance index based on Equation (4.27). Active power flow and voltage performance indices are shown in column three and four respectively. Line 1 has the highest power flow performance index indicating that this line is the most important contingency in the system. Based on the performance index, an outage on line 1 leads to overloads in the remaining lines of the system. Line 9 and 6 have performance indices greater than 1 which means their outages may lead to overloads in the system. These three lines are considered critical contingencies. They are evaluated in detail using an AC power flow to identify their outages consequences. The AC power flow analysis shows that line 1 outage causes an overload in line 2, as shown in Figure 4.5. Table 4.2 demonstrates root mean square errors (RMSE) between the AC and DC power flow analysis for different N-1 contingencies. The RMSE value differs for various contingencies in the system. It has its minimum value when the system operates without any contingency and its maximum value when the system operates under line 9 outage. The RMSE clarifies line active power flow differences between the AC and DC power flow analysis in different mode of operation (section 3.5).

Table 4.1 Contingency screening based on Flow Performance Index for 7-bus system

ContingencyNumber	BusFrom	BusTo	PerformanceIndexFlow
1	1	2	89.309
9	7	5	4.8607
6	2	6	2.1948
7	3	4	0.55151
3	2	3	0.44342
4	2	4	0.3262
8	4	5	0.3075
10	6	7	0.26241
11	6	7	0.26241
2	1	3	0.24415
5	2	5	0.1908

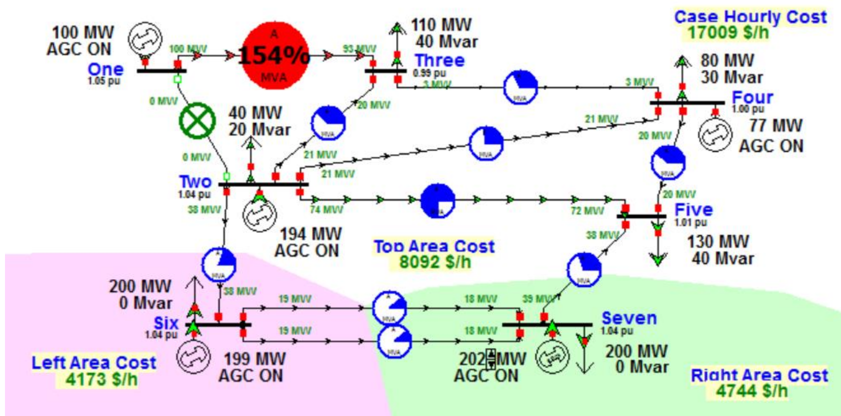


Figure 4.5 Overload due to line 1 outage in 7-bus system

Table 4.2 Root mean square error between AC and DC power flow for different contingency in the 7-bus system

Contingency Number	Bus From	Bus To	RMSE
Non	-	-	1.8521
1	1	2	3.4428
2	1	3	2.4258
3	2	3	2.3091
4	2	4	2.3479
5	2	5	3.0761
6	2	6	3.4493
7	3	4	2.7320
8	4	5	2.3173
9	7	5	4.1573
10	6	7	2.9315
11	6	7	2.9315

Table 4.3 classifies N-1 contingencies based on active power flow performance for the 39-bus system. Contingencies with a performance index higher than 1 may lead to violations in the system. Theses contingencies should be evaluated by an AC power flow. The line 35 outage is the most important contingency for the system. Its outage leads to overloads in line flow of a few remaining lines, as shown in Figure 4.6.

Table 4.3 Contingency screening of 39-bus system based on Flow Performance Index

ContingencyNumber	BusFrom	BusTo	PerformanceIndexFlow
35	21	22	128.2
23	13	14	18.899
19	10	13	6.0666
38	23	24	5.6727
13	6	11	5.3534
28	16	21	4.195
42	26	27	3.8289
18	10	11	3.4312
9	4	14	1.897
10	5	6	1.2028
1	1	2	0.94017
26	16	17	0.80946

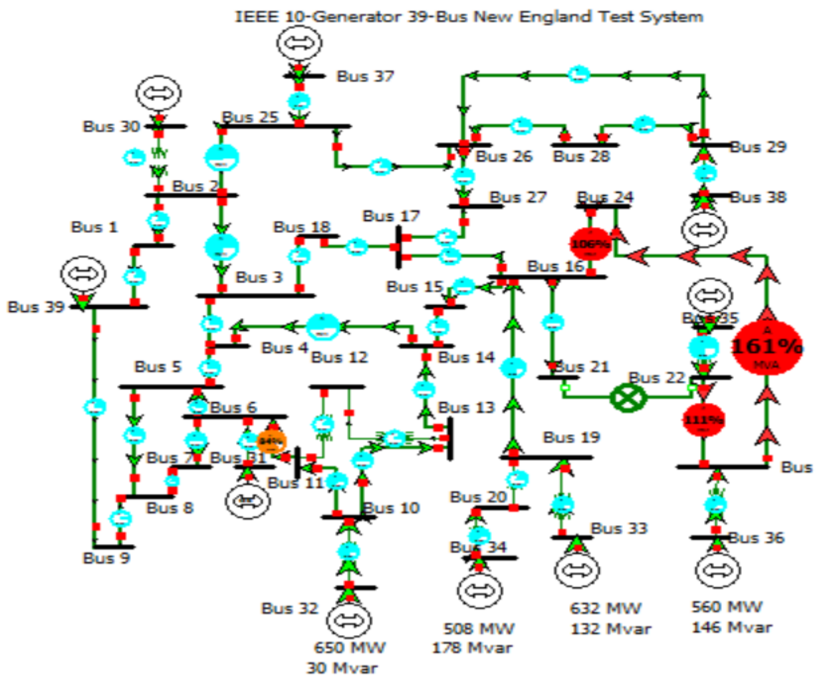


Figure 4.6 Overloads due to line 35 outage in IEEE 39-bus system

Table 4.4 shows the RMSE values of the 39-bus system for different mode of operation. In normal mode of operation, the RMSE has its minimum value indicating that DC power flow estimates line flows more accurately in this mode of operation. As shown in the Table 4.4, the value of the RMSE differs for various contingencies indicating that a DC power flow result and accuracy change with the change in system topology and loading condition. Although the RMSE has its maximum value for line 35 outage, the accuracy of power flow accomplished by a DC power flow is acceptable in comparison with an AC power flow analysis.

Table 4.4 Root mean square error between AC and DC power flow for different contingencies in the 39-bus system

Contingency Number	Bus From	Bus To	RMSE
35	21	22	16.193
42	26	27	15.341
45	28	29	15.138
25	15	16	13.618
13	6	11	13.256
8	4	5	12.977
10	5	6	12.814
44	26	29	12.791
38	23	24	12.723
28	16	21	12.574
4	2	25	12.541
2	1	39	12.533
43	26	28	12.17
30	17	18	12.122
6	3	4	12.022
12	6	7	12.009
24	14	15	11.975
40	25	26	11.956
18	10	11	11.901
23	13	14	11.824
16	8	9	11.568
9	4	14	11.464
26	16	17	11.455
29	16	24	11.453
3	2	3	11.381
19	10	13	11.337
1	1	2	11.33
11	5	8	11.323
15	7	8	11.307
31	17	27	11.3
7	3	18	11.297
36	22	23	11.287
22	12	13	11.007
21	12	11	10.94
Non	-	-	10.752

4.7 Summary

In this chapter, N-1 contingency analysis is explained. Performance indices are used to classify important N-1 contingencies for online contingency analysis. DC power flow analysis is used to classify important contingencies. Important contingencies are evaluated by AC power flow analysis in detail. Line outage distribution factors (LODFs) are formulated. Active power flow performance index is used to classify N-1 contingencies for the IEEE 7 and 39 benchmark systems. Contingencies are listed in descending orders based on their performance index. A few important contingencies are considered for online contingency analysis. The root mean square error index is used to show the difference between AC and DC power flow in estimating line active power flows. Based on the simulation results, the DC power flow has its best performance compared to the AC power flow method in normal mode operation of the system while its results for various contingencies are within acceptable range. The root mean square error varies for different contingencies indicating that the DC power flow accuracy depends on the system structure.

Chapter 5

N-2 Contingency Analysis for Power Systems

5.1 Introduction

Transmission lines are highly stressed to cover a continual load growth and to assure an economical operation in the deregulated environment. Considering multiple contingencies is inevitable in systems with such highly loaded transmission lines. The North American Electric Reliability Corporation (NERC) transmission planning (TPL) introduced new standards requiring secure power system operations with multiple line outages to deal with such incredibly stressed transmission lines. These standards are intended to ensure the reliability of the system in the new deregulated environment [2, 35-39].

The number of multiple outages is extremely high. Evaluating a huge number of possible contingencies faces technical challenges. In online security assessment, predefined contingencies, screened as important contingencies that may lead to overloads in the power system, are evaluated by the state estimator model. It takes a longer time to assess a larger list of contingencies [35, 36, 38].

