Ranking of Bulk Transmission Assets for Maintenance Decisions

by

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A Thesis Presented in Partial Fulfillment
of the Requirements for the Degree
Master of Science

Approved July 2019 by the
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ARIZONA STATE UNIVERSITY

August 2019

ABSTRACT

Reliable and secure operation of bulk power transmission system components is an important aspect of electric power engineering. Component failures in a transmission network can lead to serious consequences and impact system reliability. The operational health of the transmission assets plays a crucial role in determining the reliability of an electric grid. To achieve this goal, scheduled maintenance of bulk power system components is an important activity to secure the transmission system against unanticipated events. This thesis identifies critical transmission elements in a 500 kV transmission network utilizing a ranking strategy.

The impact of the failure of transmission assets operated by a major utility company in the Southwest United States on its power system network is studied. A methodology is used to quantify the impact and subsequently rank transmission assets in decreasing order of their criticality. The analysis is carried out on the power system network using a node breaker model and steady state analysis. The light load case of spring 2019, peak load case of summer 2023 and two intermediate load cases have been considered for the ranking. The contingency simulations and power flow studies have been carried out using a commercial power flow study software package, Positive Sequence Load Flow (PSLF). The results obtained from PSLF are analyzed using Matlab to obtain the desired ranking. The ranked list of transmission assets will enable asset managers to identify the assets that have the most significant impact on the overall power system network performance. Therefore, investment and maintenance decisions can be made effectively. A conclusion along with a recommendation for future work is also provided in the thesis.

DEDICATION

To my beloved grandmother.

ACKNOWLEDGMENTS

I would like to offer my deepest gratitude to Prof. Vijay Vittal and Prof. Gerald Heydt for providing me with the opportunity to work on this project. This research would not have been possible without their continuous guidance and support. I would also like to thank Prof. Raja Ayyanar for being a part of my graduate supervisory committee.

My association with the local utility for this project has provided me with valuable inputs to this research. I wish to acknowledge the local utility for providing financial support and useful data for this work.

I am deeply indebted to my parents Mr. Nandlal Bhandari and Mrs. Asha Bhandari for their love and support. I am also thankful to my wife Tejasvi, my sister Deepika, and my brother-in-law Jitendra for their constant support and encouragement throughout the course of this project.

Lastly, I would like to thank all my wonderful friends for making my stay at ASU a memorable one.

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NOMENCLATURE

B_{ij}	Susceptance of the branch between node *i* and node *j*
CA	Contingency analysis
$d_{ij,lm}$	Line outage distribution factor for branch *i-j* when branch *l-m* is on outage
EPRI	Electric Power Research Institute
F_i	Flow in the i^{th} branch
$F_{i,lim}$	Flow rating of the i^{th} branch
f_{ij}^c	Post-contingency power flow on a branch *i-j*
f_{ij}^o	Pre-contingency power flow on a branch *i-j*
Δf_{ij}	Change in the flow of active power on the branch between bus *i* and bus *j*
J	Jacobian matrix element
k	Multiplying factor to compute final ranking index
LODF	Load transfer distribution factor
n	Exponent of the penalty function
N	Number of transmission elements in a power system network
N_B	Number of buses
N_c	Number of loading scenarios under study
N_L	Number of branches in the system
N_G	Number of generators in the system
NERC	North American Electric Reliability Corporation
N_L	Number of branches
N_V	Number of branch rating violations in the system post contingency
P_i	Active power at injection at bus *i*

PI_F	Flow based performance index
PI_V	Voltage based performance index
PI_{VQ}	Voltage-reactive power based performance index
$P_{gen,i}$	Active power generation at bus *i*
$P_{gen,max}$	Maximum active power generation capacity
P_i^{lim}	MW capacity of branch *i*
$P_{load,i}$	Active power component of the load connected at bus *i*
PSLF	Positive sequence load flow
PTDF	Power transfer distribution factor
ΔP_k	Change in the active power injection at bus *k*
Q_i	Reactive power at injection at bus *i*
$Q_{gen,i}$	Reactive power generation at bus *i*
$Q_{load,i}$	Reactive power component of the load connected at bus *i*
Q_i^{max}	Maximum allowable reactive power at bus *i*
r	Resistance of a branch
$R_{k,i}$	Rank of k^{th} contingency for i^{th} loading scenario
$R_{F,k}$	Final ranking index of k^{th} contingency considering N_c loading scenarios
V_i	Voltage magnitude at bus *i* in p.u.
V_i^{sp}	Specified voltage magnitude at bus *i* in p.u.
V_i^{max}	Maximum allowable voltage magnitude at bus *i* in p.u.
V_i^{min}	Minimum allowable voltage magnitude at bus *i* in p.u.
ΔV_i^{lim}	Voltage deviation limit for bus *i* in p.u.
ΔV_{avg}	Average bus voltage deviation

W_{Vi}	Real non-negative weighting factor for bus *i*
W_{Qi}	Real non-negative weighting factor for bus *i*
W_i	Weight assigned to a loading scenario/branch *i*
x_{ij}	Reactance of the branch *i*-*j*
X_{ij}	Reactance of the branch *i*-*j* from the *X* matrix
Y_{ij}	Admittance of the branch between node *i* and node *j*
δ_i	Voltage angle at bus *i*
$\rho_{ij,k}$	PTDF for branch *i*-*j* with respect to injected power at bus *k*

CHAPTER 1: INTRODUCTION

1.1 Motivation

In 2017, approximately 3,723 billion kWh of electric energy were generated by all the utilities combined in the United States [1]. An electric power transmission system is responsible for transmitting this bulk electric power from a generating station to an electrical substation. A transmission system is comprised of various transmission assets such as transformers, transmission lines, circuit breakers, and various switches. To ensure the reliable operation of an electric power grid, the health of these transmission assets is of importance. Electric power utilities perform maintenance of these transmission assets to reduce the number of failures and to render those failures in a more planned environment. The cost incurred by the maintenance of these transmission assets is a significant part of operating cost. For example, the Southern California Edison Company was forecasted to expend about 13% of total operating expenditures on maintenance in 2015 [2].

The expansion of the transmission infrastructure is not at par with the rapid increase in electric power consumption. The transmission assets are required to be operated very close to their rated limits to cater to the increased demand in electric energy. This results in faster aging of these assets since they are not designed to sustain a prolonged duration of the higher magnitude of power flows during peak load seasons. According to U.S. Energy Information Administration (EIA), expenditures on operations and maintenance of the transmission grid by the companies from FERC data, has increased from $3.3 billion in 1996 to $13.5 billion in 2016 [3]. With all the foregoing in view, it appears that asset maintenance is an important focus of transmission engineering.

Maintenance strategies can be broadly categorized into corrective, preventive, condition-based and risk-based maintenance [4]. Using the latter two strategies, issues like unnecessary expenses resulting from early maintenance and resulting shutdowns, while ensuring timely maintenance of the critical components, can be addressed. In condition-based maintenance, the real time state of the transmission assets is evaluated by timely monitoring of appropriate parameters and resulting changes [5]. This is used to predict the residual life of the critical components as well as to predict the probability of failure at a given period. Based on the real time values and trends in the equipment condition, the maintenance activities are scheduled.

Risk-based bulk transmission equipment maintenance and replacement have recently gained significant interest among several electric utilities. The objective of risk-based maintenance is to frame a procedure of allotting resources (human and economic) and schedule maintenance tasks among different transmission assets. This is based on the risk they impose on the system upon failure [6]. These risks are broadly quantified in terms of overloads, under-voltages, cascading failures, and voltage instability.

The maintenance strategies described above have evolved from the smart condition monitoring systems which are used to improve the grid resiliency. The notion of a resilient grid focuses on the three elements articulated by the Electric Power Research Institute (EPRI) as follows [7]. The subject of this thesis addresses element (i) of these resilient grid objectives.

i. Prevention – To prevent the failures by designing the maintenance routines, inspection procedures and recovery practices using innovative technologies.

ii. Recovery – To provide rapid damage control by faster deployment of the man-power to attend the contingencies and replace the components with if required.

iii. Survivability – To provide some basic level of electrical functionality to the consumers in the event of blackout.

One of the important factors of power system operation, that assists in implementing risk-based maintenance strategy, is to study and investigate the impact of outages on the electric grid in terms of the severity of those outages. This is termed as *contingency analysis* [8]. A contingency analysis provides essential results regarding the effects of various equipment outages on the electric power network. The severity of an equipment outage can be quantified in terms of performance indices based either on the network topology or on operating electrical parameters. These indices are used to *rank* the transmission equipment in terms of their criticality (i.e. their *impact* upon failure). The ranking list can be used to make various investment decisions such as planning risk-based maintenance, maintaining equipment spare parts, replacement strategies, human resource allocation of maintenance crews, and related operational responsibilities. Also, in condition-based maintenance, continuous monitoring of all the transmission assets is very expensive and needs a significant amount of data analysis. The critical elements identified through contingency analysis would be the best candidates for condition monitoring, reducing the amount of data to be processed. The concept of contingency analysis and ranking of the transmission assets is discussed in several reported works [9] – [12].

1.2 Research Objectives

The prime objective of this research is to obtain the relative ranking of the assets such as transformers, transmission lines, and circuit breakers of an operating utility in terms of their criticality. The criticality of a transmission asset relative to others determines the severity of the impact following its failure on the electric power network. This is achieved by running a post-outage power flow study and evaluating the flow based and voltage based performance indices. The outages are ranked in decreasing order of these performance indices, with the most critical equipment ranked to the top and the least critical equipment ranked at the bottom. Each outage corresponds to a transformer, transmission line or a circuit breaker failure. A circuit breaker failure results in additional components taken out of service. The study is conducted for varying load patterns which includes spring light load of the year 2019, a forecasted summer peak load of the year 2023 and two intermediate loading scenarios. The entire analysis is conducted on the node breaker model of the electric power system of the operating utility under study.

1.3 Thesis Organization

The entire thesis is organized into five main chapters.

- Chapter 1 describes the motivation behind this work along with the research objectives.
- Chapter 2 is focused on the contingency analysis of the power system network. Contingency analysis has evolved from its earlier days in terms of its methodology and applications. One of the aspects of the contingency analysis is to carry out the power flow study following a contingency. This chapter describes the two widely used alternatives to the conventional power flow study namely the fast-decoupled power flow and the methods of distribution factors. These methods are applied to a test system and a comparison of the results is shown towards the end of this chapter.

- Chapter 3 describes the bus branch and node breaker model of the power system network. The benefits of using node breaker model over a bus branch model are discussed in this chapter. Details regarding the power system network of the operating utility under study along with various loading scenarios, considered while doing the analysis, are given in the subsequent sections.
- Chapter 4 discusses various forms of flow and voltage based performance indices mentioned in the literature. Application of the performance indices for relatively ranking the transmission assets is described. Contingency ranking results for transformers, transmission lines, and circuit breakers failure are presented and discussed. A list of the identified critical transmission assets is given at the end of the chapter.
- Chapter 5 concludes the thesis by highlighting the main findings of the research. Recommendations for future work are given in this chapter.

The thesis also contains more voluminous data and computer code which are presented in five appendices:

A. List of circuit breaker contingencies

B. EPCL code

C. Matlab code

D. Transmission line and transformer contingencies

E. Circuit breaker contingencies

CHAPTER 2: CONTINGENCY ANALYSIS

2.1 An Introduction to Power System Contingency Analysis

Operation of an electric grid is a complex process since the system is large and operating conditions vary frequently. A disturbance in an electric grid can originate either from a change in load, an equipment failure (for example generator, transmission line, transformer outage) or a change of state of a device. The change of device status includes an unplanned opening of a circuit breaker in a substation or a failure of a circuit breaker to operate when required. Such a disturbance is usually termed as a *contingency*. It is always desired to evaluate the power system security and plan operational strategies to maintain the stable system operation when one or more elements fail. According to North American Electric Reliability Corporation (NERC) utility power system operation standards, each utility's power system should be able to tolerate and recover from any single element failure scenario [13]. Hence in general, an electric grid is designed to be invulnerable against an *N-1* contingency scenario (failure of a single element will not affect the grid operation).

It is customary for an electric power utility to analyze the effect of all possible contingencies before-hand. This enables power system planners and engineers to determine the power network's strengths or weaknesses and devise appropriate planning and operational strategies to be implemented in an event of a contingency. Following a contingency, the power system is exposed to a range of problems, which can be categorized as below [14]:

(1) none – the power system recovers from the contingency completely, without overloading any element.

(2) severe – several lines or transformers may get overloaded and risk failure/damage in future.

(3) critical – the power system becomes unstable and will quickly collapse.

Contingency analysis (static security analysis) is also a primary tool used for strategizing maintenance plans and assigning maintenance priority of certain transmission assets over others. This chapter describes the contingency analysis methodology and process. Various techniques developed over time for contingency analysis are discussed. A comparison of results between two different methods is shown.

2.2 Contingency Analysis Methodology and Process

The contingency analysis process requires a detailed electrical model of the power system, called a network model. The network model is initialized with starting values reflecting the current operating conditions of the power system. These parameters include bus voltages, generation levels at each generator, loads and power interchanges among adjacent zones. Parameters like equipment ratings are also specified for calculating overloads and violations. Additionally, generator participation factors and priority order are also essential to reschedule the generation in case of loss of a generating station. With the available power network model, initialized with a specific operating condition, contingency analysis can be executed. A contingency list is prepared that consists of all the elements that will be removed from the power system one by one, to test their impact on the overall network. A typical contingency list may consist of the following:

(1) loss of a line

(2) loss of a transformer

(3) loss of a generator

(4) loss of a load

(5) circuit breaker failure.

Following the removal of each element, the modified network is solved for the voltages (magnitude and angle) at each bus as well as active and reactive power flow in each branch. The results obtained for each contingency – the modified network solution – are compared with the base case network solution or the limits for each element in the network. Following a contingency, the results may show a transmission line being overloaded above its rated limit, for example, 110% or the bus voltages may fall below a certain value, say 90% of its nominal voltage. Depending upon the severity of the impact, each contingency is ranked (contingency with most severe impact at the top and least at the bottom).

The contingency analysis requires the following data inputs:

- equipment list to be included in the analysis
- rating of the power system elements (for example lines, generators, transformers)
- base case network data to initialize the network model prior to evaluating each contingency
- power system loading scenarios (these may be part of the base cases).

The severity of each contingency can be evaluated based on various factors like branch current or MVA flow, bus voltages, reactive power generation, or bus voltage deviations which are often termed as the *performance indices* (described in detail in Chapter 4).

The flowchart [15] depicting the steps involved in the contingency analysis is shown in Figure 2.1.