Important N-2 contingencies generated by screening algorithms are processed faster than whole double outage contingencies. It is believed that every line outage affects a small percentage of other line flows in the system, which means that the number of selected contingencies is much smaller than the number of possible contingencies. Evaluating all possible N-2 contingencies using AC power flow is far more reliable but unfeasible. Identifying critical contingencies in a computationally efficient way is necessary [35, 36].

This chapter explains the analysis methods for multiple contingencies. Linear distribution factors, used for N-1 contingency analysis, are extended to evaluate the N-2 line outages. Different contingency screening algorithms are discussed for multiple contingency screening. The effectiveness of the methods is examined through a case study.

5.2 North American Electric Reliability Corporation (NERC) Standard

Planning and operating rules defined by reliability standards are followed by electrical utilities ensuring the most possible reliable planning and operation. Table 5.1 clarifies different categories for transmission system planning and operation in normal and emergency conditions. Based on the transmission planning standards, TPL-001-3, required by NERC, the planning authority and transmission planner should each explain that its section of the interconnected transmission system is planned in a way that the system can supply all demands in all levels under the contingency conditions defined in categories A-C in Table 5.1[39]. The explanation should be done through a valid assessment annually. The assessment should be done for near-term and longer-term and should be validated through current or past system simulation to test the system performance following contingencies defined through different categories. The assessment should address any planned required upgrades to meet the contingencies.

Table 5.1 Transmission system standards – Normal and Emergency conditions

Category	Contingencies	System Limits or Impacts		
	Initiating Event(s) Contingency Element(s)	System Stable and both Thermal and Voltage Limits within Applicable Rating	Loss of Demand Or Curtailed Firm Transfers	Cascading Outages
A No Contingency	All facilities in service	Yes	No	No
B Event resulting in the loss of a single element.	Single line ground or 3-phase fault, with normal cleaning. 1. Generator 2. Transmission lines 3. Transformer Loss of element without a fault.	Yes Yes Yes Yes	No No No No	No No No No
C Event(s) resulting in the loss of two or more (multiple) elements.	- SLG fault, with normal clearing: 1. Bus Section 2. Breaker (failure or internal Fault) - SLG or 3Ø fault, with normal clearing, manual system adjustments, followed by another SLG or 3Ø Fault, with normal clearing: 3. Category B (B1, B2, B3, or B4) contingency, manual			

	system adjustments, followed by another Category B (B1, B2, B3, or B4) contingency - Bipolar block, with normal clearing: 4. Bipolar (dc) Line Fault (non 3Ø), with normal clearing: 5. Any two circuits of a multiple circuit tower line - SLG fault, with delayed clearing (stuck breaker or protection system failure): 6. Generator 7. Transformer 8. Transmission circuit 9. Bus Section	Yes	Planned/ Controlled	No

5.3 Multiple Contingency Analysis

The most accurate but infeasible way of evaluating N-2 outages in a power system is accomplishing an AC power flow analysis for every possible N-2 outage in the system. As system operational condition is continuously changing due to the change in loads and system topology, the number of N-2 outages is extremely high which makes it impossible to do online assessment of all N-2 contingencies using AC power flow analysis. Online evaluation of all N-2 contingencies even with a DC power flow analysis is infeasible, in contrast with the N-1 contingency analysis, due to the large number of these contingencies. The maximum allowed time, considering changes in a power system condition, to evaluate contingencies in online application imposes a limit on the number of contingencies considered for online assessment. It is necessary and logical to consider a limited number of N-2 contingencies for online evaluations since not all of them lead to violation in system constraints. Selecting critical contingencies while filtering unimportant contingencies is a very important and challenging task which is done through contingency ranking and screening methods.

Contingency ranking ranks various outages based on post contingent overloads, and contingency screening screens important contingencies and ignores unimportant contingencies. Line outage distribution factors (LODFs) used to estimate line flows for each contingency are a fast and accurate way based on DC power flow analysis. These distribution factors and performance indices were used to rank N-1 contingencies in chapter four. In this section, the application of LODFs are extended to evaluate N-2 contingencies. Linear sensitivities such as line outage distribution factors (LODFs) and power transfer distribution factors ($PTDF_s$), obtained from DC power flow analysis and used in N-1 contingency analysis, have been used to approximate line active power flow changes due to multiple line outages. The LODF for line α is defined by (5.1) as a change in active power flow on line α as a percentage of the pre-outage flow on line β when the β is disconnected. Using a pre-defined LODF, the new flow on line α is calculated by (5.2).

$$d_{\alpha,\beta} = \frac{\Delta f_{\alpha,\beta}}{f_{\beta}} \tag{5.1}$$

$$f_{\alpha}^{new} = f_{\alpha} + \Delta f_{\alpha,\beta} = f_{\alpha} + d_{\alpha,\beta}\, f_{\beta} \tag{5.2}$$

To formulate the LODFs for two outages, the effect of line β and line δ simultaneous outages on line α is considered. These outages affect the flow on line α and each other, as well. The altered flows are unknown. By assuming known values for altered flows, a system of equations can be written and solved for altered values. Equation (5.3) explains a system of two equations for new line flows due to line β and line δ outages, one after another, using their pre-outage flows and related LODFs. The new flows are calculated in (5.5).

$$\tilde{f}_\beta = f_\beta + d_{\beta,\delta}\ \tilde{f}_\delta$$
$$\tilde{f}_\delta = f_\beta + d_{\delta,\beta}\ \tilde{f}_\beta \tag{5.3}$$

$$\begin{bmatrix} f_\beta \\ f_\delta \end{bmatrix} = \begin{bmatrix} 1 & -d_{\beta,\delta} \\ -d_{\delta,\beta} & 1 \end{bmatrix} \begin{bmatrix} \tilde{f}_\beta \\ \tilde{f}_\delta \end{bmatrix} \tag{5.4}$$

$$\begin{bmatrix} \tilde{f}_\beta \\ \tilde{f}_\delta \end{bmatrix} = \begin{bmatrix} 1 & -d_{\beta,\delta} \\ -d_{\delta,\beta} & 1 \end{bmatrix}^{-1} \begin{bmatrix} f_\beta \\ f_\delta \end{bmatrix} \tag{5.5}$$

The flow change on line α due to simultaneous outage of lines β and δ can be calculated using (5.7) since the altered flow is known by (5.5). The LODFs for double line outages and hence the new line flows, affected by the outages, are calculated using (5.7). Equation (5.8) demonstrates the general idea which can be extended for more than two simultaneous outages.

$$\Delta f_\alpha = \begin{bmatrix} d_{\alpha,\beta} & d_{\alpha,\delta} \end{bmatrix} \begin{bmatrix} \tilde{f}_\beta \\ \tilde{f}_\delta \end{bmatrix} \tag{5.6}$$

$$\Delta f_\alpha = \begin{bmatrix} d_{\alpha,\beta} & d_{\alpha,\delta} \end{bmatrix} \begin{bmatrix} 1 & -d_{\beta,\delta} \\ -d_{\delta,\beta} & 1 \end{bmatrix}^{-1} \begin{bmatrix} f_\beta \\ f_\delta \end{bmatrix} \tag{5.7}$$

$$\Delta f_\alpha = L_\alpha M^{-1} F \tag{5.8}$$

By definition, LODFs measure the effect of a line outage on the other line flows. Using these metrics, the line interactions on each other can be determined effectively. It is believed that a line outage can alter the nearby line flows but does not affect distant line flows. Generally, LODFs decrease with an increase in distance from disconnected lines, proving the mentioned beliefs, but not for all cases. A line outage has a large impact on a distant line flow in the case of islanding in the system that means the outaged line and the distant line are connecting two island systems to each other [2, 37, 38].

5.4 Contingency Selection Methods for N-2 Line Outages

A number of contingencies in a system with L branches and K outage elements is given in (5.9). The number of contingencies for two element outages, given in (5.10), even a moderately sized network is considerably high. For example, a small IEEE 39 bus benchmark with 46 branches has 1035 double branch outages [40].

$$list\ size = \binom{L}{k} = \frac{L!}{k!\left(L-k\right)!} \tag{5.9}$$

$$\binom{L}{2} = \frac{L\left(L-1\right)}{2} = \frac{L^2 - L}{2} \tag{5.10}$$

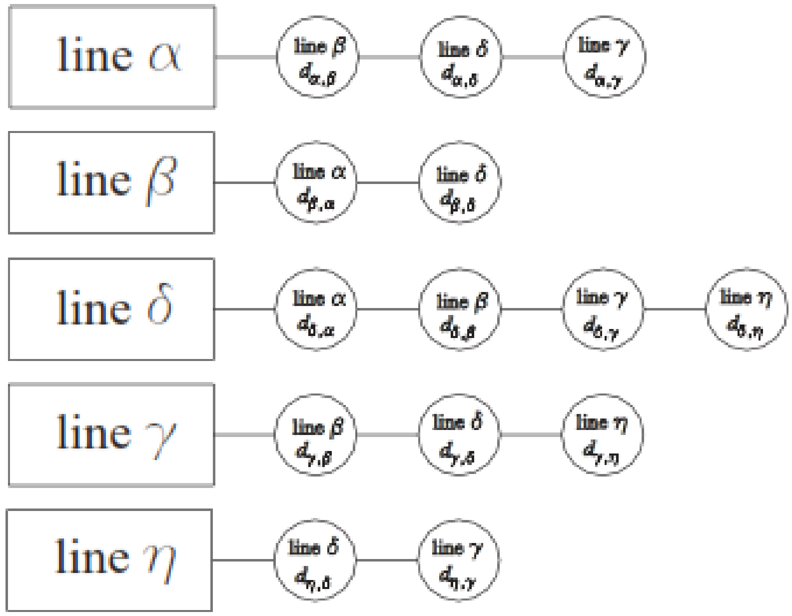
Evaluating all possible double line outages are both impossible and unnecessary. Therefore, contingency classification is necessary for multiple contingency analysis. To classify the contingencies, different contingency screening algorithms have been proposed. These algorithms try to classify contingencies based on their impact on post contingent line flows. A line whose outage will lead to higher violations in system line flows should be ranked as a highly critical contingency. The screening algorithm is successful if it selects dangerous contingencies without entering a large number of unimportant contingencies into the online contingency assessment list.

Impact Tracking Structure (ITS) and Overload Tracking Structure (OTS) are two screening algorithms proposed for multiple contingency screening in [35]. The ITS algorithm considers only sensitivity information, and the OTS algorithm considers line flow and limit information, as well. Both screening algorithms have two steps. They are looking at the effect of lines on each other, known as track structure, in the first step and are building a list of contingencies based on track structure in the second step.

A) Impact Tracking Structure:

First, the impact of the lines on each other is identified using LODFs. Every line whose outage affects a specific line flow is entered in its list. LODFs define the impact of line outages on each other. In ITS, each line has a row which includes lines of the system that have related LODFs more than a pre-defined threshold value, called d^*. The threshold value defines the size of contingency list. For a higher threshold value, the contingency list has smaller entities. If the threshold value is considered zero, the contingency list will include all possible contingencies. Based on track structure, every single line outage which has a high impact on other lines in the system is determined. Table 5.2 demonstrates this structure.

Table 5.2 Impact track structure



The row for line α, for example, has three entries, lines β, δ, γ, which means that these three line outages have a high impact on flow of line α. As shown in the figure, a very sparse structure is generated since every line outage affects limited number of line flows. After ITS construction, every possible pair is produced for each row of the ITS structure. Every double line outages which has an impact on a specific line is identified. The rationale for the approach is if each of these lines has a high impact on the determined line flow, probably their combinations also would have a high impact on the line flow. The final double line outage list is created by removing any non-unique outages. The contingencies on the final list are considered as critical double line outages. These contingencies are evaluated using an AC power flow analysis for detail information.

B) Overload Tracking Structure:

This algorithm uses line flow and line flow limit information beside the system topology information used in the ITS algorithm. The OTS uses line flow information instead of just using LODFs information. The line flows are estimated by LODFs and compared against their emergency rating limits. This makes this algorithm more complicated but very accurate. Like ITS overload threshold value, o^*, is used to identify important outages. The overload threshold value is a margin from emergency flow limit for a single line outage. For example, a threshold value of 10% means that a single line outage resulting in a post contingent line flow of 90% of its emergency rate will be considered in the OTS. In this algorithm, every line has a row which lists other lines if their outages result in violation in its flow based on predefined overload threshold value and its emergency flow limit. Every pair of the contingencies in each row with other lines of the system is considered as double outages in the OTS. The final double outage contingency list is generated after removing repeated contingencies. This method tends to capture more contingencies, and is designed to consider a single outage contingencies resulting in violations when they are combined with other lines in the system. The concept behind this selection method is that the single line outage resulting in violations will contribute to violations when it is a part of double line outage in the system [35, 38].

5.5 Illustration Using an Example

The IEEE 14 bus system, shown in Fig. 5.1, is used to explain the strengths and weaknesses of ITS and OTS algorithms. Table 5.3 shows the general information for the 14 bus system [8].

Table 5.3 Data for IEEE 14 bus system

Number of Lines	Number of Generators	Number of Loads	Generations		Loads	
			MW	MVAr	MW	MVAr
20	5	11	259	73.5	272	82.4

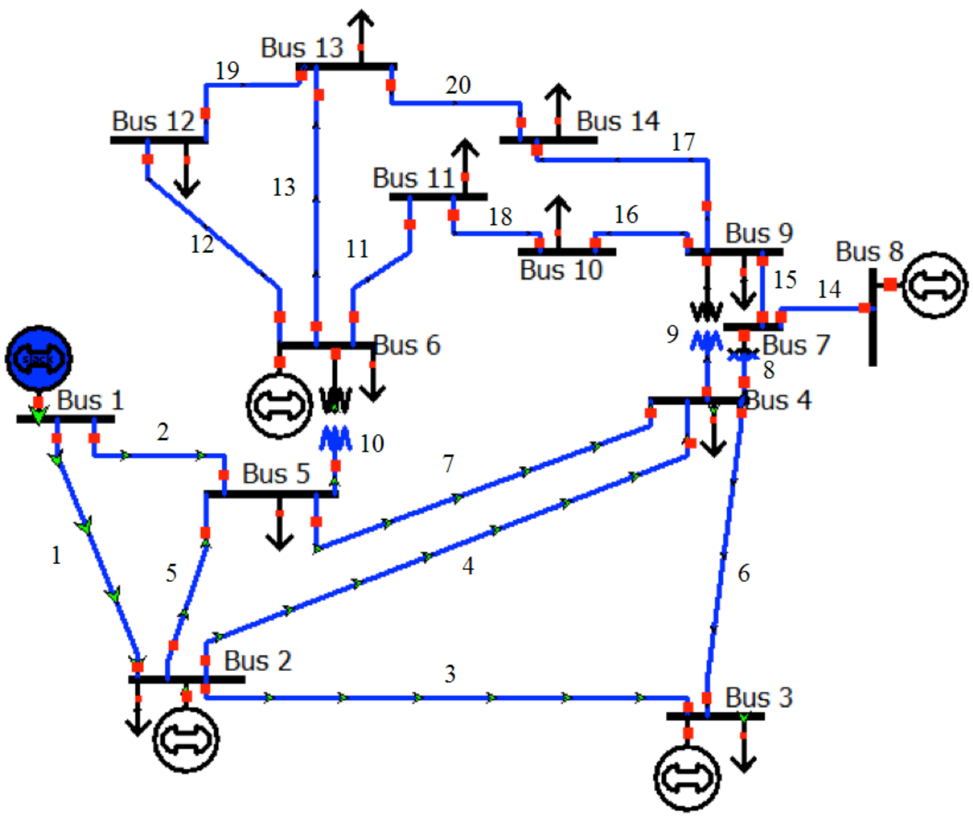


Figure 5.1 Single line digram for IEEE 14 bus system

Table 5.4 shows the line impacts on each other. The threshold is considered 10 percent. Every line has a row, and each row consists of lines which impact that line flow. For example, row one in Table 5.4 consists of lines 2, 3, 4, 5, 6, 7, indicating that these lines have an impact on line one based on line outage distribution values. Every pair of these lines will be considered as important double line outages for line one based on ITS algorithm. That means their outages may lead to a flow violation in line one, and they should be examined in online contingency analysis.

Table 5.4 Impact Track Structure for IEEE 14 bus system

1	2	3	4	5	6	7										
	100	-21	-27	-36	-21	-29										
2	1	3	4	5	6	7										
	100	20.8	27.2	36.1	20.8	29.2										
3	1	2	4	5	6	7										
	-17	16.9	28.6	20.7	-100	-25										
4	1	2	3	5	6	7	10									
	-35	35.3	45.5	43.3	45.5	-52	10.6									
5	1	2	3	4	6	7										
	-48	47.8	33.7	44.2	33.7	47.4										
6	1	2	3	4	5	7										
	-17	16.9	-100	28.6	20.7	-25										
7	1	2	3	4	5	6	8	9	10	11	13	15	16	17	18	20
	-49	49.4	-52	-68	60.5	-52	41.5	30.1	-84	-50	-14	41.5	50.2	41.5	50.2	-42
8	7	9	10	11	13	15	16	17	18	20						
	14.9	64.3	63.5	37.8	10.8	-100	-38	-31	-38	31.3						
9	8	10	11	15	16	17	18	20								
	50.8	36.5	21.7	50.8	-22	-18	-22	18								
10	7	8	9	11	13	15	16	17	18	20						
	-23	49.2	35.7	-59	-17	49.2	59.5	49.2	59.5	-49						
11	7	8	9	10	13	15	16	17	18	20						
	-14	29.6	21.5	-60	17.6	29.6	100	-51	100	50.8						
12	13	17	19	20												
	65.4	22.2	-100	-22												
13	8	9	10	11	12	15	16	17	18	19	20					
	15.2	11.1	-31	31.5	86.8	15.2	-32	77.8	-32	86.8	-78					
15	7	8	9	10	11	13	16	17	18	20						
	14.9	-100	64.3	63.5	37.8	10.8	-38	-31	-38	31.3						
16	7	8	9	10	11	13	15	17	18	20						
	14.1	-30	-22	60.2	100	-18	-30	50.8	-100	-51						
17	8	9	10	11	12	13	15	16	18	19	20					
	-20	-14	39.8	-41	13.2	34.6	-20	40.5	40.5	13.2	100					
18	7	8	9	10	11	13	15	16	17	20						
	14.1	-30	-22	60.2	100	-18	-30	-100	50.8	-51						
19	12	13	17	20												
	-100	65.4	22.2	-22												
20	8	9	10	11	12	13	15	16	17	18	19					
	19.6	14.2	-40	40.5	-13	-35	19.6	-41	100	-41	-13					