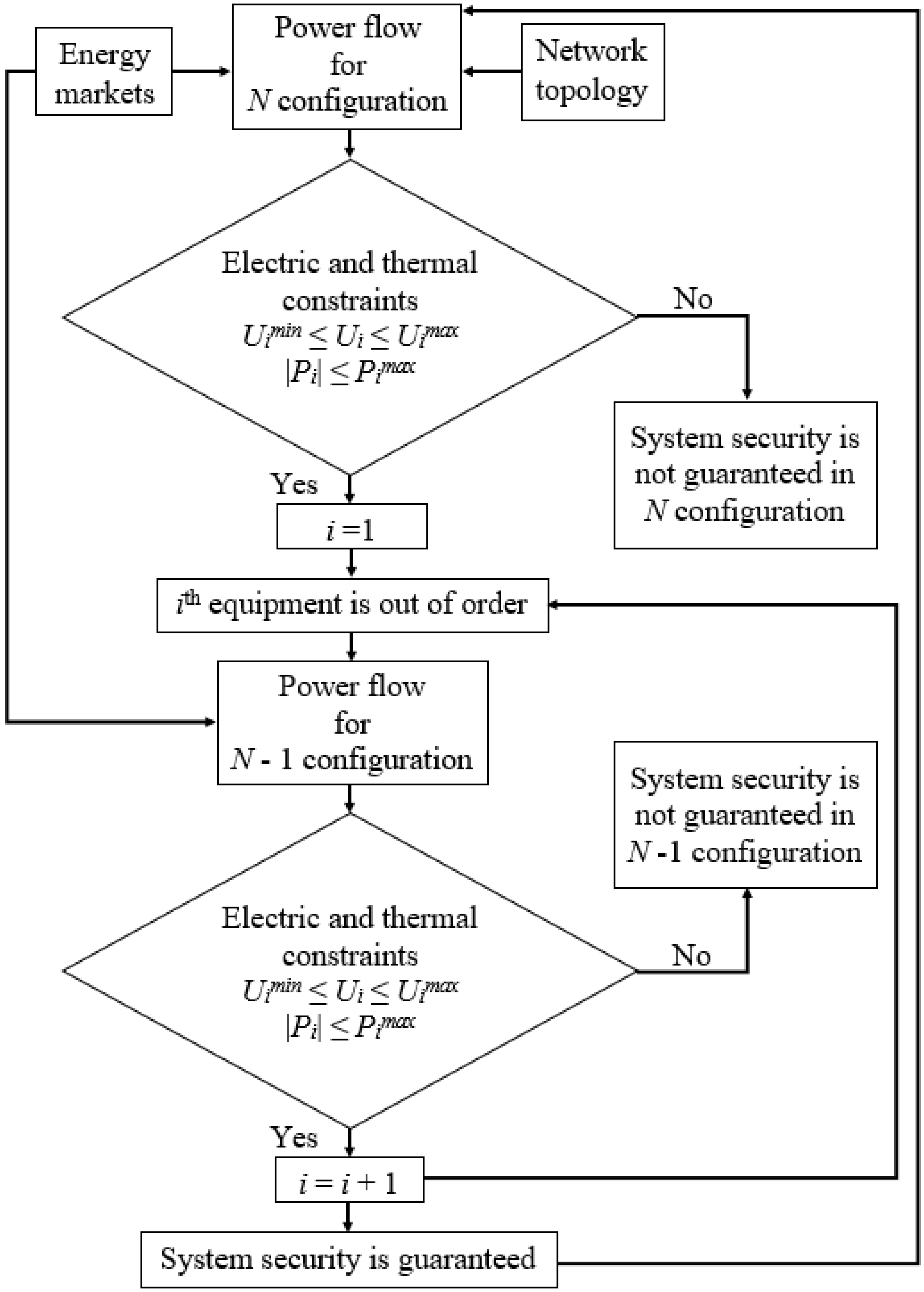

Figure 2.1 Contingency Analysis Flowchart

2.3 Alternatives to AC Power Flow for Contingency Analysis

As mentioned above, to carry out a contingency analysis, a power flow study is must on the network model after the contingency is simulated. The number of iterations in a flat start Newton-Raphson or Gauss-Seidel power flow study [16] is independent to the number of system buses. However, the time and memory requirements of each iteration are highly dependent on the number of buses. Matrix triangular factorization followed by a forward and backward substitution is required to solve any network model for its bus voltages and angles. To do the same, sparsity techniques have been developed, but the processing time varies as the cube of the number of buses [16]. Although the conventional methods of power flow study provide very accurate results, the techniques used for contingency analysis must have enough speed with reasonable accuracy to be effective. Several attempts have been made to overcome these difficulties.

The widely used alternatives to the conventional power flow study are the *fast-decoupled power flow* [17] and the *methods of distribution factors* [18]. A decoupled power flow study relies upon close relation of active power flow and bus voltage phase angle, and reactive power flow and bus voltage magnitude. In methods of distribution factors, the net active power is expressed as the function of voltage phase angles at each bus. This section describes each method in brief detail. A comparison of results in terms of branch active power flows is shown at the end, with a justification for the method used in this thesis.

Fast-decoupled power flow

Fast decoupled power flow technique is one of the modifications of the conventional power flow study. The Jacobian matrix entries for a Newton-Raphson power flow study are mentioned below [16], Diagonal entries of the Jacobian matrix

$$J_1(i,i) = \frac{\partial P_i}{\partial \delta_i} = \sum_{\substack{j=1 \\ j \neq i}}^{N} V_i V_j \left|Y_{ij}\right| \sin\left(\delta_i - \delta_j - \theta_{ij}\right) \tag{2.1}$$

$$J_2(i,i) = \frac{\partial P_i}{\partial V_i} = \sum_{\substack{j=1 \\ j \neq i}}^{N} V_j \left|Y_{ij}\right| \cos\left(\delta_i - \delta_j - \theta_{ij}\right) - 2V_i |Y_{ii}| \cos(-\theta_{ii}) \tag{2.2}$$

$$J_3(i,i) = \frac{\partial Q_i}{\partial \delta_i} = \sum_{\substack{j=1 \\ j \neq i}}^{N} V_i V_j \left|Y_{ij}\right| \cos\left(\delta_i - \delta_j - \theta_{ij}\right) \tag{2.3}$$

$$J_4(i,i) = \frac{\partial Q_i}{\partial v_i} = \sum_{\substack{j=1 \\ j \neq i}}^{N} V_j \left|Y_{ij}\right| \sin\left(\delta_i - \delta_j - \theta_{ij}\right) - 2V_i |Y_{ii}| \sin(-\theta_{ii}). \tag{2.4}$$

In (2.1) – (2.4), the expressions involve summation over *N*-1 terms, where each term is a product of three or more terms. The calculation of Jacobian matrix elements involves many computations, resulting in increased convergence time for large systems in a power flow study. In a fast-decoupled power flow, these summation terms are avoided as explained below. The expressions for active and reactive power mismatches are as follows,

$$\Delta P_i = -\sum_{j=1}^{N} \left|Y_{ij}\right| V_j V_i \cos\left(\delta_i - \delta_j - \theta_{ij}\right) + P_i \tag{2.5}$$

$$\Delta Q_i = -\sum_{j=1}^{N} \left|Y_{ij}\right| V_j V_i \sin\left(\delta_i - \delta_j - \theta_{ij}\right) + Q_i. \tag{2.6}$$

The above expressions indicate remarkable similarity with the diagonal entries of the Jacobian matrix given by (2.1) to (2.4). Upon substituting the terms from (2.5) and (2.6) and with the approximation of $\Delta P_i = 0$ and $\Delta Q_i = 0$, the equations can be simplified as given below. These formulas are known as the fast formulas.

$$J_1(i,i) = Q_i - |Y_{ii}|V_i^2 \sin(-\theta_{ii}) \tag{2.7}$$

$$J_2(i,i) = -\frac{P_i}{V_i} - V_i|Y_{ii}|\cos(-\theta_{ii}) \tag{2.8}$$

$$J_3(i,i) = -P_i + |Y_{ii}|V_i^2 \cos(-\theta_{ii}) \tag{2.9}$$

$$J_4(i,i) = \frac{Q_i}{v_i} - V_i|Y_{ii}|\sin(-\theta_{ii}). \tag{2.10}$$

For systems with low *r*/*x* line impedance ratios, the active power flow and the difference in the bus voltage phase angle are very closely related. The reactive power flow in a similar manner depends mainly on the difference in the bus voltage magnitude. This can be ascertained by the dominance of $\partial P/\partial \delta$ (J_1 of the Jacobian) and $\partial Q/\partial |V|$ (J_4 of the Jacobian) entries in the Jacobian matrix as explained in [16]. Hence, the J_2 and J_3 entries can be completely ignored. The modified P - δ and Q - $|V|$ can now be written as,

$$\begin{pmatrix} \Delta\delta \\ \Delta|V| \end{pmatrix} = \begin{pmatrix} J_1 & 0 \\ 0 & J_4 \end{pmatrix}^{-1} \begin{pmatrix} \Delta P \\ \Delta Q \end{pmatrix} \tag{2.11}$$

$$\Delta\delta = {J_1}^{-1}\Delta P \tag{2.12}$$

$$\Delta|V| = {J_4}^{-1}\Delta Q. \tag{2.13}$$

It can be observed from (2.12) and (2.13) that the P - δ and Q - $|V|$ equations are completely decoupled. The decoupled equations along with the fast formulas for Jacobian are together termed as *fast-decoupled power flow*.

Method of distribution factors

Distribution factors play a crucial role in fast contingency screening and operational planning applications. *Line Outage Distribution Factors* (LODFs) of a power system network involves assessing the sensitivity of the system power flows with respect to a branch outage. It quantifies how sensitive the flow in a branch i is with respect to the flow in a branch j of the network. The LODFs are computed using *Power Transfer Distribution Factors* (PTDFs). The PTDFs computes the sensitivity of the power flow in a branch with respect to change in active power injection at an arbitrary bus in the network [19]. These factors are derived from the linear DC power flow model.

The DC power flow is a simplified version of the full AC power flow. It considers only the active power flows but neglects voltage support or reactive power management and transmission losses. The DC power flow model assumes the following [19]:

- Flat voltage profile - the magnitude of bus voltages is assumed to be constant and equal to 1.0 p.u.
- Low r/x ratios for the branches – neglecting the branch resistances (hence, ignoring the resistive losses in the branches).
- Small voltage angle differences – approximating $\sin(\delta_i-\delta_j) = (\delta_i-\delta_j)$ and $\cos(\delta_i-\delta_j) = 1$.

With the above assumptions, the only variables in the DC power flow are voltage angles and active power injections. Since the losses are neglected, all active power injections are known in advance. Hence the DC power flow becomes linear and there is no need for an iterative method to solve the equations. Table 2.1 summarizes the comparison of various aspects of the AC power flow versus the DC power flow [20].

Table 2.1 AC Power Flow vs DC Power Flow

Aspects	AC power flow	DC power flow
Model	Non-linear	Linear
Solution approach	Iterative	Non-iterative
Convergence	Not guaranteed	Guaranteed
Variables	P, Q, $\lvert V \rvert$, δ	P, δ
Power losses	Incorporated	Neglected
Accuracy	As per specified tolerance limit	Case and system dependent

In case of a DC power flow model, the following equations hold true for each node i in the system,

$$P_i = \sum_{j=1}^{N_B} B_{ij}(\delta_i - \delta_j) \tag{2.14}$$

$$\sum_{i=1}^{N_B} \{P_{gen,i} - P_{load,i} - P_i\} = 0, \tag{2.15}$$

where,

P_i : active power leaving node i,

$P_{gen,i}$: active power injection at node i,

$P_{load,i}$: load connected at a node i.

It is to be noted that each of these assumptions has some effect on the accuracy of the solution. There are several published efforts in the literature that aims at quantifying the tolerance that must be met to obtain an acceptable accuracy of the network solution using the DC power flow. For example, if the following conditions on the assumptions are met, then it would limit the P_{error} (active power estimation error) to 5% [21],

- negligible line resistance assumption can be justified for $r/x < 0.25$
- the flat voltage profile means the standard deviations must be < 0.01.

The PTDFs relating the loading in the line from bus *i* to bus *j* with respect to injected complex power S_k at bus *k* can be expressed as [22],

$$\rho_{ij,k} = \frac{(X_{ik} - X_{jk})}{x_{ij}}. \tag{2.16}$$

It is to be noted that the DC power flow assumptions are used while deriving the above equation. Using the above relation, a PTDF matrix of dimensions N_L by N_B is constructed as,

$$\rho = \begin{bmatrix} \rho_{1,1} & \rho_{1,2} & \cdots & \rho_{1,N_B} \\ & & \cdots & \\ \rho_{N_L,1} & \rho_{N_L,2} & \cdots & \rho_{N_L,N_B} \end{bmatrix}. \tag{2.17}$$

The change in the flow of active power on the branch between bus *i* and bus *j* can be expressed in terms of ΔP_k (change in the active power injection at bus *k*) as,

$$\Delta f_{ij} = \sum_{k=1}^{N_B} \rho_{ij,k} \Delta P_k. \tag{2.18}$$

The LODF $d_{ij,lm}$ (distribution factor for branch *i-j* when branch *l-m* is on outage) are expressed in terms of the PTDFs by using the *compensation theorem* as explained in [16],

$$d_{ij,lm} = \frac{(\rho_{ij,m}^{out} - \rho_{ij,m})}{\rho_{lm,m}}. \tag{2.19}$$

ρ^{out} corresponds to the PTDFs of the power system network post-outage. The post contingency power flow on a branch *ij* (f_{ij}^{c}), following the outage of a branch *lm* can be expressed in terms of LODF $d_{ij,lm}$ as [16],

$$f_{ij}^{c} = f_{ij}^{o} + d_{ij,lm} f_{lm}^{o}, \tag{2.20}$$

where f_{ij}^{o} and f_{lm}^{o} are the pre-contingency flows on branches *ij* and *lm*. The LODFs are computed based entirely on the network parameters and topology. It is to be noted that the distribution factors remain the same unless the network topology is changed. Hence, they can be used repeatedly and rapidly to analyze reconfigurations occurring in the network, irrespective of change in operating conditions.

2.4 Comparison of AC Power Flow Study Alternatives

The power flow study alternatives discussed earlier are implemented on a 200 bus test system [23]. The test system is not related to the actual grid except that the generation and load profiles are made to resemble the actual scenario. The methodology used to create the test system is discussed in [24]. Table 2.2 summarizes the important aspects of the test system under study. PSLF provides an option to compute the line outage distribution factors (LODFs) for all the branches in the designated area and outputs the results in a text file. The LODFs computation feature in PSLF also scans all the branches in the designated area for overloads. In PSLF, the LODFs and post-outage power flow in the branches are calculated using (2.19) and (2.20) respectively. As discussed earlier, the method of distribution factors uses a linear DC power flow model which neglects the transmission lines resistance. To handle this assumption, PSLF provides an option to increase the loads across the designated area by a factor known as '*loss factor*' to account for the absence of resistive transmission losses. The loss factor is specified under losses records in the `.efx` file [25].