Table 5.5 explains the ITS algorithm output. The first row shows line numbers, and each line has a column consisting of all double lines considered as important outages for that specific line. For example, line 1 has a column consisting of double line outages identified by ITS algorithm as important outages for line one. Lines (2, 3), (2, 4) ..., (5, 7), and (6, 7) shown in the first column of the Table are important double line outages for line number

one. In order to examine strengths and weaknesses of the ITS algorithm, all double line outages are evaluated by AC power flow, and the result of ITS algorithm is compared with that.

Table 5.5 Important two line outages identified by Impact Track Structure for IEEE 14 bus system

1		2		3		4		5		6		7			
2	3	1	3	1	2	1	2	1	2	1	2	1	2	5	15
2	4	1	4	1	4	1	3	1	3	1	3	1	3	5	16
2	5	1	5	1	5	1	5	1	4	1	4	1	4	5	17
2	6	1	6	1	6	1	6	1	6	1	5	1	5	5	18
2	7	1	7	1	7	1	7	1	7	1	7	1	6	5	20
3	4	3	4	2	4	1	10	2	3	2	3	1	8	6	8
3	5	3	5	2	5	2	3	2	4	2	4	1	9	6	9
3	6	3	6	2	6	2	5	2	6	2	5	1	10	6	10
3	7	3	7	2	7	2	6	2	7	2	7	1	11	6	11
4	5	4	5	4	5	2	7	3	4	3	4	1	13	6	13
4	6	4	6	4	6	2	10	3	6	3	5	1	15	6	15
4	7	4	7	4	7	3	5	3	7	3	7	1	16	6	16
5	6	5	6	5	6	3	6	4	6	4	5	1	17	6	17
5	7	5	7	5	7	3	7	4	7	4	7	1	18	6	18
6	7	6	7	6	7	3	10	6	7	5	7	1	20	6	20
						5	6					2	3	8	9
						5	7					2	4	8	10
						5	10					2	5	8	11
						6	7					2	6	8	13
						6	10					2	8	8	15
						7	10					2	9	8	16
												2	10	8	17
												2	11	8	18
												2	13	8	20
												2	15	9	10
												2	16	9	11
												2	17	9	13
												2	18	9	15
												2	20	9	16
												3	4	9	17
												3	5	9	18
												3	6	9	20
												3	8	10	11
												3	9	10	13
												3	10	10	15
												3	11	10	16
												3	13	10	17
												3	15	10	18
												3	16	10	20
												3	17	11	13
												3	18	11	15
												3	20	11	16
												4	5	11	17
												4	6	11	18
												4	8	11	20
												4	9	13	15
												4	10	13	16
												4	11	13	17
												4	13	13	18
												4	15	13	20
												4	16	15	16
												4	17	15	17
												4	18	15	18
												4	20	15	20
												5	6	16	17
												5	8	16	18
												5	9	16	20
												5	10	17	18
												5	11	17	20
												5	13	18	20

8		9		10		11		12		13	
7	9	8	10	7	8	7	8	13	17	8	9
7	10	8	11	7	9	7	9	13	19	8	10
7	11	8	15	7	11	7	10	13	20	8	11
7	13	8	16	7	13	7	13	17	19	8	12
7	15	8	17	7	15	7	15	17	20	8	15
7	16	8	18	7	16	7	16	19	20	8	16
7	17	8	20	7	17	7	17			8	17
7	18	10	11	7	18	7	18			8	18
7	20	10	15	7	20	7	20			8	19
9	10	10	16	8	9	8	9			8	20
9	11	10	17	8	11	8	10			9	10
9	13	10	18	8	13	8	13			9	11
9	15	10	20	8	15	8	15			9	12
9	16	11	15	8	16	8	16			9	15
9	17	11	16	8	17	8	17			9	16
9	18	11	17	8	18	8	18			9	17
9	20	11	18	8	20	8	20			9	18
10	11	11	20	9	11	9	10			9	19
10	13	15	16	9	13	9	13			9	20
10	15	15	17	9	15	9	15			10	11
10	16	15	18	9	16	9	16			10	12
10	17	15	20	9	17	9	17			10	15
10	18	16	17	9	18	9	18			10	16
10	20	16	18	9	20	9	20			10	17
11	13	16	20	11	13	10	13			10	18
11	15	17	18	11	15	10	15			10	19
11	16	17	20	11	16	10	16			10	20
11	17	18	20	11	17	10	17			11	12
11	18			11	18	10	18			11	15
11	20			11	20	10	20			11	16
13	15			13	15	13	15			11	17
13	16			13	16	13	16			11	18
13	17			13	17	13	17			11	19
13	18			13	18	13	18			11	20
13	20			13	20	13	20			12	15
15	16			15	16	15	16			12	16
15	17			15	17	15	17			12	17
15	18			15	18	15	18			12	18
15	20			15	20	15	20			12	19
16	17			16	17	16	17			12	20
16	18			16	18	16	18			15	16
16	20			16	20	16	20			15	17
17	18			17	18	17	18			15	18
17	20			17	20	17	20			15	19
18	20			18	20	18	20			15	20
										16	17
										16	18
										16	19
										16	20
										17	18
										17	19
										17	20
										18	19
										18	20
										19	20

15		16		17		18		19		20	
7	8	7	8	8	9	7	8	12	13	8	9
7	9	7	9	8	10	7	9	12	17	8	10
7	10	7	10	8	11	7	10	12	20	8	11
7	11	7	11	8	12	7	11	13	17	8	12
7	13	7	13	8	13	7	13	13	20	8	13
7	16	7	15	8	15	7	15	17	20	8	15
7	17	7	17	8	16	7	16			8	16
7	18	7	18	8	18	7	17			8	17
7	20	7	20	8	19	7	20			8	18
8	9	8	9	8	20	8	9			8	19
8	10	8	10	9	10	8	10			9	10
8	11	8	11	9	11	8	11			9	11
8	13	8	13	9	12	8	13			9	12
8	16	8	15	9	13	8	15			9	13
8	17	8	17	9	15	8	16			9	15
8	18	8	18	9	16	8	17			9	16
8	20	8	20	9	18	8	20			9	17
9	10	9	10	9	19	9	10			9	18
9	11	9	11	9	20	9	11			9	19
9	13	9	13	10	11	9	13			10	11
9	16	9	15	10	12	9	15			10	12
9	17	9	17	10	13	9	16			10	13
9	18	9	18	10	15	9	17			10	15
9	20	9	20	10	16	9	20			10	16
10	11	10	11	10	18	10	11			10	17
10	13	10	13	10	19	10	13			10	18
10	16	10	15	10	20	10	15			10	19
10	17	10	17	11	12	10	16			11	12
10	18	10	18	11	13	10	17			11	13
10	20	10	20	11	15	10	20			11	15
11	13	11	13	11	16	11	13			11	16
11	16	11	15	11	18	11	15			11	17
11	17	11	17	11	19	11	16			11	18
11	18	11	18	11	20	11	17			11	19
11	20	11	20	12	13	11	20			12	13
13	16	13	15	12	15	13	15			12	15
13	17	13	17	12	16	13	16			12	16
13	18	13	18	12	18	13	17			12	17
13	20	13	20	12	19	13	20			12	18
16	17	15	17	12	20	15	16			12	19
16	18	15	18	13	15	15	17			13	15
16	20	15	20	13	16	15	20			13	16
17	18	17	18	13	18	16	17			13	17
17	20	17	20	13	19	16	20			13	18
18	20	18	20	13	20	17	20			13	19
				15	16					15	16
				15	18					15	17
				15	19					15	18
				15	20					15	19
				16	18					16	17
				16	19					16	18
				16	20					16	19
				18	19					17	18
				18	20					17	19
				19	20					18	19

Table 5.6 shows double line outages and corresponding line violations based on full AC power flow analysis for all possible double line outages. Column one shows the violated lines numbers. Each violated line has a row consisting of double lines whose outages lead to a violation in that specific line flow. For instance, the flow on line two violates the line thermal limit if any of the following double line outages happens in the system: lines (3,4), (3,5), (4,5) and (4,7). The first row explains double lines whose outages lead to a blackout

in the system. Table 5.5 identifies important double line outages according to ITS algorithm, and Table 5.6 clarifies double line outages which lead to a flow violation in a specific line identified by full AC power flow analysis. By comparing these two tables, it is possible to show the strengths and weaknesses of the ITS algorithm in identifying important double line outages and to understand the reasons behind those characteristics.