Table 2.2 System Description for the 200 Bus Test Case

No. of generators in service	49
No. of transmission lines in service	179
No. of transformers in service	66
Total P_{gen} (MW)	1488.26
Total Q_{gen} (MVAr)	105.78
Total P_{load} (MW)	1475.65
Total Q_{load} (MVAr)	420.57

The comparison of Newton Raphson power flow, fast decoupled power flow, and method of distribution factors is carried out for the outage of a 115 kV line between bus numbers 124 and 9 in the test system. The simulation is carried out in PSLF version 21.0_03. Table 2.3 shows the simulation results to draw a comparison between the power flow study alternatives. For illustrative purpose, the results for nine branches following the outage of the transmission line are shown. The distribution factors and the post outage flows are computed for the loss factors of 1.02 and 1.05.

Table 2.3 Simulation Results for the Power Flow Study Alternatives

Transmission lines		Power flow study method							
		Newton Raphson	Fast decoupled	Method of distribution factors					
				Loss factor =1.02			Loss factor = 1.05		
From bus	To bus	P^c (MW)	P^c (MW)	d	P^c (MW)	Absolute % error	d	P^c (MW)	Absolute % error
1	124	-50.9	-50.8	-0.268	-51.259	0.705	-0.268	-52.004	2.169
1	193	31.1	31.2	-0.270	31.666	1.820	-0.270	32.620	5.118
7	86	-13.5	-13.5	-0.030	-13.635	1.001	-0.030	-13.880	2.817
7	148	14.1	14.1	0.025	14.428	2.332	0.025	14.867	5.441
9	141	-9.9	-9.9	-0.326	-10.276	3.806	-0.326	-10.694	8.026
9	193	-27.2	-27.2	-0.514	-27.930	2.682	-0.514	-28.761	5.740
9	131	-5.6	-5.6	-0.159	-5.330	4.832	-0.159	-5.360	4.285
29	140	-20.9	-20.9	0.048	-21.007	0.516	0.048	-21.707	3.862
29	124	-38.3	-38.4	-0.048	-39.259	2.506	-0.048	-40.333	5.308
				Average error		2.244	Average error		4.752

* *d* denotes the distribution factor.
* P^c denotes the post-outage active power flow in MW.
* Absolute % error is computed with respect to the flow obtained using Newton Raphson power flow method.

The observations from the simulation results shown in Table 2.3 are discussed below.

- The post-outage active power flows computed using Newton Raphson and fast decoupled power flow methods are almost identical.
- The distribution factors are independent of the loss factors and are identical for the loss factors of 1.02 and 1.05. This is evident from the fact that the distribution factors depend only on the network topology and they remain unchanged unless the topology itself is changed. Hence, the distribution factors for a power system network are required to be computed just once and they can be used repeatedly to analyze various contingencies. Such is not the case with Newton Raphson and fast decoupled power flow study methods. This saves a lot of computation time making the method of distribution factors more suitable for online studies.
- However, the post-outage active power flow in the branches varies with the loss factor. This is expected since the value of the loads in the network changes in proportion to the loss factor used for calculations.
- The calculation of distribution factors is based on the linear DC power flow model which involves several assumptions mentioned earlier. These assumptions affect the accuracy of the power flow results. The average of absolute percentage errors in the flows for the loss factors of 1.02 and 1.05 are observed to be 2.244 and 4.752 respectively.
- The research conducted in this thesis is based on an offline study where the computation time is not a constraint. At the same time, it is desired that the results of

the power flow study are accurate, since any inaccuracy would affect the final results in the thesis. Therefore, the results for the post contingency power flows in this work are obtained using a Newton Raphson power flow study method.

CHAPTER 3: SYSTEM DESCRIPTION AND DATA PREPARATION

3.1 System Modeling

An important aspect of contingency analysis is the choice of the system model. Operational near-term and long-term planning studies utilize power flow models with topological data that considers the physical connection and the operating condition of the power system. These models generally represent a substation with a single bus at a certain voltage level. The buses are connected to other substations by transmission lines and/or transformers usually termed as branches. Such models are called bus branch models. A bus branch model ignores the breaker schematic within a given substation. A bus branch model schematic for a part of a power system network is shown in Fig. 3.1.

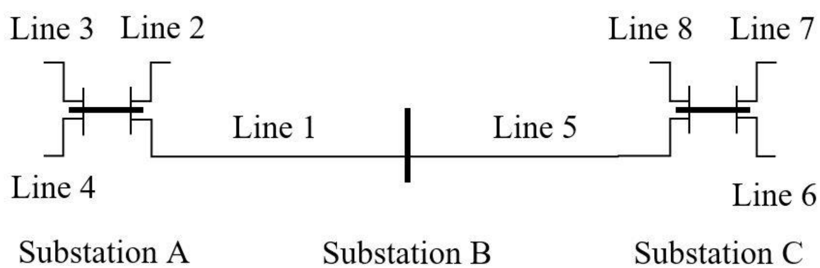

Figure 3.1 Substation Schematic: Bus Branch Model

However, it must be noted that the equipment outages within a substation can change the system topology to the point that it may affect the reliability of the network, at a given operating point. Hence, the contingencies that may arise due to the change of a switch status within a substation are completely oblivious when using the bus-branch model. The accurate representation of all the contingencies associated with a power system network requires the substation configuration to be incorporated in the model. Also, as discussed in [26], the lessons learned from 2011 Arizona-Southern California blackout suggests the need for duplicating real-time system conditions. Real time system conditions are very difficult to capture using the bus branch model and can only be implemented efficiently using a node breaker model.

Node-breaker model

A node-breaker model of the power system fully represents the breaker configuration at each station. This model reflects the actual operating conditions of the system obtained from a real time *energy management system* (EMS). Disconnect switches, circuit breakers, fuses, links and other switching devices are modeled explicitly in a node breaker model. Each breaker is characterized by a status flag and a type flag. A status flag of 1 or 0, signifies if the breaker is connected online or not respectively. Similarly, a type flag indicates the control mechanism exerted on the breaker, which is usually 1 for an automatic switching device and 0 for a manual switching device. Fig. 3.2 shows such a model.

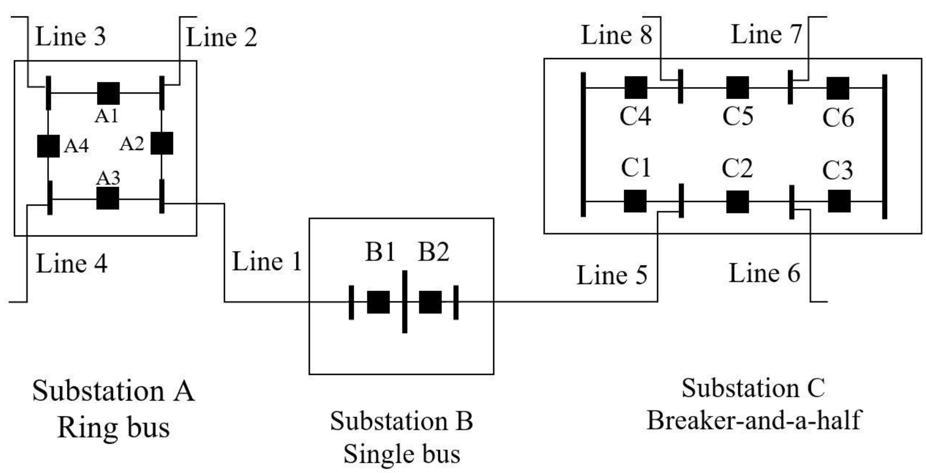

Figure 3.2 Substation Schematic: Node Breaker Model

It is to be noted that using a node breaker model, the substation configuration like a ring bus or the breaker-and-a-half bus can be modeled accurately. The type of system model used while performing contingency analysis greatly affects the accuracy of the results. Contingencies like the stuck breakers can only be represented in a node breaker model. A comparison of the simulation of various contingencies is given in Table 3.1. For this comparison, the bus branch and node breaker substation schematics of Fig. 3.1 and Fig. 3.2 are used.

Table 3.1 Comparison of the Contingency Simulation Using the Bus Branch and Node Breaker Model

Contingency	Bus branch model	Node breaker model
Fault on line 1	Line 1: Open	Breaker A2: Open Breaker A3: Open Breaker B1: Open
Fault on line 1 with breaker A4 out for maintenance	Line 1: Open No lines are isolated Bus split is not captured	Breaker A2: Open Breaker A3: Open Breaker B1: Open Line 4 gets isolated from line 2 and line 3

From the above comparison in Table 3.1, it is apparent that the bus branch model fails to capture all the network changes resulting from contingency 2 (fault on line 1 with breaker A4 out of service), which on the other hand are obvious with the node breaker model. To summarize, a node-breaker model greatly improves the following as listed by NERC [27]:

- visibility of equipment status
- station configuration
- associated critical contingencies
- simulation of protection system operation.

In addition to the bus branch and node breaker model, a power system network can also be represented with a *hybrid model* [28]. In a hybrid model, a node breaker representation is used only for substations of interest, whereas all other areas are modeled using bus branch model. This greatly reduces the complexity associated with using the node-breaker model for large power systems.

3.2 System Description

The analysis is done on an operative power system network of a major utility company in the Southwest United States which is a part of the Western Interconnection. Since it was desired to analyze the circuit breaker contingencies, a node breaker model is used for this study. This section gives a brief description of the power system network. Table 3.2 lists various loading scenarios on which the study has been conducted. The loading scenarios have been selected to understand the impact of the failure of transmission assets at various operating conditions. Table 3.3 summarizes the important aspects of the transmission system at different loading scenarios.

Table 3.2 List of Different Loading Scenarios of an Operating Utility

Scenario	Load connected to the utility	
	P_{load} (MW)	Q_{load} (MVAr)
1	2666.31	182.76
2	4655.52	244.37
3	6047.73	327.35
4	7231.23	291.68

Table 3.3 Data Description for Different Scenarios

Parameter	Scenario			
	1	2	3	4
No. of generators in service	27	28	29	38
Total P_{gen} (MW)	3166.39	4606.69	5627.10	6187.17
Total Q_{gen} (MVAr)	306.25	352.10	717.0	1044.02
Total P_{load} (MW)	2666.31	4655.52	6047.73	7231.23
Total Q_{load} (MVAr)	182.76	244.38	327.35	291.68
Total active power interchange to other areas (MW)	444.07	-158.38	-567.29	-1241.29
Total reactive power interchange to other areas (MVAr)	172.50	-160.20	-650.76	-1102.58

Scenario 1 corresponds to the light load case, where all generators are not at maximum or online. Also, in this case, some power is being exported to the neighboring areas. On the other hand, in scenarios 2,3, and 4, the power is being imported from the neighboring areas, since the local generation was not enough. Scenario 4 corresponds to the summer peak case when most of the generators are operating at their maximum generation limit $P_{gen,max}$.

3.3 Data Preparation

A West-wide System Model (WSM) power flow data file corresponding to scenario 1 was provided by the operating utility. WSM is a full node breaker model representing the entire Western Interconnection. In addition to this, a power flow data file corresponding to the 2023 summer peak load case in the bus branch format was also provided. This chapter describes the methodology by which the power flow study case files corresponding to loading scenarios 2, 3 and 4 were developed in the node breaker format, from the given bus branch power flow data file. The operating conditions, load levels, generators in service and other details were matched as closely to the actual operating conditions as possible. A step by step procedure to create the power flow study case files is given as follows:

1. Create a mapping list for the loads in the bus-branch model to the loads in the node breaker model. Only the loads which are having a service status of 1 in the bus branch model are considered.
2. Update the P_{load} (active power) and Q_{load} (reactive power) values of the loads in the node breaker model from the bus branch model. Keep updating the loads sequentially until the desired loading condition is obtained. It is to be noted that the mapping of a load profile from the bus branch model is an approximate representation of a similar load profile in the node breaker model (due to the difference in the load nomenclatures).
3. To account for increased load, new generators will be required to be switched on. A generation dispatch order list provided by the operating utility was followed. Table 3.4 lists the dispatch order along with the maximum generation limit for each generator.
4. Ramp the active power generation of the generators already in service or switch on new generators if required, to match the desired load. Solve the power flow case. Save the power flow case file in `.sav` format.

Table 3.4 Generation Rescheduling Priority Order List

Priority number	Bus number	Capacity $P_{gen,max}$ (MW)
1	9248	1376
2	9252	1379
3	9253	1377
4	102138	812
5	102140	809
6	102135	809
7	100299	416
8	100298	419
9	105208	437
10	105210	420
11	103364	181
12	103368	163
13	103365	264
14	103363	175
15	103371	134
16	101956	185
17	101957	185
18	101955	321
19	102527	230
20	102529	230
21	102531	300
22	101585	156
23	101593	100
24	7579	18
25	7580	18
26	37116	185
27	37117	185
28	37113	321
29	35010	213
30	35009	213
31	35006	304
32	37177	250
33	37183	138
34	103379	92
35	103381	92
36	103380	92
37	103382	92
38	100121	42.6
39	100120	42.6
40	100123	42.6
41	100124	42.6
42	100126	42.6
43	100127	42.6
44	100112	42.6
45	100113	42.6
46	100115	42.6
47	100116	42.6
48	100118	42.6
49	100119	42.6
50	99240	66
51	99239	65
52	99236	66
53	101590	67
54	101589	67
55	101591	59

List of swing buses in each area

To maintain the consistency and avoid regulation conflicts arising due to multiple swing buses, only one swing bus is assigned in each area. In an area, a generator bus having the maximum available generation capacity is selected as the swing bus. The nomenclature used for bus types in PSLF is mentioned below [19],

- type 0: swing bus ($|V| - \delta$ bus)
- type 1: load bus ($P - Q$ bus)
- type 2: generator bus ($P - |V|$ bus).

The selected swing buses are designated as a type 0, generator buses are designated as type 2 and the remaining buses are made type 1. Table 3.5 contains the list of swing buses for each area. No swing buses were designated in area 10 and 17, since assigning swing buses resulted in the divergence of the power flow.

List of breakers to be switched on for new generators

Out of 52 generators listed in the priority list, only 27 generators are in service to cater to a load of 2666.31 MW corresponding to scenario 1. To meet the increased load requirement pertaining to scenarios 2,3, and 4, new generators are required to be committed. To ensure a generator is committed, the status of a generator is changed from 0 (out of service) to 1 (in service). In addition to this, a node-breaker model also requires that all the disconnect switches and breakers located downstream of a generator are switched on. In some cases, even the status of the unit transformer is required to be changed. Table 3.6 lists all the disconnect switches and/or breakers and unit transformers required to be switched on for the generators which are not in service in the base case.