Table 5.6 Double line outages and corresponding violated lines extracted from AC power flow analysis

Blackout	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	8	10							
	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	10	15							
1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	7								
	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	10								
2	3	3	4	4																							
	4	5	5	7																							
3	2	2	4	7																							
	4	5	5	10																							
4	2	2	3	3	3	7																					
	3	5	5	7	10	10																					
5	2	2	3																								
	3	4	4																								
6	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3										
	3	4	5	7	8	9	10	11	12	13	14	15	16	17	18	19	20										
7	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	10	10	10	10	10	10	10	10	10	10
	4	10	11	12	13	14	16	18	19	20	10	11	12	13	18	19	20	9	11	12	13	14	16	17	18	19	20

The double line outages which lead to line flow, based on AC power flow analysis, and identified by ITS algorithm is highlighted by red colour in Table 5.5. These lines cause flow violations and are successfully identified by ITS algorithm. The outaged lines, shown in yellow, cause a blackout in the system. The ITS identified them correctly. The remaining lines, identified as important lines by the ITS algorithm, do not lead to any line flow violations in the system. These lines are identified as important double outages by the algorithm and are classified unimportant outages by an AC power flow analysis. For example, lines 3 and 4 outages lead to a flow violation in line 2, identified by AC power flow analysis and shown in Table 5.6. This outage is identified as an important outage by ITS algorithm as well, shown in Table 5.5. On the other hand, lines 6 and 7 outage is identified as an important outage for line 2 by ITS algorithm while this outage is not a dangerous outage based on AC power flow. The higher the number of these extra lines, the lower the speed of online contingency evaluation.

Identifying unimportant double line outages as important ones is one of the algorithm's weaknesses. The other issue with this algorithm is that it failed to recognize a few important double line outages. Simultaneous outages of lines 7 and 10 lead to flow violations in lines 1 and 3. This outage is not identified as an important outage for neither line 1 nor line 3 by ITS algorithm. Although this line is considered as an important outage for line 4 and entered in online contingency analysis list, the ITS algorithm failed to identify that as an important outage for line 1 and 3 as it is supposed to do based on its definition. It should be mentioned that none of the lines 7 and 10 single outage leads to a violation in the system.

The ITS algorithm fails to identify those double line outages and which one of the line outage leads to flow violation in corresponding line. For instance, line 2 outage leads to a flow violation in line 1, so almost any pair of other lines with line 2 lead to the flow violation in line 1, but this algorithm fails to identify all these outages. Line 3 single outage leads to flow violation in lines 4 and 7, and the algorithm is not able to identify all pairs of line 3 as important contingencies for neither line 4 nor line 7.

The main advantage of this algorithm is that it is able to identify double outages which lead to violations when both of the lines go out. As examples, line 3 and line 4 outages leading to a flow violation in line 2 and line 2 and line 5 outages leading to a flow violation in line 3 are identified by the algorithm while none of the outage of these lines alone leads to violation in the corresponding specific line.

In order to examine the functionality of the OTS algorithm, all single line outages are analysed by AC power flow. The violated lines and lines whose outages lead to a specific line flow violation are identified since the OTS algorithm is built upon single line outage violation in the system. Based on AC power flow, the outage of line 1 leads to a blackout in the system, and line 2 outage cause a flow violation in line 1. Line 3 outage leads to flow violations in line 6 and line 7. A flow in line 7 is violated by line 10 outage as well.

Table 5.7 Violated and outages lines identified by OTS algorithm

Blackout	1 2	1 3	1 4	1 5	1 6	1 7	1 8	1 9	1 10	1 11	1 12	1 13	1 14	1 15	1 16	1 17	1 18	1 19	1 20
1	2 3	2 4	2 5	2 6	2 7	2 8	2 9	2 10	2 11	2 12	2 13	2 14	2 15	2 16	2 17	2 18	2 19	2 20	
6	3 4	3 5	3 7	3 8	3 9	3 10	3 11	3 12	3 13	3 14	3 15	3 16	3 17	3 18	3 19	3 20			
7	3 4	3 5	3 6	3 8	3 9	3 10	3 11	3 12	3 13	3 14	3 15	3 16	3 17	3 18	3 19	3 20			
7	4 10	5 10	6 10	8 10	9 10	10 11	10 12	10 13	10 14	10 15	10 16	10 17	10 18	10 19	10 20				

Table 5.7 demonstrates the OTS algorithm output. Column one shows violated lines due to single line outages. For any violated line, there is a row which includes every pair of the line whose outage leads to a flow violation in that specific line with other lines of the system. For instance, line 2 outage leads to a flow violation in line 1, so the corresponding row for line 1 includes all pairs of line 2 with other lines of the system.

Double line outages shown in Table. 5.7, identified as important lines by OTS algorithm, are compared to those dangerous double line outages shown in Table 5.6, identified by AC power flow, in order to examine the accuracy of the algorithm in identifying important double line outages in the system. The double line outages which are correctly identified by the OTS algorithm as important contingencies are highlighted and underlined in red colour and in Table 5.7. For instance, lines 4 and 10 outage leads to a violation in line 7 flow is identified correctly by the OTS algorithm. On the other hand, lines 5 and 10 outage is identified as an important outage by the algorithm while this outage doesn't lead to a violation in the system based on AC power flow analysis.

This algorithm tends to identify double line outages when either of those lines outage leads to a violation in the system. On the other hand, the algorithm fails in identifying double line outages whose simultaneous outages lead to a violation in the system. For example, simultaneous outages of lines 4 and 7 leading to a flow violation in line 4 are not identified by this method since neither line 4 nor line 7 single outage leads to any violation in the system.

5.6 Summary

The N-2 contingency analysis is explained in this chapter. Instead of implementing full AC or DC power flow analysis to evaluate every double line outages in the system, which is infeasible and unnecessary, contingency screening algorithms are used to identify important contingencies for online contingency evaluations. The impact tracking structure (ITS) and overload tracking structure (OTS) algorithms are used to determine important double line outages. These methods use line outage distribution factors, line flows, and line flow limits to identify contingencies which are further evaluated in detail in online contingency analysis. The results of these algorithms in identifying important double line outages are compared to those of AC power flow analysis to examine their competencies. Based on the simulation, the ITS algorithm acts better in identifying double line outages when simultaneous outages lead to a violation in the system and there is no violation when any of these lines fails individually. The OTS algorithm has a better performance in identifying those double line outages whose any of them individually leads to a violation in the system in comparison to the ITS. Both algorithms missed some important double line outages and they classified some unimportant ones as important double line outages.

Chapter 6

Case Study for Double Line Outages

6.1 Introduction:

It this chapter, the studied algorithms for double line outage identification in chapter five are examined through a case study. The impact track structure (ITS) and overload track structure (OTS) algorithms, explained in chapter five, are used to classify double line outages in important and unimportant categories based on line outage distribution factors (LODFs), line flows and line thermal limits. Their performance is important since only important double line outages identified by the algorithms are evaluated in online contingency analysis. Their malfunction will lead to either missing important double line outage in the final list or adding unimportant ones to the final list for online contingency analysis. The performance of impact track structure (ITS) and overload track structure (OTS) algorithms in identifying important double line outages are examined through a case study.

6.2 Case study

Figure 6.1 shows the 39 bus IEEE benchmark system. It has 46 branches consisting of 34 transmission lines and 12 transformers. Outages of transformer branches are not analyzed in this simulation since their outages stimulate generator outages due to the system topology, shown in Fig. 6.1. There are 34 single line outages and 561 double line outages in this system. Table 6.1 shows general information for the 39 system [40].

Table 6.1 IEEE 39 bus benchmark system

Number of Lines and Transformers	Number of Loads	Number of Generators	Generations		Loads		Shunts
			MW	MVAr	MW	MVAr	MVAr
46	31	10	6104.4	816.4	6063	1408.9	-343.2

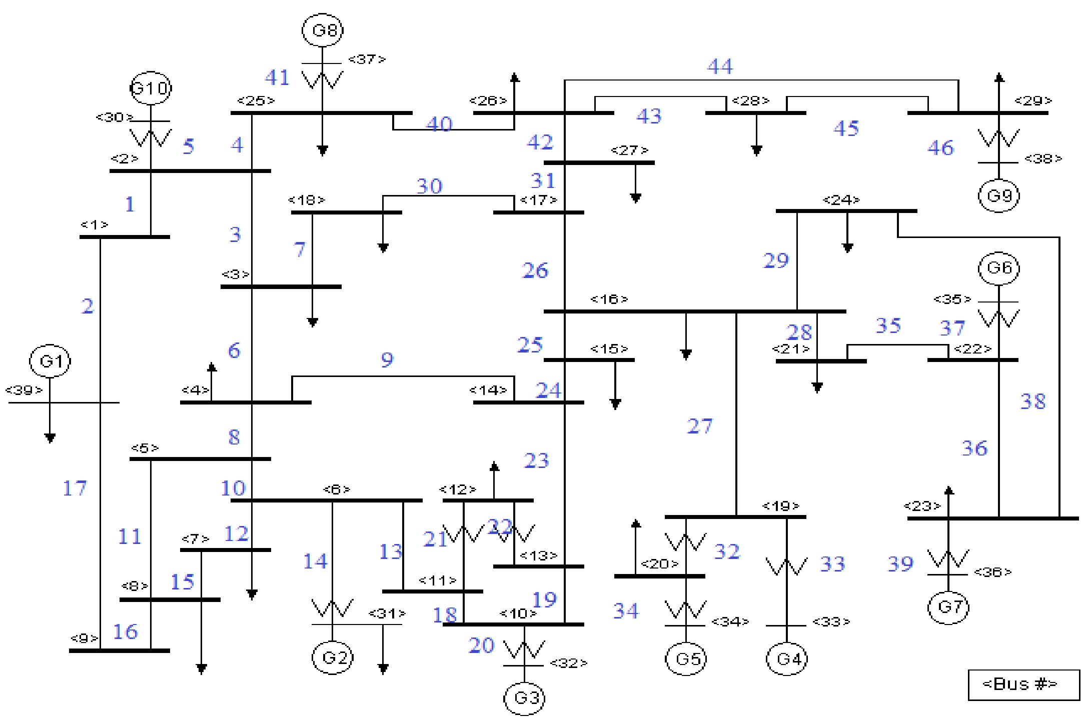


Figure 6.1 Single line diagram for the IEEE 39 bus system

In order to evaluate the results of the ITS and OTS algorithms, all possible N-2 contingencies are analyzed by both an AC and a DC power flow, and their results are used to evaluate the accuracy of the mentioned contingency screening algorithms. The number of double line outages leading to a violation in the system is 281 for an AC power flow analysis and 274 for a DC power flow analysis. The number of violations due to the double line outages is 601 for an AC power flow and 583 for a DC power flow. Lines 9 and 13 outages lead to flow violation in seven lines of the system. Lines 10 and 12 outage lead to a flow violation in five lines, violate line flows of lines 9, 23, and 19 by 194, 192, and 183 percent of their emergency rating respectively. This outage is the worst case from maximum violation point of view.

6.3 Impact and Overload Track Structure Algorithms

Table 6.2 shows the results of the impact track structure algorithm for the IEEE 39 bus system. For each line of the system, there is a row containing the number of lines which have line outage distribution factor higher than the threshold value for the algorithm. The LODFs values are shown under the line numbers. The ITS threshold values is considered 10 percent. For instance, line number one has a row in the table indicating line numbers whose outages have high impact on line one flow. The level of the impact is determined by LODFs written under the line numbers in the table. Line 27 flow is affected by only its outage. Lines 10, 8, 24, 25, and 26 have the longest rows in ITS algorithm showing that these lines are affected by a lot of outages in the system. This indicates that these lines are either a low resistance path or the only path to the loads while there is an outage in the system.

Table 6.2 The impact track structure result for the IEEE 39 bus system

1	1	2	3	4	6	8	16	17	24	25	26	31	40	42						
	-100	100	-35	-12	-29	-18	-100	-100	16	16	16	12	-12	-12						
2	1	2	3	4	6	8	16	17	24	25	26	31	40	42						
	100	-100	35	12	29	18	100	100	-16	-16	-16	-12	12	12						
3	1	2	3	4	6	7	8	16	17	30	31	40	42							
	-80	80	-100	88	-39	-48	-17	-80	-80	48	-88	88	88							
4	1	2	3	4	7	16	17	24	25	26	30	31	40	42						
	-20	20	65	-100	44	-20	-20	22	22	22	-44	100	-100	-100						
6	1	2	3	4	6	7	8	9	16	17	24	25	26	30	31	40	42			
	-69	69	-41	14	-100	52	-25	-35	-69	-69	-84	-84	-84	-52	-14	14	14			
7	1	2	3	4	6	7	9	13	16	17	23	24	25	26	30	31	40	42		
	-11	11	-59	74	61	-100	28	12	-11	-11	12	78	78	78	100	-74	74	74		
8	1	2	3	6	7	8	9	10	11	13	16	17	18	19	23	24	25	26	30	
	-67	67	-28	-38	10	-100	65	-34	-11	-90	-67	-67	60	-60	-90	-12	-12	-12	-10	
9	3	4	6	7	8	9	10	13	18	19	23	24	25	26	30	31	40	42		
	-13	17	-62	42	75	-100	29	83	-56	56	83	-72	-72	-72	-42	-17	17	17		
10	1	2	6	7	8	9	10	11	12	13	15	16	17	18	19	23	24	25	26	30
	-11	11	-20	11	-81	59	-100	89	-93	-87	-93	-11	-11	58	-58	-87	-19	-19	-19	-11
11	1	2	3	6	8	10	11	12	15	16	17									
	-56	56	-20	-18	-19	66	-100	93	93	-56	-56									
12	1	2	3	6	10	11	12	13	15	16	17	23								
	-44	44	-15	-11	-67	91	-100	13	-100	-44	-44	13								
13	1	2	7	8	9	10	13	16	17	18	19	23	24	25	26	30				
	33	-33	14	-82	66	-33	-100	33	33	67	-67	-100	-28	-28	-28	-14				
15	1	2	3	6	10	11	12	13	15	16	17	23								
	-44	44	-15	-11	-67	91	-100	13	-100	-44	-44	13								
16	1	2	3	4	6	8	16	17	24	25	26	31	40	42						
	-100	100	-35	-12	-29	-18	-100	-100	16	16	16	12	-12	-12						
17	1	2	3	4	6	8	16	17	24	25	26	31	40	42						
	-100	100	-35	-12	-29	-18	-100	-100	16	16	16	12	-12	-12						
18	1	2	7	8	9	10	13	16	17	18	19	23	24	25	26	30				
	-30	30	-13	74	-60	30	91	-30	-30	-100	100	91	25	25	25	13				
19	1	2	7	8	9	10	13	16	17	18	19	23	24	25	26	30				
	30	-30	13	-74	60	-30	-91	30	30	100	-100	-91	-25	-25	-25	-13				
23	1	2	7	8	9	10	13	16	17	18	19	23	24	25	26	30				
	33	-33	14	-82	66	-33	-100	33	33	67	-67	-100	-28	-28	-28	-14				
24	1	2	4	6	7	9	13	16	17	18	19	23	24	25	26	30	31	40	42	
	31	-31	26	-71	56	-34	-17	31	31	11	-11	-17	-100	-100	-100	-56	-26	26	26	
25	1	2	4	6	7	9	13	16	17	18	19	23	24	25	26	30	31	40	42	
	31	-31	26	-71	56	-34	-17	31	31	11	-11	-17	-100	-100	-100	-56	-26	26	26	
26	1	2	4	6	7	9	13	16	17	18	19	23	24	25	26	30	31	40	42	
	31	-31	26	-71	56	-34	-17	31	31	11	-11	-17	-100	-100	-100	-56	-26	26	26	
27	27																			
	-100																			
28	28	29	35	36	38															
	-100	100	-100	-100	-100															
29	28	29	35	36	38															
	100	-100	100	100	100															
30	1	2	3	4	6	7	9	13	16	17	23	24	25	26	30	31	40	42		
	11	-11	59	-74	-61	100	-28	-12	11	11	-12	-78	-78	-78	-100	74	-74	-74		
31	1	2	3	4	7	16	17	24	25	26	30	31	40	42						
	20	-20	-65	100	-44	20	20	-22	-22	-22	44	-100	100	100						
35	28	29	35	36	38															
	-100	100	-100	-100	-100															
36	28	29	35	36	38															
	-100	100	-100	-100	-100															
38	28	29	35	36	38															
	-100	100	-100	-100	-100															
40	1	2	3	4	7	16	17	24	25	26	30	31	40	42						
	-20	20	65	-100	44	-20	-20	22	22	22	-44	100	-100	-100						
42	1	2	3	4	7	16	17	24	25	26	30	31	40	42						
	-20	20	65	-100	44	-20	-20	22	22	22	-44	100	-100	-100						
43	43	44	45																	
	-100	100	-100																	
44	43	44	45																	
	100	-100	100																	
45	43	44	45																	
	-100	100	-100																	

Based on the idea that if the individual outage of two lines has a high impact on a specific line's flow, then simultaneous outages will also have a high impact on that line's flow, every pair of lines is produced for each row. After eliminating repeated and duplicated double line outages, the ITS algorithm classified 301 double line outages as important outages. These contingencies are considered for online contingency evaluation.