Table 3.5 List of Swing Buses for Each Area

Area number	Swing bus number
1	5714
2	9252
3	11912
4	12634
5	13255
6	18668
7	25296
8	33587
9	34770
10	No swing bus
11	35336
12	36343
13	36742
14	37100
15	37129
16	37152
17	No swing bus
18	37527
19	38757
20	41068
21	43336

Area number	Swing bus number
22	45737
23	49119
24	53060
25	60911
26	73284
27	75240
28	82768
29	86502
30	92536
31	94678
32	96584
33	100299
34	104606
35	105726
36	106336
37	106820
38	107910
39	113938
40	114128
41	114230

Table 3.6 List of Disconnect Switches/Breakers Required to be Switched on for Newly Committed Generators

Generator bus no.	Disconnect switches/breakers no.	Unit transformer no.
100298	96199, 96197, 96211, 96178, 96207, 96179, 96208, 96108, 96177, 96180	5926
105210	100890	-
103364	99144	-
103365	99146	-
7579	6764	-
7580	6765	-
35009	33294	-
37177	35324	-
37183	35325	-
103379	99140, 99092	-
103381	99141	-
103380	99142, 99097	-
103382	99143, 99088, 99082, 99134	6032
100121	96034	-
100120	96038	-
100123	96039	-
100124	96040	-
100126	96041	-
100127	96042	-
100112	96043	-
100113	96044	-
100115	96045	-
100116	96035	-
100118	96036	-
100119	96037	-
99240	95214	-
99239	95215	-
99236	95216	-
101590	97387	-
101589	97388	-
101591	97384, 97249	-

List of in-service generators power output at various loading scenarios

Table 3.7 - 3.10 consists of the list of in-service generators along with their power generation levels (P_{gen} and Q_{gen}) for scenarios 1,2,3 and 4 respectively. There are several generators owned by the operating utility, which are not a part of the list mentioned in Table 3.4. It is to be noted that only the generators that appear in the generation dispatch order list of Table 3.4 are included here.

Table 3.7 List of In-Service Generators for Loading Scenario 1: P_{load} = 2666.31 MW, Q_{load} = 182.76 MVAr

Bus number	P_{gen} (MW)	Q_{gen} (MVAr)	Bus number	P_{gen} (MW)	Q_{gen} (MVAr)
9248	1337.14	-143.05	101957	154.50	14.65
9252	1187.81	-114.15	101955	277.32	29.71
9253	1329.30	-152.02	102527	129.09	0.27
102138	463.54	-51.38	102529	143.62	5.09
102140	412.38	-77.97	102531	165.83	4.84
102135	328.02	-57.07	101585	94.11	-14.38
100299	158.07	-103.58	101593	66.78	-10.39
105208	288.11	9.69	37116	75.88	1.21
103368	10.34	-28	37117	75.92	2.62
103363	103.04	6.28	37113	134.45	48.09
103371	69.55	-22.89	35010	151.71	0.42
101956	153.78	7.53	35006	73.74	5.82

Table 3.8 List of In-Service Generators for Loading Scenario 2: P_{load} = 4655.52 MW, Q_{load} = 244.38 MVAr

Bus number	P_{gen} (MW)	Q_{gen} (MVAr)
9248	1376	-89.15
9252	1310.89	-50.16
9253	1377	-96.19
102138	812	24.92
102140	809	2.80
102135	809	24.12
100299	116.95	-52.43
105208	437	0
105210	420	-139.64
103368	181	48.47
103363	84.72	38.12
103371	103.04	26.58
101956	69.55	-2.95
101957	154.50	18.65
101955	277.32	36.99
102527	129.09	6.97
102529	143.62	11.78
102531	165.83	13.84
101585	94.11	6.12
101593	66.78	0.43
37116	75.88	5.19
37117	75.92	6.58
37113	134.45	55.45
35010	151.71	6.11
35006	73.74	14.91

Table 3.9 List of In-Service Generators for Loading Scenario 3: P_{load} = 6047.73 MW, Q_{load} = 327.35 MVAr

Bus number	P_{gen} (MW)	Q_{gen} (MVAr)
9248	1376	-34.08
9252	1251.26	-2.48
9253	1377	-40.10
102138	812	33.95
102140	809	11.85
102135	809	33.10
100299	136.75	-35.27
105208	437	0
105210	420	-132.51
103364	181	60.62
103368	163	69.99
103365	264	111.57
103363	175	44.63
103371	134	12.58
101956	185	0

Bus number	P_{gen} (MW)	Q_{gen} (MVAr)
101957	185	0
101955	321	69.56
102527	230	30.61
102529	230	34.14
102531	300	0
101585	156	29.25
101593	100	13.54
7579	18	0.80
7580	18	0.80
37116	185	0
37117	185	0
37113	321	97.93
35010	182.10	19.42
35006	73.74	29.27

Table 3.10 List of In-Service Generators for Loading Scenario 4: P_{load} = 7231.23 MW, Q_{load} = 291.68 MVAr

Bus number	P_{gen} (MW)	Q_{gen} (MVAr)
9248	1376	28.75
9252	1134.14	46.61
9253	1377	23.89
102138	812	46.13
102140	809	24.07
102135	809	45.20
100299	138.77	-13.72
105208	437	0
105210	420	-123.90
103364	181	80.67
103368	163	70
103365	264	151.42
103363	175	64.32
103371	134	31.89
101956	185	0
101957	185	0
101955	321	83.82
102527	230	39.60
102529	230	43.11
102531	300	0
101585	156	52.85

Bus number	P_{gen} (MW)	Q_{gen} (MVAr)
101593	100	26.02
7579	18	1.66
7580	18	1.66
37116	185	0
37117	185	0
37113	321	112.40
35010	213	33.99
35009	213	19.44
35006	304	0
37177	250	15.49
37183	138	30.74
103379	92	6.78
103381	92	0.11
103380	92	6.78
103382	92	11.19
100121	42.59	3.49
100120	42.59	3.49
100123	42.59	3.49
100124	42.59	3.49
100126	19.65	1.65

Contingency list preparation

A contingency list consists of the elements that will be removed from the network model, one by one, to study the effects on the power system network. In general, the criteria for selection of the transformers, transmission lines and circuit breakers for the contingency simulation are stated as follows,

- voltage level must be 500 kV
- equipment must be in-service
- equipment must be operated or owned by the operating utility.

In addition to the above criteria, the conditions shown below should be met for a transmission line and a circuit breaker to include them in the contingency list:

- In PSLF, a jumper is modeled as a transmission line with zero resistance and zero reactance ($r = 0$ and $x = 0$), whereas a series capacitor is modeled as a transmission line with zero resistance and a negative reactance ($r = 0$ and $x < 0$) [25]. Hence, while creating the contingency list, only the transmission lines with a positive reactance ($x > 0$) are considered. This filters out the 500 kV jumpers as well as series capacitors from the contingency list.
- A circuit breaker in PSLF's node breaker format does not carry the "owner number" attribute. Hence to identify a circuit breaker owned by the operating utility, the owner of the breaker's terminal buses is determined. If the identified owner is the operating utility under consideration, then the circuit breaker is included in the contingency list. It is to be noted that the disconnect switches (manual and motor operated), are not considered for the analysis.

Three separate contingency lists consisting of 35 transformers, 29 transmission lines, and 112 circuit breakers are prepared. Tables 3.11 to 3.12 summarize the list of transformers and transmission lines identified for ranking. The list of circuit breakers is given in Appendix A.

Table 3.11 List of 500 kV Transformers for Contingency Analysis and Ranking

Transformer name	From bus	To bus	Primary winding kV	Secondary winding kV	Tertiary winding kV
Tr 1	99485	99488	500	115	-
Tr 2*	99766	99832	500	230	12.5
Tr 3*	99767	99833	500	230	12.5
Tr 4	100257	100294	500	69	-
Tr 5	100285	100293	500	345	-
Tr 6	100284	100292	500	345	-
Tr 7*	100264	100297	500	22	-
Tr 8	100465	100469	500	230	-
Tr 9	101451	101467	500	230	34
Tr 10	101452	101468	500	230	34
Tr 11	101924	101933	500	230	-
Tr 12	101922	101932	500	230	-
Tr 13*	102131	102139	500	26	-
Tr 14*	102132	102134	500	26	-
Tr 15*	102133	102136	500	26	-
Tr 16*	102419	102443	500	24	-
Tr 17*	102428	102444	500	24	-
Tr 18*	102385	102445	500	24	-
Tr 19*	102487	102536	500	18	-
Tr 20*	102504	102540	500	18	-
Tr 21*	102508	102541	500	18	-
Tr 22*	102500	102539	500	18	-
Tr 23*	102447	102525	500	18	-
Tr 24*	102450	102526	500	18	-
Tr 25*	102514	102542	500	18	-
Tr 26*	102459	102528	500	18	-
Tr 27*	102466	102530	500	18	-
Tr 28*	102469	102532	500	18	-
Tr 29	102738	102756	500	230	-
Tr 30	102737	102755	500	230	-
Tr 31	103145	103169	500	230	-
Tr 32	103147	103162	500	230	-
Tr 33	103144	103165	500	230	-
Tr 34	103148	103166	500	230	-
Tr 35	103604	103655	500	230	34

* Denotes a generator step-up transformer

Table 3.12 List of 500 kV Transmission Lines for Contingency Analysis and Ranking

Transmission line name	From bus	To bus
Ln 1	102439	7516
Ln 2	100973	9782
Ln 3	100982	9783
Ln 4	101007	9048
Ln 5	100976	37154
Ln 6	102377	87944
Ln 7	101006	96580
Ln 8	100288	103616
Ln 9	100265	103791
Ln 10	102769	100463
Ln 11	100464	102725
Ln 12	100992	101293
Ln 13	101921	100989
Ln 14	101923	100995
Ln 15	100987	102442
Ln 16	102442	102390
Ln 17	100972	102441
Ln 18	102441	102387
Ln 19	101008	102440
Ln 20	102376	102440
Ln 21	100963	102764
Ln 22	101296	102479
Ln 23	102481	101283
Ln 24	101442	99759
Ln 25	101445	101286
Ln 26	102379	103152
Ln 27	102728	99771
Ln 28	103610	99768
Ln 29	102732	105242

CHAPTER 4: RANKING METHODOLOGY AND RESULTS

4.1 System Performance Indices

The critical elements in a transmission network are identified by carrying out a contingency analysis followed by the ranking of the transmission assets. However, to rank the assets, it is necessary to quantify the impact of their failure on the system. Depending upon the nature of severity, some outages may result in network constraints violation, such as bus voltages deviation outside limit and transmission lines or transformers overload. The ranking is usually achieved by computing the system wide *performance indices*. These indices are formulated to capture the effect of the contingencies in terms of the bus voltage deviations, branch overloads, or generator reactive power limits. Several contingency ranking methods have been introduced in references [29]-[31]. In all these methods a performance index is defined and calculated. The methods differ from each other in terms of performance index definition and their effectiveness in the identification of the critical elements.

In [32], the authors Ejebe and Wollenberg, have developed a fast technique for contingency ranking and selection. The authors have proposed a methodology for the ranking of transmission lines and generator outages based on their impacts on bus voltages and branch power flows. This method evaluates the effect of outages on the system bus voltages by using the non-linear ac load flow equations, whereas a dc load flow model is used to rank the contingencies based on active power flows. The ranking obtained using this method provides the severity of each contingency relative to the others. The contingencies are analyzed further by carrying a full ac power flow starting at the top of the list and stopping when the cases do not pose significant problems. This method selects the contingencies in an adaptive way based on the system operating condition, instead of using a fixed list based on offline studies. The indices defined by the authors in [32] are based on the voltage constraints at the load buses and flow constraints on the transmission lines and transformers. The bus voltages are constrained between the high limit imposed by the maximum system voltage value and a low limit below which the system is vulnerable to voltage collapse. Similarly, the power flow on the transmission lines and transformers is constrained due to the thermal limits. These constraints are treated as 'soft' constraints by introducing a penalty function. This way the performance indices are penalized based on the magnitude of constraints violation. The voltage based performance index, termed as PI_V, is defined in [32] as,

$$PI_V = \sum_{i=1}^{N_B} \frac{W_{V_i}}{2n} \left(\frac{|V_i| - |V_i^{sp}|}{\Delta V_i^{lim}} \right)^{2n}, \tag{4.1}$$

where,

$|V_i|$: voltage magnitude at bus i in p.u.,

$|V_i^{sp}|$: specified voltage magnitude at bus i in p.u.,

ΔV_i^{lim} : voltage deviation limit for bus i in p.u.,

n : exponent of the penalty function,

N_B : number of buses in the system,

W_{Vi} : real non-negative weighting factor for bus i.

From (4.1), it can be observed that the PI_V index accounts for voltage deviations across all the buses in the power system. Also, the PI_V index will be higher for contingencies that result in larger system wide voltage deviation. The index largely depends on the exponent n and the weight coefficient W_{Vi}. For the same amount of voltage deviation, the value of PI_V index will be greater for a greater value of *n*. Similarly, a higher value of W_{Vi} can be assigned to a bus where voltage deviation is not acceptable and may cause stability issues. This would increase the sensitivity of the PI_V index with respect to the buses with higher weight coefficients. The authors in [32] have also defined a voltage-reactive power performance index PI_{VQ} given as,

$$PI_{VQ} = \sum_{i=1}^{N_B} \frac{W_{V_i}}{2n} \left(\frac{|V_i| - |V_i^{sp}|}{\Delta V_i^{lim}} \right)^{2n} + \sum_{j=1}^{N_G} \frac{W_{Q_j}}{2n} \left(\frac{Q_j}{Q_j^{max}} \right)^{2n}, \tag{4.2}$$

where,

Q_j : reactive power produced at bus *i*,

Q_j^{max} : maximum allowable reactive power at bus i,

N_G : number of generators in the system,

W_{Qj} : real non-negative weighting factor for bus *j*.

In (4.2), the second summation accounts for violations occurring in the reactive power constraints of the generating units. However, the reactive power limits on the generators are usually considered while carrying out an AC power flow study in most of the software packages available these days. The weight coefficient W_{Qj} can be set to zero if the reactive power violations are not required to be accounted for.

An index for quantifying the impact of contingency in terms of branch overloads is also defined in [32]. The active power performance index is given by,

$$PI_{MW} = \sum_{i=1}^{N_L} \frac{W_i}{2n} \left(\frac{P_i}{P_i^{lim}} \right)^{2n}, \tag{4.3}$$

where,

P_i : active power flow on branch *i* in MW,

P_i^{lim} : the MW capacity of branch *i*,

N_L : number of branches in the system,

W_i : real non-negative weighting factor.

The authors have introduced a concept of computing the sensitivities of the performance indices given by (4.1), (4.2), and (4.3) with respect to the outages. However, computing the sensitivities is more complicated than the performance indices. As suggested by Eftekharnejad in [33], the performance indices by themselves are enough to provide a reasonable ranking of the contingencies. This holds true for a larger power system with a larger number of buses.