Table 6.3 shows the results of the overload impact track structure for this system. The threshold value is considered to be 5 percent. All single line outages are evaluated by AC power flow analysis. Violated lines and lines leading to the violations are identified. Every violated line has a row containing line numbers whose outages lead to a flow violation in that specific line. The amount of violation in line flow due to each outage is written under the outaged line number. For example, line 42 outage causes a flow violation for line 3 by 116 percent of its emergency limit.

Table 6.3 The overload track structure result for IEEE 39 bus system

3		42		
		116		
4		42		
		106		
9		13		
		117		
13		19	23	9
		122	138	120
18		19	23	
		109	104	
19		13	18	
		103	108	
23		13		
		108		
28		38		
		115		
29		35		
		106		
35		38		
		107		
36		35		
		11		
38		35	28	
		161	114	

Every pair of each of these lines that caused a violation in N-1 contingency, with other lines of the system is considered as an important contingency in OTS. After eliminating duplicate contingencies, the OTS produces 261 double line outages for online contingency evaluation.

It is clear that neither ITS nor OTS can identify all important N-2 contingencies that lead to violations in the system, completely, and all contingencies, identified as important contingencies by either ITS or OTS, are not N-2 dangerous contingencies.

6.4 Performance of ITS and OTS algorithms

Table 6.4 shows statistics for these screening algorithms. The ITS fails to identify 45.2 percent of important contingencies while the OTS has a better performance by missing 11.4 percent of important contingencies. Meanwhile, the ITS listed unimportant contingency by 52 percent of all double outage contingencies while this statistic is 4 percent for OTS. As explained through Table. 6.4, the OTS algorithm has a better performance in identify important double line outages, and it has a shorter list for online contingency analysis.

Table 6.4 The statistics for ITS and OTS algorithm performances

	Compared to full contingency evaluation done by an AC power flow	
Screening algorithm	Error (%)	Extra (%)
ITS	45.2	52.32
OTS	11.39	4.27

Chapter 7

Conclusion and Future Work

7.1 Recap of the Thesis

Electrical energy has penetrated all aspect of human life due to its outstanding features, compared to other forms of energy, such as compatibility with environment, efficiency and reliability. Large interconnected transmission lines within the countries or even within a continent connect loads to generation centers economically, efficiently and reliably. Electrical blackout is an inherent nature of any power system. Blackouts have economic, social and political consequences, and it is impossible to prevent them from happening. Their frequencies and consequences can be contained by investment in power system infrastructures and by detail analysis of power systems in steady state and dynamic mode of operation.

Power flow equations are used to model and analyze a power system performance in steady state mode of operation. An AC power flow with nonlinear equations is the most accurate modeling of the power system in steady state mode. It has convergence difficulties and convergence speed limitations which make it non-functional in some applications such as online contingency analysis. On the other hand, a DC power flow with linear equations is able to estimate line active power flow with acceptable accuracy. Various DC power flow models consider a flat voltage profile of 1 per unit for all buses and ignore reactive power conservation of the system. The active power losses of transmission lines are ignored or approximated by these models. Various DC power flow performances in estimating line active power flows in comparison to an AC power flow are evaluated using root mean square error index. It is shown that a DC power flow with single multiplier and zero line resistance has a better performance in line active power flow estimation which is essential in contingency analysis.

Contingency analysis is an important tool in power system security analysis. Contingency analysis involves evaluating any event that may occur in the future. The power system operators and designers should deal with these contingencies and should be prepared for them. Through contingency analysis, all single or multiple outages are considered and evaluated to predict their consequences in order to carry out preventive and corrective actions. N-1 contingency analysis models evaluate any single outages in power systems. Evaluating all single outages by an AC power flow is infeasible due to a large number of outages. It is unnecessary since not all of the contingencies are credible nor critical. In this study, all single outages are evaluated by a DC power flow. Credible contingencies are identified by a DC power flow and classified according to their criticality by using performance indices. The final list of critical contingencies are evaluated by an AC power flow in detail.

The North American Electric Reliability Corporation (NERC) Transmission Planning (TPL) introduced a new standard in place for highly stressed transmission lines in new deregulated networks. Based on the new regulations, double line outages should be considered in designing and operating power systems. The number of N-2 contingencies are extremely high for large power systems. Evaluating all N-2 contingencies even with a DC power flow is infeasible. Screening algorithms are used to identify important double line outages based on line outage distribution factors and N-1 contingency analysis. Impact Tracking Structure (ITS) and Overload Tracking Structure (OTS) algorithms are used to identify critical double line outages. Their performances are evaluated in detail using case studies. Both of the algorithms failed to identify some important outages while some unimportant ones are classified as important double line outages. The ITS is successful in identifying those double line outages which lead to violations when both of the lines go out simultaneously. The OTS has a better performance in identifying double line outages for which an outage of any one line leads to a violation in the system.

7.2 Summary of the Research and Contribution of the Thesis

The main contribution of this research can be summarized as follows:

1. Various DC power flow models are formulated and studied in detail. Their performances in estimating line active power flows are evaluated.

2. N-1 contingency analysis and screening by both an AC power flow and a DC power flow are investigated. A DC power flow and performance indices application in identifying important N-1 contingencies are examined.

3. Double line outages are studied by an AC power flow and screening algorithms.

4. Impact Tracking Structure (ITS) and Overload Tracking Structure (OTS) screening algorithms are studied comprehensively. Their performances in identifying critical double line outages are evaluated completely.

7.3 Possible Future Research

Multiple contingency analysis is a demanding area for research. In this study, double line outages are investigated in steady state mode of operation in power systems. The following areas could be considered for future work in multiple contingency analysis:

1. Dynamic multiple contingency analysis.
2. Multiple contingency analysis of the power system with high penetration of renewable energy resources.
3. Multiple contingency analysis using phasor measurement units.
4. Studying multiple contingency analysis using data from real power systems.

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Appendix A: The IEEE 7-Bus Power System Data

The information of 7-bus power system is presented in this appendix. Figure A.1 shows a single line diagram of the system. Loads and generations on buses are given in Table A.1. Transmission line parameters and power flow limits are shown in Table A.2[24]. The base voltage and power are considered 138 kv and 100 MVA respectively.

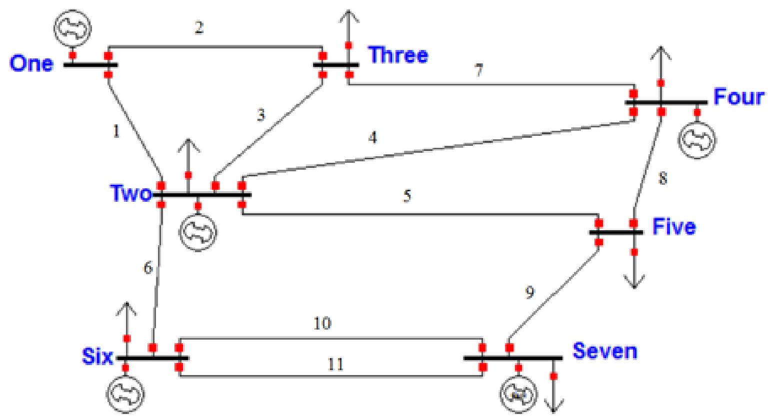

Figure A.1 One line diagram of the 7-bus power system

Table A.1 Load demand and generation schedule for the 7-bus system

Bus Number	Load MW	Load Mvar	Gen MW	Gen Mvar
1			101.85	5.25
2	40	20	170.08	33.24
3	110	40		
4	80	30	95.03	19.99
5	130	40		
6	200	0	200.33	-6.59
7	200	0	200.65	51.29

Table A.2 Line data for the 7-bus system

From Number	To Number	R	X	B	Limit on MVA
1	2	0.02	0.06	0.06	150
1	3	0.08	0.24	0.05	65
2	3	0.06	0.18	0.04	80
2	4	0.06	0.18	0.04	100
2	5	0.04	0.12	0.03	100
2	6	0.02	0.06	0.05	200
3	4	0.01	0.03	0.02	100
4	5	0.08	0.24	0.05	60
7	5	0.02	0.06	0.04	200
6	7	0.08	0.24	0.05	200
6	7	0.08	0.24	0.05	200

Appendix B: The IEEE 14-Bus Power System Data

The 14-bus system data is presented in this appendix. The single line diagram of the system is shown in Figure B.1. Table B.1 contains loads and generation schedule on various buses of the system. Table B.2 gives line data of the system. The base voltage and power are considered as 138 kv and 100 MVA respectively.

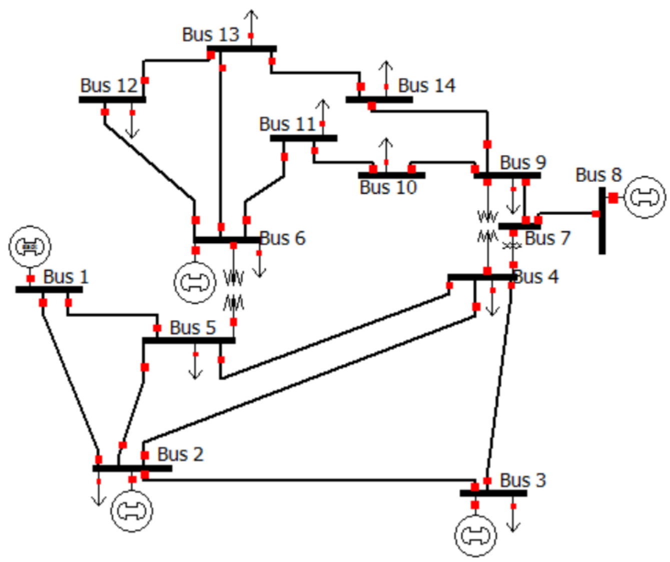

Figure B.1 One line diagram of the 14-bus power system

Table B.1 Load demand and generation schedule for the 14-bus system

Bus Number	Load MW	Load Mvar	Gen MW	Gen Mvar
1			232.39	-16.55
2	21.7	12.7	40	43.56
3	94.2	19	0	25.07
4	47.8	-3.9		
5	7.6	1.6		
6	11.2	7.5	0	12.73
7				
8			0	17.62
9	29.5	16.6		
10	9	5.8		
11	3.5	1.8		
12	6.1	1.6		
13	13.5	5.8		
14	14.9	5		

Table B.2 Line data for the 14-bus system

From Number	To Number	R	X	B	Limit on MVA
1	2	0.01938	0.05917	0.0528	200
1	5	0.05403	0.22304	0.0492	100
2	3	0.04699	0.19797	0.0438	100
2	4	0.05811	0.17632	0.034	100
2	5	0.05695	0.17388	0.0346	100
3	4	0.06701	0.17103	0.0128	100
4	5	0.01335	0.04211	0	100
4	7	0	0.20912	0	100
4	9	0	0.55618	0	100
5	6	0	0.25202	0	100
6	11	0.09498	0.1989	0	100
6	12	0.12291	0.25581	0	100
6	13	0.06615	0.13027	0	100
7	8	0	0.17615	0	100
7	9	0	0.11001	0	100
9	10	0.03181	0.0845	0	100
9	14	0.12711	0.27038	0	100
10	11	0.08205	0.19207	0	100
12	13	0.22092	0.19988	0	100
13	14	0.17093	0.34802	0	100

Appendix C: The 39-Bus System Data

The 39-bus system data is presented in this appendix. The single line diagram of the system is shown in Figure C.1. Table C.1 contains loads and generation schedule on various buses of the system. Table C.2 gives line data of the system.

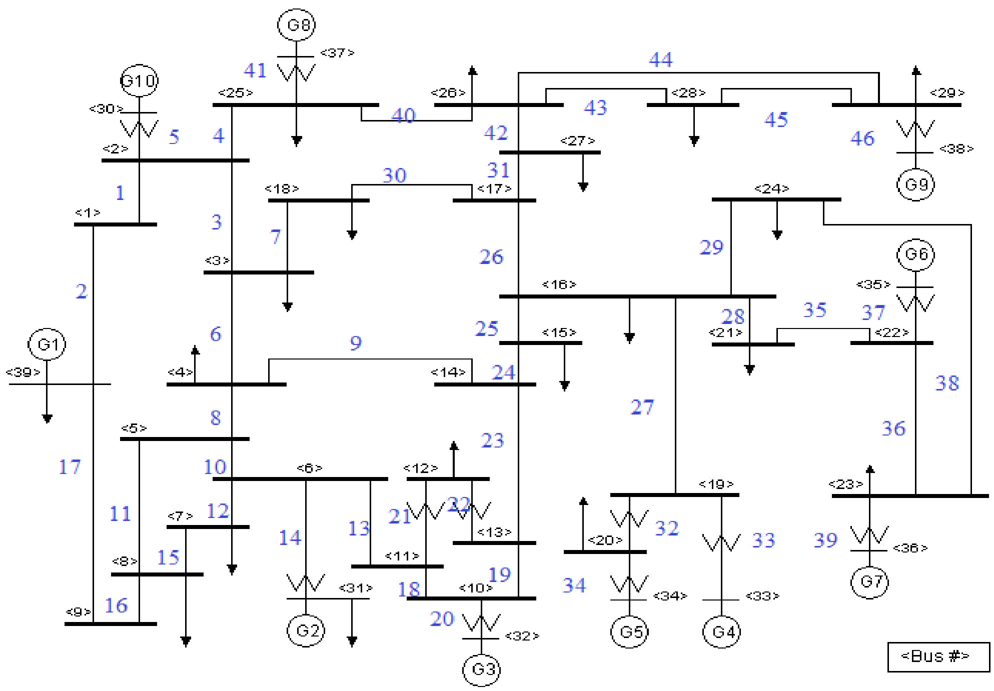

Figure C.1 Single line diagram for the IEEE 39 bus system

Table C.1 Load demand and generation schedule for the 39-bus system

Bus Number	Load MW	Load Mvar	Gen MW	Gen Mvar	Act B Shunt Mvar
1	0	0			0
2	0	0			0
3	235.51	2.4			0
4	500	184			112.34
5	0	0			230.82
6	0	0			0
7	233.8	84			0
8	522	176			0
9	0	0			0
10	0	0			0
11	0	0			0
12	7.5	88			0
13	0	0			0
14	0	0			0
15	320	153			0
16	329.4	32.3			0
17	0	0			0
18	158	30			0
19	0	0			0
20	680	103			0
21	274	115			0
22	0	0			0
23	247.5	84.6			0
24	308.6	-92.2			0
25	224	47.2			0
26	139	17			0
27	281	75.5			0
28	206	27.6			0
29	283.5	26.9			0
30			250	81.18	0
31	9.2	4.6	484.65	351.75	0
32			650	-0.74	0
33			632	68.87	0
34			508	148.42	0
35			650	166.14	0
36			560	74.94	0
37			540	-36.1	0
38			830	-0.99	0
39	1104	250	1000	-37.01	0

Table C.2 Line data for the 39-bus system

From Number	To Number	R	X	B	Lim MVA
1	2	0.0035	0.0411	0.6987	600
1	39	0.001	0.025	0.75	1000
2	3	0.0013	0.0151	0.2572	500
2	25	0.007	0.0086	0.146	500
2	30	0	0.0181	0	900
3	18	0.0011	0.0133	0.2138	500
3	4	0.0013	0.0213	0.2214	500
4	14	0.0008	0.0129	0.1382	500
4	5	0.0008	0.0128	0.1342	600
5	8	0.0008	0.0112	0.1476	900
5	6	0.0002	0.0026	0.0434	1200
6	11	0.0007	0.0082	0.1389	480
6	7	0.0006	0.0092	0.113	900
7	8	0.0004	0.0046	0.078	900
8	9	0.0023	0.0363	0.3804	900
9	39	0.001	0.025	1.2	900
10	32	0	0.02	0	900
10	13	0.0004	0.0043	0.0729	600
10	11	0.0004	0.0043	0.0729	600
12	13	0.0016	0.0435	0	500
12	11	0.0016	0.0435	0	500
13	14	0.0009	0.0101	0.1723	600
14	15	0.0018	0.0217	0.366	600
15	16	0.0009	0.0094	0.171	600
16	24	0.0003	0.0059	0.068	600
16	21	0.0008	0.0135	0.2548	600
16	19	0.0016	0.0195	0.304	600
16	17	0.0007	0.0089	0.1342	600
17	27	0.0013	0.0173	0.3216	600
17	18	0.0007	0.0082	0.1319	600
19	33	0.0007	0.0142	0	900
19	20	0.0007	0.0138	0	900
20	34	0.0009	0.018	0	900
21	22	0.0008	0.014	0.2565	900
22	35	0	0.0143	0	900
22	23	0.0006	0.0096	0.1846	600
23	36	0.0005	0.0272	0	900
23	24	0.0022	0.035	0.361	600
25	37	0.0006	0.0232	0	900
25	26	0.0032	0.0323	0.513	600
26	29	0.0057	0.0625	1.029	600
26	28	0.0043	0.0474	0.7802	600
26	27	0.0014	0.0147	0.2396	600
28	29	0.0014	0.0151	0.249	600
29	38	0.0008	0.0156	0	1200
31	6	0	0.025	0	1800

Published Papers

Conference papers

Y. Salami, B. Jeyasurya, “A Comprehensive Evaluation of “DC” Power Flow Models and their Application to Power System Security Analysis,” *in 2016 CIGRE Canada Conference*, Vancouver, BC, Oct. 2016, pp. 1–8.

Y. Salami, T. Iqbal, B. Jeyasurya, “Dynamic Modeling and Grid Impact of an Existing Wind Farm in Ardabil, Iran.” *In Twenty-Fifth Annual Newfoundland Electrical and Computer Engineering Conference (NECEC)*, Nov. 2016, IEEE.

Posters

Y. Salami, B. Jeyasurya, “Contingency Analysis in Power Systems,” in Annual Research Posters Memorial University, Mar. 2016.

Y. Salami, B. Jeyasurya, “N-2 Contingency Analysis in Power Systems,” in Annual Research Posters Memorial University, April. 2017.