It is to be noted that the performance index defined by (4.3), considers all the lines flow irrespective of the ratio $\frac{P_i}{P_i^{lim}}$. A contingency may result in several branch overloads while the other branches operate below their respective limits. A simpler flow based performance index is defined by (4.4),

$$PI_F = \left\{ \max\left(\frac{F_i}{F_{i,lim}}\right), N_V \right\}, \tag{4.4}$$

where $i = 1$ to N_L (number of branches in the system). In (4.4), F_i and $F_{i,lim}$ are the flow and the rating of the i^{th} branch respectively expressed in terms of current for transmission lines and in terms of MVA for transformers. The term N_V is the number of rating violations encountered for the i^{th} contingency. The index in (4.4) considers only the branches with maximum loading in the network since those heavily loaded elements are more prone to failure. The contingency that resulted in maximum overloading gets ranked higher. If two or more contingencies resulted in the same overloading, then the number of rating violations N_v is used to resolve the 'tie' and ultimately rank the contingencies.

A contingency ranking method that focuses on detecting the voltage problems has been described in [34]. The authors have introduced the concept of contingency stiffness to address the issue of inaccurate rankings due to nonlinearities of the reactive power equations, negligence of the effects of voltage regulators, and discontinuities due to limits on the reactive power generation devices. In this method, a stiffness index is calculated for each contingency. The stiffness index defined in [34] measures the amount of local disturbance caused by an outage. Two different stiffness indices corresponding to branch and generator outages are defined. The contingencies are categorized into two groups based on the value of the stiffness index. In general, the first group consists of the contingencies having a stiffness index below a certain threshold. A smaller stiffness index implies that the system states and the power flow change linearly with respect to parameters of the circuit or generating unit under outage [34]. Hence such contingencies can be ranked using performance indices which are based on the linearized model around the operating point. However, the contingencies in the second group with a larger stiffness index imply the need for using alternative methods like subnetwork solution for ranking purpose [34]. A voltage based performance index described in [34] is given as,

$$M = \sum_{i=1}^{N_B} W_i \left(\frac{2V_i - V_i^{max} - V_i^{min}}{V_i^{max} - V_i^{min}} \right)^{2n}, \tag{4.5}$$

where,

V_i : voltage magnitude at bus i in p.u.,

V_i^{max} : maximum allowable voltage magnitude at bus i in p.u.,

V_i^{min} : minimum allowable voltage magnitude at bus i in p.u.,

W_i : weighting factor for bus i,

n : exponent of the penalty function.

The performance index M defined by (4.5), is smaller when the voltage magnitudes are within the given voltage limits V_i^{max} and V_i^{min} and it assumes a larger value when the bus voltages are outside the specified range. The contingency ranking method given in [34] further involves the computation of the derivative of the performance index M with respect to the contingency parameters. The ranking of contingencies is done based on the values of the derivative. It is to be noted that this method is not applicable for contingencies with a higher stiffness index.

4.2 Ranking Methodology

A step by step procedure to obtain the ranking of the transmission assets is as follows:

1. Create the power flow case files for different loading scenarios.
2. Load the `.sav` power flow file for a loading scenario in PSLF.
3. Simulate a transmission asset contingency from a contingency list.
    - For transformers and transmission lines contingencies, change the service status of the concerned equipment to 0.
    - To simulate a stuck breaker contingency, all the equipment including breakers, transmission lines, transformers, generators, or shunts that would trip due to a breaker getting stuck are taken out of service.
4. Perform generation rescheduling if a contingency result in loss of a generator.
5. Solve the power flow for the modified power system network.
6. Upon convergence of the power flow study performed in step 5, save the results comprising of bus voltages and branch flows in a `.txt` file. Go to step 8.

7. If the power flow study for the modified power system network in step 5 fails to converge, an attempt is made to resolve the power flow by changing the solution parameters as follows,
   a. Increase the number of iterations before the VAR limit is imposed on the generators
   b. Increase the mismatch tolerance
   c. Increase the total number of power flow iterations.
8. Repeat steps 3 to 7 for all the contingencies in the list.
9. Export the `.txt` files containing the power flow results obtained in step 6 in Matlab.
10. Compute the performance indices PI_V and PI_F given by (4.1) and (4.4) for all types of contingencies.
11. Rank the transmission assets in decreasing order of the performance indices - PI_V and PI_F.
12. Repeat steps 2 to 11 for all the loading scenarios.

The contingency simulation of transmission assets is automated in PSLF using EPCL. EPCL is a programming language exclusively developed to work in conjunction with PSLF. It has direct access to the data tables of the power flow cases under study and can be used effectively to perform data manipulations, automate the simulations and generate reports [25].

4.3 Simulation Results for 500 kV Transformer Contingencies

The transformer is a crucial equipment in an electrical utility's transmission assets arsenal. In many cases, transformers are operated way beyond their predicted life of 25 to

40 years [35]. With the increase in demand for electric energy, some transformers are operated above their rated MVA capacity. Operating utilities perform several off-line and on-line analysis to monitor the health of the transformers so that any upcoming failure can be diagnosed and dealt in a planned manner. It is often desired to identify a set of critical transformers from the entire fleet. This would help prioritize the maintenance and investment decisions for the most critical transformers over the lesser ones, and hence optimize the operation and maintenance expenditure.

The transformers are ranked relative to each other to identify the critical ones. The relative ranking of the transformers listed in Table 3.11 is achieved by quantifying the impact of their failure on the rest of the system in terms of the performance indices PI_V and PI_F given by (4.1) and (4.4) respectively. The PI_V and PI_F values corresponding to each *N*-1 transformer contingency for four different loading scenarios are presented in this section. The EPCL code used to simulate each transformer contingency one-by-one and store the results in `.txt` files is given in Appendix B. The Matlab script that reads the `.txt` files containing the contingency power flow results and computes the performance indices is described in Appendix C.

The simulation results of the transformer contingencies corresponding to scenario 1 (light load case) and scenario 4 (summer peak load case) are discussed in this section. The results of transformer contingencies for scenario 3 and scenario 4 (intermediate load cases) are given in Appendix D. As described earlier, the performance indices capture the impact of transformer failures on the rest of the power system network in terms of branch overloads and bus voltage deviations. The transformers with higher values of PI_V and PI_F are identified as critical ones since their failure impact is severe relative to the transformers with lower values of PI_V and PI_F indices. The values of PI_V, PI_F, and N_V for each one of the 35 transformer contingencies corresponding to scenario 1 is listed in Table 4.1.

Table 4.1 List of PI_V and PI_F Indices for Transformer Contingencies for Scenario 1 (P_{load} = 2666.31 MW, Q_{load} = 182.76 MVAr)

Transformer name	PI_V	PI_F	N_V
Tr 1	111.726	0.899	0
Tr 2	104.911	0.899	0
Tr 3	104.911	0.899	0
Tr 4	111.213	0.899	0
Tr 5	114.307	0.899	0
Tr 6	115.092	0.899	0
Tr 7	135.455	0.925	0
Tr 8	108.298	0.898	0
Tr 9	97.253	0.898	0
Tr 10	97.211	0.898	0
Tr 11	106.522	0.898	0
Tr 12	106.882	0.898	0
Tr 13	110.717	0.925	0
Tr 14	111.536	0.925	0
Tr 15	110.771	0.925	0
Tr 16	136.628	0.977	0
Tr 17	132.655	0.934	0
Tr 18	137.260	0.977	0

Transformer name	PI_V	PI_F	N_V
Tr 19	107.700	0.894	0
Tr 20	115.119	0.924	0
Tr 21	112.998	0.924	0
Tr 22	112.514	0.924	0
Tr 23	112.297	0.924	0
Tr 24	110.725	0.924	0
Tr 25	111.658	0.924	0
Tr 26	112.173	0.924	0
Tr 27	112.109	0.924	0
Tr 28	112.313	0.924	0
Tr 29	112.446	0.899	0
Tr 30	112.446	0.899	0
Tr 31	108.698	0.899	0
Tr 32	108.698	0.899	0
Tr 33	108.731	0.899	0
Tr 34	108.564	0.899	0
Tr 35	121.960	0.899	0

From the results mentioned in Table 4.1, it can be observed that the indices are close to each other in most of the contingencies. The indices differ from others only for a few critical contingencies. Also, it can be noted that for scenario 1, no branch limit violations are observed for any of the 35 transformer contingencies (i.e., $N_V = 0$ for all the contingencies). This is expected since scenario 1 corresponds to a light load case (~37 % of the peak load case) where the assets are not loaded to their maximum capacity in the base case. Hence, none of the branches in the power system network of the operating utility gets overloaded following a contingency.

The transformer contingencies with higher PI_V are not always the cases with a high PI_F except for some of the critical contingencies. Therefore, the relative ranks of the transformers obtained based on these performance indices are quite different. For example, Tr 18 is identified as the most critical transformer relative to other transformers based on the both PI_F and PI_V performance indices, whereas the rank of transformer Tr 35 is different based on each of these performance indices. The plots of PI_V and PI_F performance indices for all the transformer contingencies under scenario 1 are shown in Fig. 4.1 to provide a better comparison.

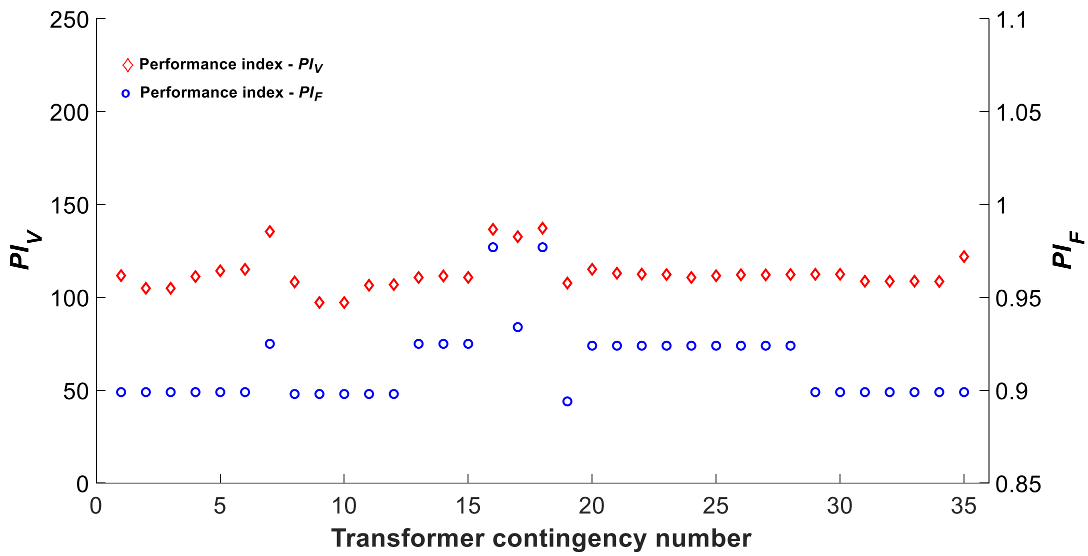

Figure 4.1 Comparison of PI_V and PI_F Indices for Transformer Contingencies of Loading Scenario 1

Fig. 4.2 and 4.3 show the buses voltage deviation plot for Tr 18 and Tr 10 respectively.

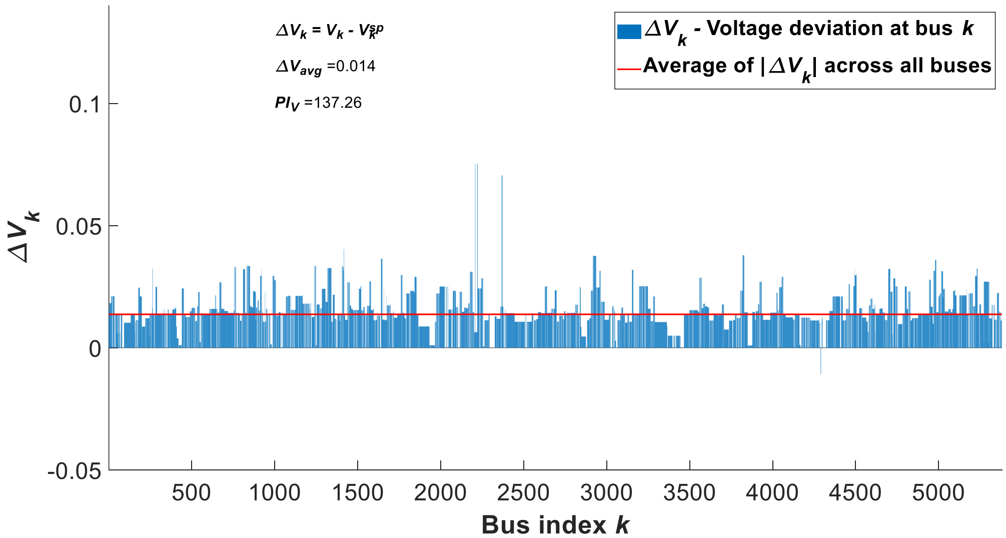

Figure 4.2 Scenario 1: Bus Voltage Deviation Plot for Most Critical Transformer Tr 18 Contingency

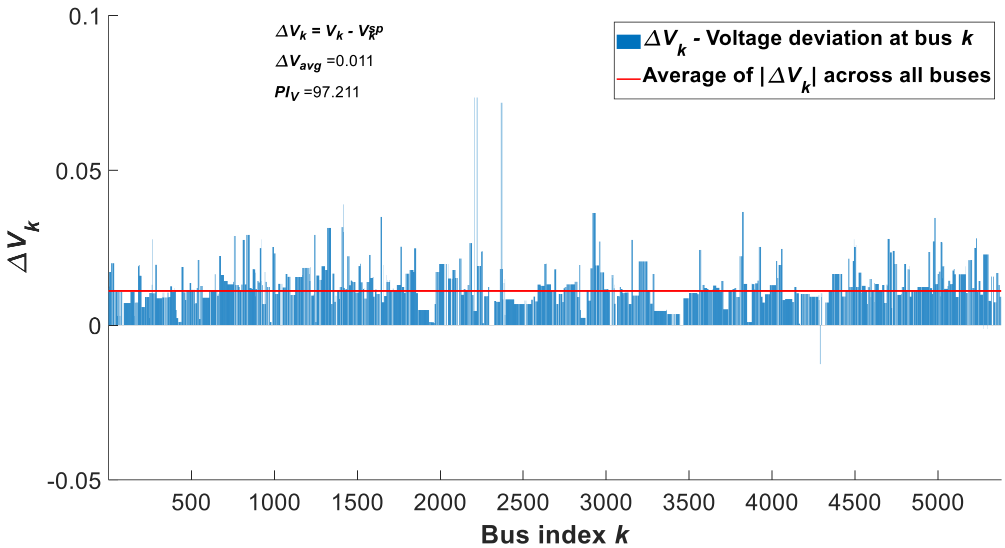

Figure 4.3 Scenario 1: Bus Voltage Deviation Plot for Least Critical Transformer Tr 10 Contingency

Tr 18 (PI_V = 137.26) is the most critical transformer while Tr 10 (PI_V = 97.211) is the least critical transformer identified based on the PI_V index for scenario 1. From Fig. 4.2, it is observed that upon failure of Tr 18, most of the buses suffer from over-voltage.

The buses in the power system network of the operating utility, following the Tr 10 transformer contingency also suffers from over-voltage. However, the voltage deviation for Tr 18 and Tr 10 transformer contingencies across all the buses in the network is below the desired ΔV^{lim} value (i.e., 0.05 p.u. for 500 kV buses and 0.075 p.u. for the buses at any other voltage levels). This is evident from the values of the average bus voltage deviation ΔV_{avg} for both the transformer contingencies shown in Fig. 4.2 and 4.3. The average bus voltage deviation of a power system network is given by,

$$\Delta V_{avg} = \frac{1}{N_B} \sum_{k=1}^{N_B} \left| V_k - V_k^{sp} \right|, \tag{4.6}$$

where,

V_k : voltage magnitude at bus k in p.u.,

V_k^{sp} : specified voltage magnitude at bus k in p.u.,

N_B : number of buses in the power system network.

The values of PI_V, PI_F, and N_V for each one of the 35 transformer contingencies corresponding to scenario 4 is listed in Table 4.2. Scenario 4 corresponds to the summer peak load case of the operating utility. During summer, the transmission assets are operated at their maximum capacity to cater to the high load demand. A 500 kV transformer contingency during such a peak load condition is expected to result in a severe impact on the rest of the system. This is evident from the results presented in Table 4.2. It can be noted that each transformer contingency irrespective of its PI_F value results in at least two branch flow limit violations in the power system network of the operating utility i.e., $N_V \geq 2$. Tr 35 is identified as the most critical transformer based on the PI_F as well as PI_V index. The PI_F value of 1.129 for Tr 35 indicates that a branch in the power system network will be loaded to 112.9 % of its rated limit, following the failure of transformer Tr 35. The value of N_V for this transformer is 4.

Table 4.2 List of PI_V and PI_F Indices for Transformer Contingencies for Scenario 4 (P_{load} = 7231.23 MW, Q_{load} = 291.68 MVAr)

Transformer	PI_V	PI_F	N_V
Tr 1	1041.682	1.066	2
Tr 2	1078.403	1.067	2
Tr 3	1078.400	1.067	2
Tr 4	1039.761	1.066	2
Tr 5	1032.990	1.066	2
Tr 6	1031.064	1.066	2
Tr 7	1024.395	1.066	2
Tr 8	1073.128	1.067	2
Tr 9	1197.026	1.073	2
Tr 10	1197.689	1.073	2
Tr 11	1076.991	1.083	4
Tr 12	1073.577	1.083	4
Tr 13	1022.795	1.065	2
Tr 14	1020.178	1.065	2
Tr 15	1022.576	1.065	2
Tr 16	970.306	1.063	4
Tr 17	974.613	1.064	2
Tr 18	969.658	1.063	4

Transformer	PI_V	PI_F	N_V
Tr 19	1060.818	1.067	2
Tr 20	1031.498	1.066	2
Tr 21	1038.592	1.066	2
Tr 22	1043.126	1.066	2
Tr 23	1041.916	1.066	2
Tr 24	1047.266	1.066	2
Tr 25	1046.641	1.066	2
Tr 26	1033.122	1.066	2
Tr 27	1034.211	1.066	2
Tr 28	1015.196	1.065	2
Tr 29	1041.999	1.066	2
Tr 30	1041.999	1.066	2
Tr 31	1067.538	1.067	2
Tr 32	1067.538	1.067	2
Tr 33	1067.027	1.067	2
Tr 34	1068.682	1.067	2
Tr 35	2149.555	1.129	4

A comparison of the PI_V and PI_F performance indices for transformer contingencies of scenario 4 is shown in Fig. 4.4. From the plots in Fig. 4.4, it is observed that the values of PI_V and PI_F performance indices follow a trend i.e., the values of PI_V and PI_F performance indices for a transformer contingency are both either relatively higher or lower than the indices for other transformer contingencies. As a result, the set of critical transformers identified based on PI_V and PI_F indices are almost identical except a few transformers. Such a trend is not observed in the relative values of the PI_V and PI_F indices for transformer contingencies of scenarios 2 and 3. For illustrative purpose, the list of top ten transformers based on the PI_V and PI_F values for scenario 4 is shown in Table 4.3.

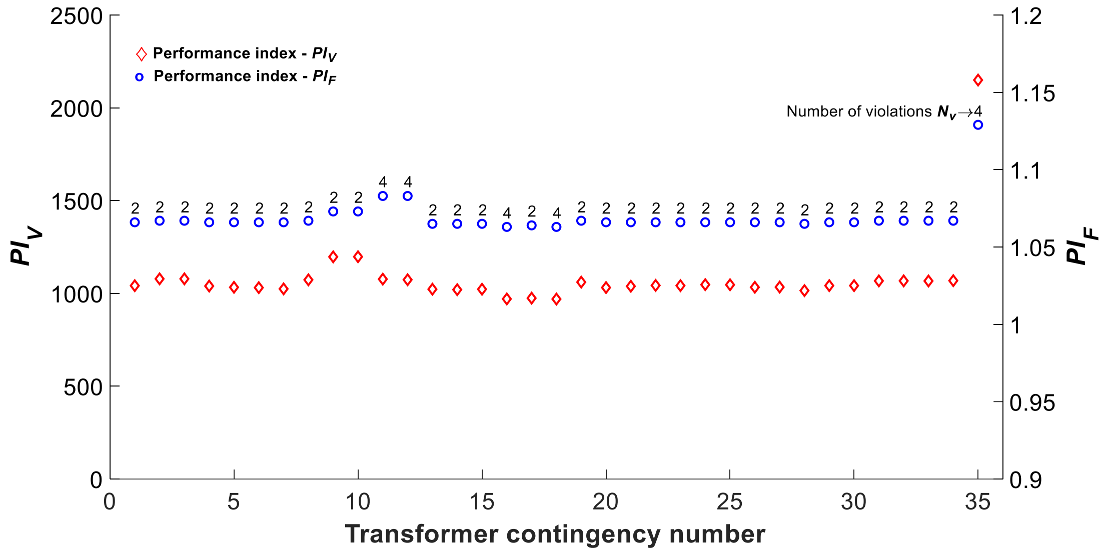

Figure 4.4 Comparison of PI_V and PI_F Indices for Transformer Contingencies of Loading Scenario 4

Table 4.3 List of Top Ten Transformers Based on the PI_V and PI_F Values for Scenario 4

Rank	PI_V based transformer	PI_F based transformer
1	Tr 35	Tr 35
2	Tr 10	Tr 11
3	Tr 9	Tr 12
4	Tr 2	Tr 10
5	Tr 3	Tr 9
6	Tr 11	Tr 8
7	Tr 12	Tr 34
8	Tr 8	Tr 31
9	Tr 34	Tr 32
10	Tr 31	Tr 33

Tr 35 and Tr 18 are identified as the most critical and least critical transformers respectively for scenario 4 using the voltage based PI_V index. Figs. 4.5 and 4.6 show the bus voltage deviation plot for Tr 35 and Tr 18 transformer contingencies of scenario 4. It can be observed that the buses in the power system network of the operating utility show significant under-voltage. The average voltage deviation for Tr 35 contingency is 0.054, which is higher than the acceptable ΔV^{lim} value of 0.05 p.u. for 500 kV buses.

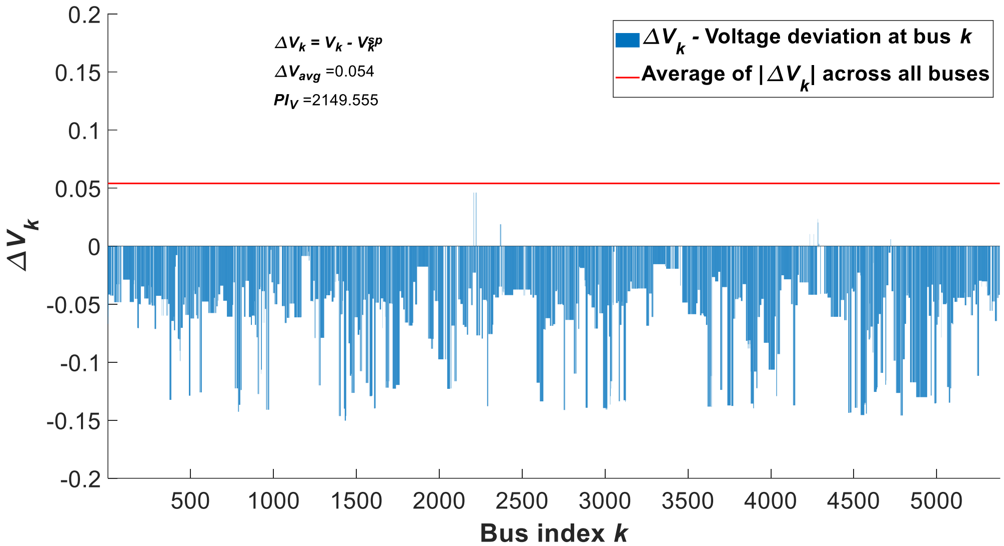

Figure 4.5 Scenario 4: Bus Voltage Deviation Plot for the Most Critical Transformer Tr 35 Contingency Based on PI_V

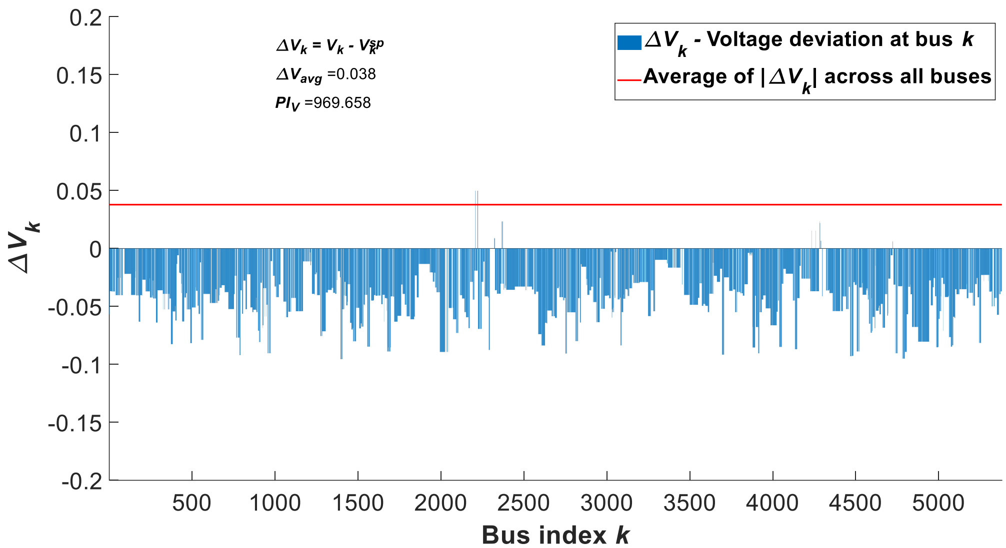

Figure 4.6 Scenario 4: Bus Voltage Deviation Plot for the Least Critical Transformer Tr 18 Contingency Based on PI_V

In general, the PI_V and PI_F indices for the transformer contingencies under scenario 4 are higher compared to similar contingencies under scenarios 1, 2 and 3. This can be seen from the plots in Figs. 4.7 and 4.8. It is to be noted that this trend is strictly observed for the PI_V index but not for the PI_F index (especially for top ten ranked transformer contingencies). The PI_F values for several transformers under scenario 1 are higher compared to the similarly ranked transformers under scenario 2 and 3.

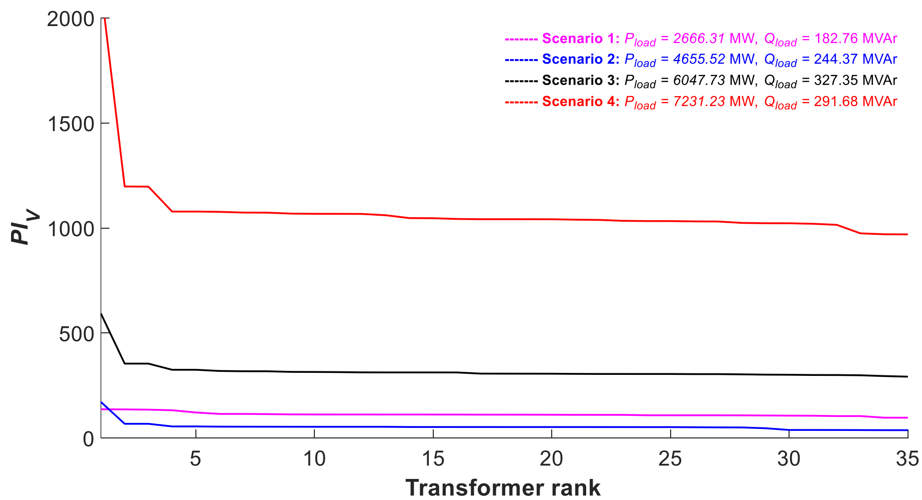

Figure 4.7 Comparison of the PI_V Index Transformer Contingencies Under Different Loading Scenarios

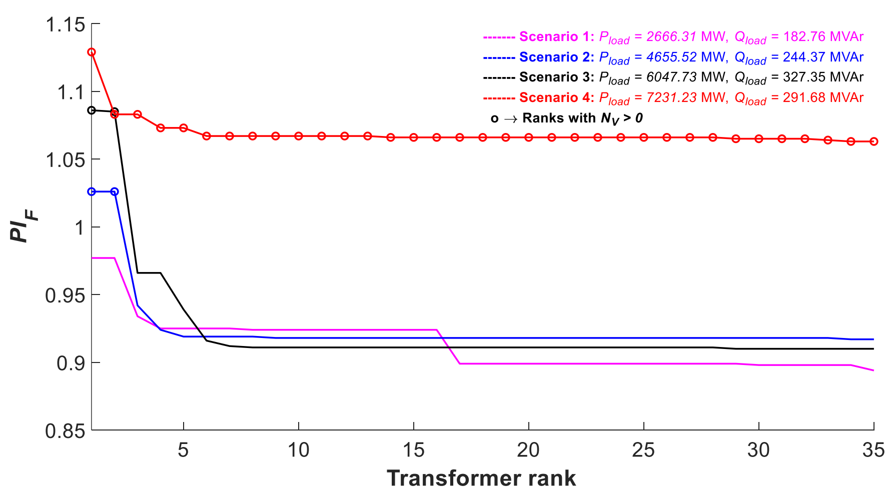

Figure 4.8 Comparison of the PI_F Index for Transformer Contingencies Under Different Loading Scenarios

Tables 4.4 and Table 4.5 summarizes the rank for the 35 transformer contingencies under different loading scenarios based on the PI_V and PI_F index respectively.

Table 4.4 List of PI_V Based Rank of the 35 Transformer Contingencies Under Different Loading Scenarios

Transformer name	PI_V based rank			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Tr 1	17	20	25	20
Tr 2	33	5	4	4
Tr 3	32	4	5	5
Tr 4	20	23	26	21
Tr 5	8	27	32	25
Tr 6	7	28	33	27
Tr 7	3	29	35	28
Tr 8	28	6	9	8
Tr 9	34	2	3	3
Tr 10	35	3	2	2
Tr 11	31	7	6	6
Tr 12	30	8	8	7
Tr 13	23	31	18	29
Tr 14	19	32	21	31
Tr 15	21	30	19	30
Tr 16	2	34	10	34
Tr 17	4	33	7	33
Tr 18	1	35	11	35
Tr 19	29	13	13	13
Tr 20	6	26	31	26
Tr 21	9	25	28	22
Tr 22	10	19	24	16
Tr 23	14	24	27	19
Tr 24	22	14	17	14
Tr 25	18	15	20	15
Tr 26	15	22	30	24
Tr 27	16	21	29	23
Tr 28	13	18	34	32
Tr 29	11	16	22	17
Tr 30	12	17	23	18
Tr 31	25	10	14	10
Tr 32	26	11	15	11
Tr 33	24	12	16	12
Tr 34	27	9	12	9
Tr 35	5	1	1	1

Table 4.5 List of PI_F Based Rank of the 35 Transformer Contingencies Under Different Loading Scenarios

Transformer name	PI_F based rank			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Tr 1	17	13	16	20
Tr 2	23	23	26	12
Tr 3	24	24	27	13
Tr 4	20	19	17	21
Tr 5	19	3	5	23
Tr 6	18	8	6	24
Tr 7	7	10	13	28
Tr 8	30	29	28	6
Tr 9	31	31	30	5
Tr 10	32	32	31	4
Tr 11	34	35	1	2
Tr 12	33	34	2	3
Tr 13	6	6	34	29
Tr 14	4	5	32	32
Tr 15	5	7	33	30
Tr 16	2	2	4	34
Tr 17	3	4	7	33
Tr 18	1	1	3	35
Tr 19	35	30	29	11
Tr 20	8	9	9	27
Tr 21	9	11	12	22
Tr 22	10	15	15	18
Tr 23	14	12	14	19
Tr 24	16	20	21	14
Tr 25	15	18	18	15
Tr 26	12	14	10	26
Tr 27	13	16	11	25
Tr 28	11	17	8	31
Tr 29	21	21	19	16
Tr 30	22	22	20	17
Tr 31	28	27	24	8
Tr 32	29	28	25	9
Tr 33	26	26	23	10
Tr 34	27	25	22	7
Tr 35	25	33	35	1

The results in Tables 4.4 and 4.5 imply that the rank of a transformer contingency relative to the others depend largely on the loading condition of the power system network under which the contingencies are simulated. The rank also varies with the type of performance index (PI_V or PI_F) used to quantify the impact of a contingency on the power system network of the operating utility. Equation (4.7) is used to consolidate the criticality associated with each transformer contingency based on a performance index under various loading scenarios.

$$R_{F,k} = k\sum_{i=1}^{N_c}\frac{W_i}{R_{k,i}}, \tag{4.7}$$

where,

k : multiplying factor,

W_i : weight assigned to a loading scenario i,

N_c : total number of loading scenarios under study,

$R_{k,i}$: rank of k^{th} contingency for i^{th} loading scenario,

$R_{F,k}$: final ranking index of k^{th} contingency considering N_c loading scenarios.

The final ranking index R_F is calculated for each transformer contingency based on both the PI_V and PI_F performance indices used here. Since N_c is 4, equation (4.7) will take the following form,

$$R_{F,k} = k\left(\frac{W_1}{R_{k,1}} + \frac{W_2}{R_{k,2}} + \frac{W_3}{R_{k,3}} + \frac{W_4}{R_{k,4}}\right). \tag{4.8}$$

After computing the final ranking index R_F using (4.8), the transformer contingencies are ranked in decreasing order of the value of R_F. In general, the contingencies with a relatively higher value of the index R_F are critical than the contingencies with a lower R_F.

The values of weights W_1, W_2, W_3, and W_4 used here are 0.33, 0.25, 0.17, and 0.25 respectively. These values reflect the percentage of days when the power system network of the operating utility operates under the respective loading scenario (note that $\sum W_i = 1$). The multiplying factor k is set to be 100 to provide better resolution in the values of R_F. Table 4.6 shows the list of all the transformer contingencies which are ranked using R_F based on the PI_V and PI_F performance indices. Tr 35 and Tr 18 are identified as the most critical transformers relative to others based on the PI_V and PI_F performance indices respectively in the 500 kV transmission network of the operating utility under study.

Table 4.6 List of PI_V and PI_F Based Ranks of Transformer Contingencies Using the R_F Index

PI_V based			PI_F based		
Rank	Transformer name	R_F	Rank	Transformer name	R_F
1	Tr 35	73.600	1	Tr 18	64.381
2	Tr 18	35.974	2	Tr 16	33.985
3	Tr 9	30.276	3	Tr 28	31.185
4	Tr 16	27.471	4	Tr 22	27.563
5	Tr 10	19.671	5	Tr 26	20.436
6	Tr 28	16.500	6	Tr 35	18.569
7	Tr 2	15.681	7	Tr 21	14.563
8	Tr 26	13.241	8	Tr 27	14.557
9	Tr 11	12.194	9	Tr 20	11.520
10	Tr 3	11.636	10	Tr 25	11.029
11	Tr 27	10.359	11	Tr 14	9.718
12	Tr 12	9.921	12	Tr 11	9.415
13	Tr 22	8.194	13	Tr 1	8.833
14	Tr 8	7.971	14	Tr 24	8.611
15	Tr 21	7.534	15	Tr 23	8.492
16	Tr 25	7.048	16	Tr 2	7.489
17	Tr 20	6.948	17	Tr 10	7.438
18	Tr 7	6.887	18	Tr 9	7.402
19	Tr 24	6.806	19	Tr 13	7.197
20	Tr 34	6.604	20	Tr 12	6.971
21	Tr 1	6.582	21	Tr 3	6.736
22	Tr 31	6.410	22	Tr 15	6.646
23	Tr 29	6.349	23	Tr 17	6.566
24	Tr 32	6.292	24	Tr 29	6.200
25	Tr 19	6.071	25	Tr 30	6.177
26	Tr 33	6.017	26	Tr 7	5.938
27	Tr 23	5.344	27	Tr 5	5.908
28	Tr 30	5.209	28	Tr 19	5.489
29	Tr 6	5.121	29	Tr 8	5.470
30	Tr 5	4.945	30	Tr 6	5.259
31	Tr 17	4.926	31	Tr 4	5.219
32	Tr 4	4.581	32	Tr 31	5.156
33	Tr 14	4.134	33	Tr 33	4.969
34	Tr 15	4.133	34	Tr 34	4.957
35	Tr 13	4.048	35	Tr 32	4.635

4.4 Simulation Results for 500 kV Transmission Line Contingencies

In this section, the voltage based performance index PI_V and the flow based performance index PI_F are used to rank the 500 kV transmission lines in the power system network of the operating utility relative to each other. The PI_V and PI_F values corresponding to each *N*-1 transmission line contingencies for four different loading scenarios are presented in this section. The simulation of each transmission line contingency is automated using the PSLF's EPCL programming language. The code for simulating the transmission line contingencies is similar to the EPCL code used for the transformers mentioned in Appendix B. The `.txt` files containing the contingency power flow results are exported to Matlab where the performance indices are computed using the script given in Appendix C.

The simulation results of the transmission line contingencies corresponding to scenario 1 (light load case) and scenario 4 (summer peak load case) are discussed in this section. The results of transmission line contingencies for scenario 3 and scenario 4 (intermediate load cases) are presented in Appendix D. The values of PI_V, PI_F and N_V performance indices for the 29 transmission line contingencies under scenario 1 are given in Table 4.7.

It can be noted from Table 4.7 that the value of PI_F is less than unity and the value of N_V is zero for all the transmission line contingencies under scenario 1. This implies that none of the transmission line contingencies result in branch limit violations. Hence, the transmission network of the operating utility does not possess any threat of branches overload from the transmission line contingencies under a light load case. However, it should be noted that the failure of any of these transmission lines, when the power system network is already under an *N*-1 contingency, may worsen the system condition further. Under a summer peak case, this could even result in a cascading failure or even a blackout.

Table 4.7 List of PI_V and PI_F Indices for Transmission Line Contingencies for Scenario 1 (P_{load} = 2666.31 MW, Q_{load} = 182.76 MVAr)

Transmission line name	PI_V	PI_F	N_V
Ln 1	117.459	0.896	0
Ln 2	110.405	0.899	0
Ln 3	110.405	0.899	0
Ln 4	98.463	0.896	0
Ln 5	105.545	0.898	0
Ln 6	99.684	0.897	0
Ln 7	103.443	0.897	0
Ln 8	51.241	0.896	0
Ln 9	107.313	0.899	0
Ln 10	95.821	0.898	0
Ln 11	95.012	0.898	0
Ln 12	99.614	0.898	0
Ln 13	106.438	0.898	0
Ln 14	106.798	0.898	0
Ln 15	104.497	0.897	0

Transmission line name	PI_V	PI_F	N_V
Ln 16	110.269	0.898	0
Ln 17	109.629	0.898	0
Ln 18	110.267	0.898	0
Ln 19	109.629	0.898	0
Ln 20	110.267	0.898	0
Ln 21	110.009	0.895	0
Ln 22	103.661	0.898	0
Ln 23	103.661	0.898	0
Ln 24	112.269	0.898	0
Ln 25	63.015	0.895	0
Ln 26	85.357	0.896	0
Ln 27	76.495	0.898	0
Ln 28	90.793	0.898	0
Ln 29	94.183	0.898	0

A comparison of the values of PI_V and PI_F performance indices for all the transmission line contingencies under scenario 1 is given in Fig. 4.9. Ln 1 and Ln 9 are identified as the most critical transmission lines relative to the others based on their PI_V and PI_F values respectively. The performance indices PI_F and PI_V quantify the impact of a contingency on the rest of the power system network in terms of branch overloads and voltage deviations. The two parameters are not directly related to each other. Hence, the critical lines identified using both the performance indices are different.

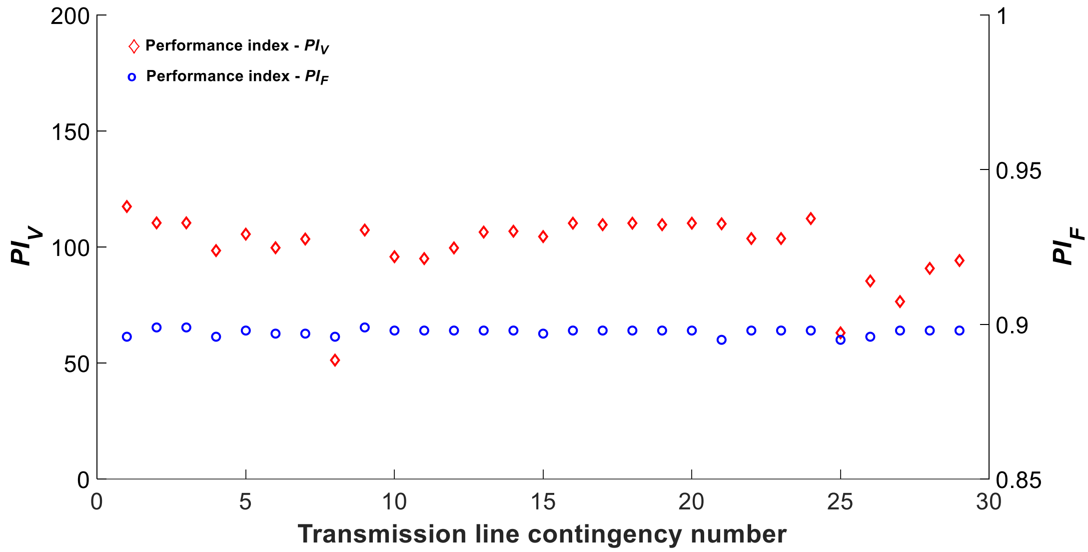

Figure 4.9 Comparison of PI_V and PI_F Indices for Transmission Line Contingencies of Scenario 1

Figs. 4.10 and 4.11 show the plots of voltage deviation across all the buses in the power system network of the operating utility for the most critical transmission line Ln 1and the least critical transmission line Ln 8. These lines are identified based on the values of their respective PI_V index. From the plots, it can be observed that the voltage deviations are not significant. This is evident from the value of average voltage deviation mentioned in the plots. The value of average voltage deviation ΔV_{avg} for the most critical line Ln 1 is 0.013 which is below the threshold. As mentioned earlier, the acceptable voltage deviation is 0.05 p.u. at 500 kV buses and 0.075 p.u. for the buses at other voltage levels. The value of ΔV_{avg} for the contingencies corresponding to other transmission lines is lesser than 0.013. Hence, from the system wide post contingency bus voltage profile, it is observed that any of the transmission line contingencies does not have a severe impact on the power system of the operating utility. However, the values of the performance index PI_V are used to rank the transmission lines relative to each other.

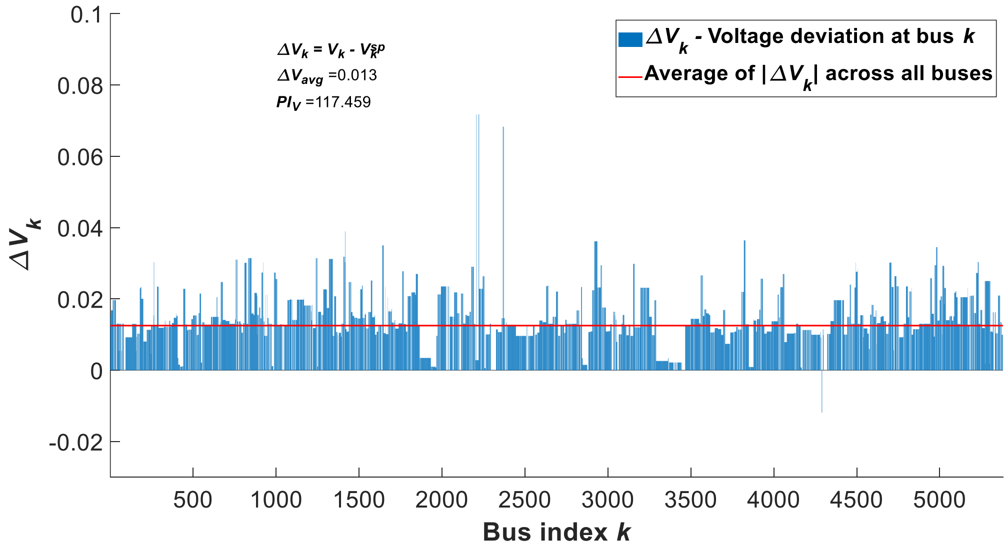

Figure 4.10 Scenario 1: Bus Voltage Deviation Plot for Most Critical Transmission Line Ln 1 Contingency based on PI_V

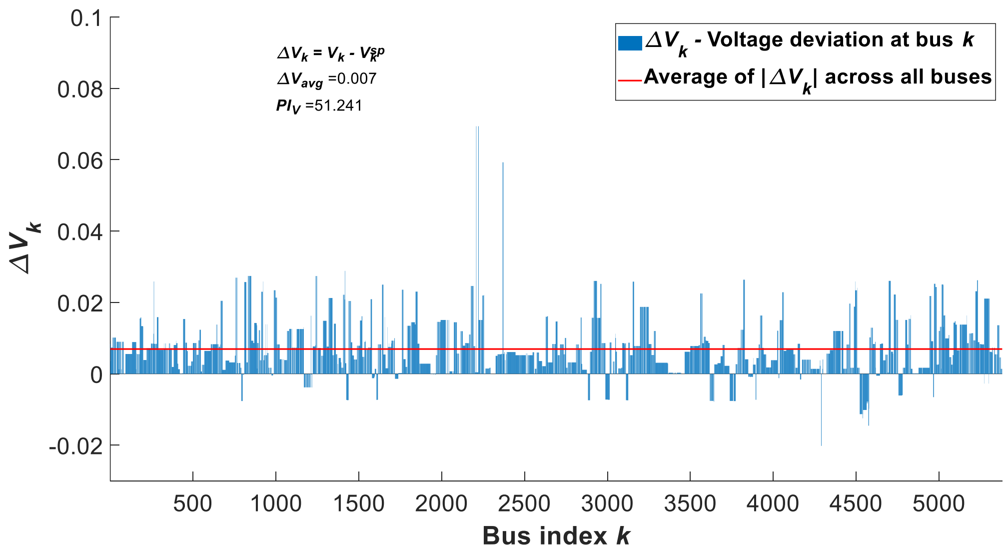

Figure 4.11 Scenario 1: Bus Voltage Deviation Plot for Least Critical Transmission Line Ln 8 Contingency Based on PI_V

The simulation results for the transmission line contingencies under scenarios 2 and 3 are given in Appendix D. Table 4.8 shows the values of performance indices PI_V, PI_F, and N_V for the transmission line contingencies under scenario 4 (summer peak load case). The transmission line contingencies during summer peak load case are expected to have a more severe impact compare to the similar contingencies under a relatively light load case (i.e., scenario 1,2, and 3). The observations from the results of Table 4.8 are discussed below.

- A transmission line contingency irrespective of its PI_F value results in at least 2 branch limit violations under a summer peak case.
- Ln 25 (PI_F = 1.088, N_V = 2) and Ln 1 (PI_F = 1.066, N_V = 2) are identified as the most critical and the least critical transmission lines for this scenario. The values of the PI_F index for these lines are very close to each other. This implies that the contingency corresponding to any line including these two (irrespective of the rank) will have a significant impact on the power system network of the operating utility. The PI_F values are used to rank the transmission lines relative to each other.
- Although the value of N_V (number of branches with rating violations) for Ln 13 and Ln 14 is 4, they are ranked lower than Ln 25 with N_V = 2. This is because the transmission lines are ranked primarily based on their PI_F values. A contingency with a higher PI_F value implies that a branch in the network will be overloaded relatively higher (and is more prone to failure), compared to the overloaded branches under other contingencies. Thus, the value of PI_F takes priority over N_V while ranking the contingencies relative to each other.
- Ln 25 (PI_V = 1813.311) and Ln 3 (PI_V = 1042.364) are identified as the most critical and the least critical transmission lines under scenario 4 based on PI_V index.

Table 4.8 List of PI_V and PI_F Indices for Transmission Line Contingencies for Scenario 4 (P_{load} = 7231.23 MW, Q_{load} = 291.68 MVAr)

Transmission line name	PI_V	PI_F	N_V	Transmission line name	PI_V	PI_F	N_V
Ln 1	1043.687	1.066	2	Ln 16	1047.646	1.066	2
Ln 2	1042.364	1.066	2	Ln 17	1049.697	1.066	2
Ln 3	1042.364	1.066	2	Ln 18	1047.610	1.066	2
Ln 4	1100.044	1.068	2	Ln 19	1049.697	1.066	2
Ln 5	1043.187	1.066	2	Ln 20	1047.610	1.066	2
Ln 6	1103.361	1.068	2	Ln 21	1131.258	1.069	2
Ln 7	1079.019	1.067	2	Ln 22	1083.453	1.067	2
Ln 8	1573.810	1.078	2	Ln 23	1083.453	1.067	2
Ln 9	1087.252	1.066	2	Ln 24	1081.243	1.071	2
Ln 10	1186.691	1.070	2	Ln 25	1813.311	1.088	2
Ln 11	1121.572	1.068	2	Ln 26	1461.389	1.078	2
Ln 12	1092.305	1.068	2	Ln 27	1290.321	1.073	2
Ln 13	1077.354	1.083	4	Ln 28	1113.953	1.068	2
Ln 14	1073.928	1.083	4	Ln 29	1151.565	1.069	2
Ln 15	1068.323	1.067	2				

A comparison of the values of PI_V and PI_F performance indices for all the transmission line contingencies under scenario 4 is given in Fig. 4.12.

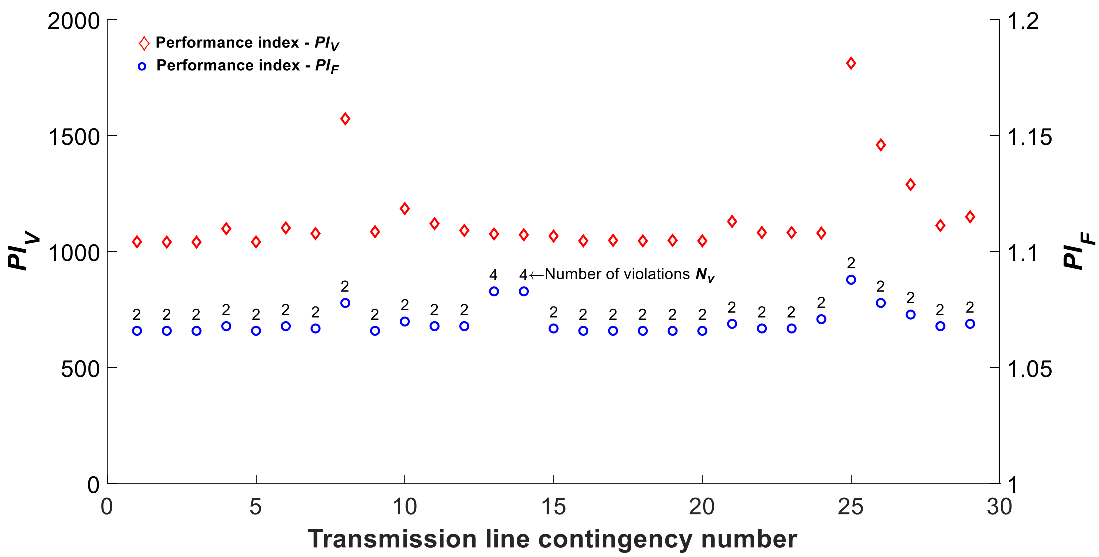

Figure 4.12 Comparison of PI_V and PI_F Indices for Transmission Line Contingencies of Scenario 4

Figs. 4.13 and 4.14 show the bus voltage deviation plots for the most critical transmission line Ln 25 and the least critical transmission line Ln 3 for scenario 4.

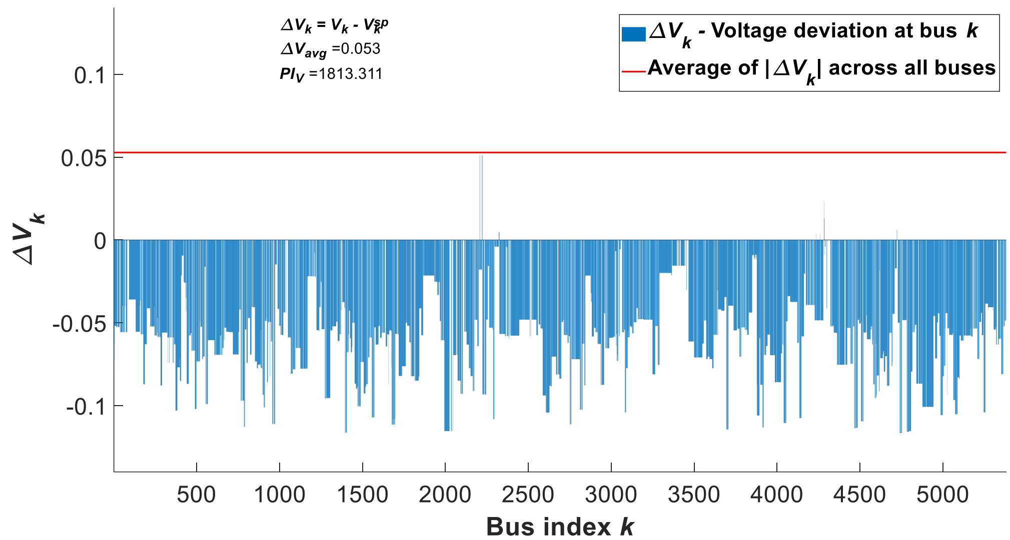

Figure 4.13 Scenario 4: Bus Voltage Deviation Plot for Most Critical Transmission Line Ln 25 Contingency Based on PI_V

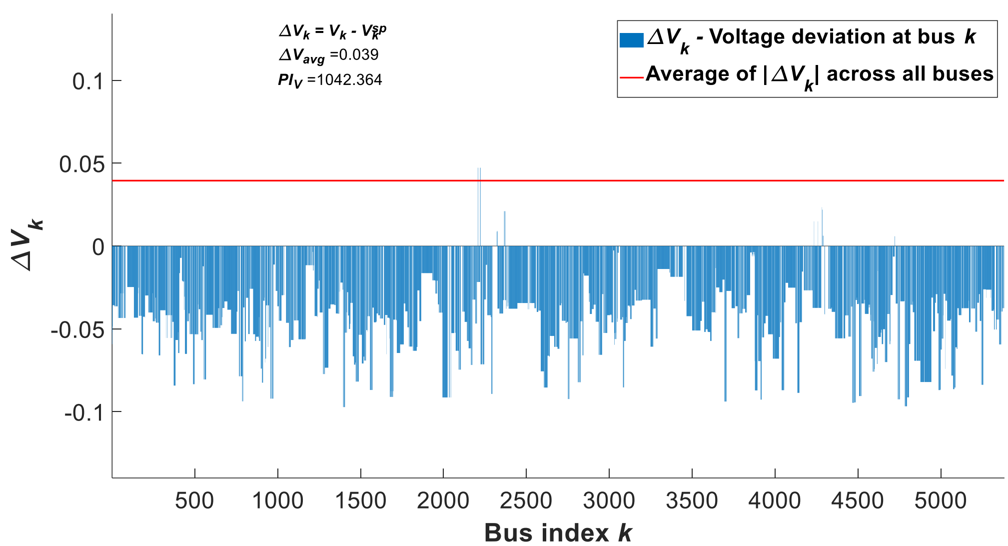

Figure 4.14 Scenario 4: Bus Voltage Deviation Plot for Least Critical Transmission Line Ln 3 Contingency Based on PI_V

The plots show under voltages at almost all the buses. The value of average voltage deviation ΔV_{avg} for Ln 25 is 0.053 which is higher than the threshold of 0.05 p.u. for 500 kV buses. However, the value of ΔV_{avg} for Ln 3 is 0.039. It can be noted that, although Ln

3 is identified as the least critical line, the value of ΔV_{avg} is close to the threshold. Hence, any further contingency can significantly impact the voltage across all the buses and may even cause a voltage stability issue in the power system network of the operating utility.

The comparison of PI_V and PI_F values for transmission line0 contingencies of similar ranks under various loading scenarios is shown in Figs. 4.15 and 4.16 respectively. In general, the PI_V value for a transmission line contingency under scenario 4 (summer peak load case) is greater than the PI_V value of a contingency of similar ranks under scenarios with the relatively lesser load. This trend is not observed strictly in the ranking using the PI_F index. Also, it can be noted that the performance indices for only the top ranked contingencies differ from each other. These indices tend to saturate at lower ranks irrespective of the loading scenario.

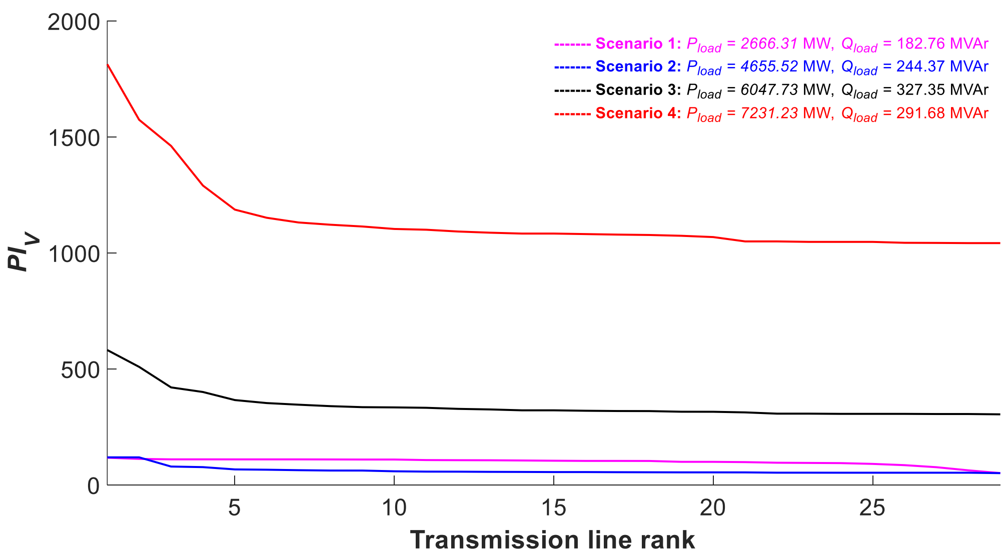

Figure 4.15 Comparison of the PI_V Index Transmission Line Contingencies Under Different Loading Scenarios

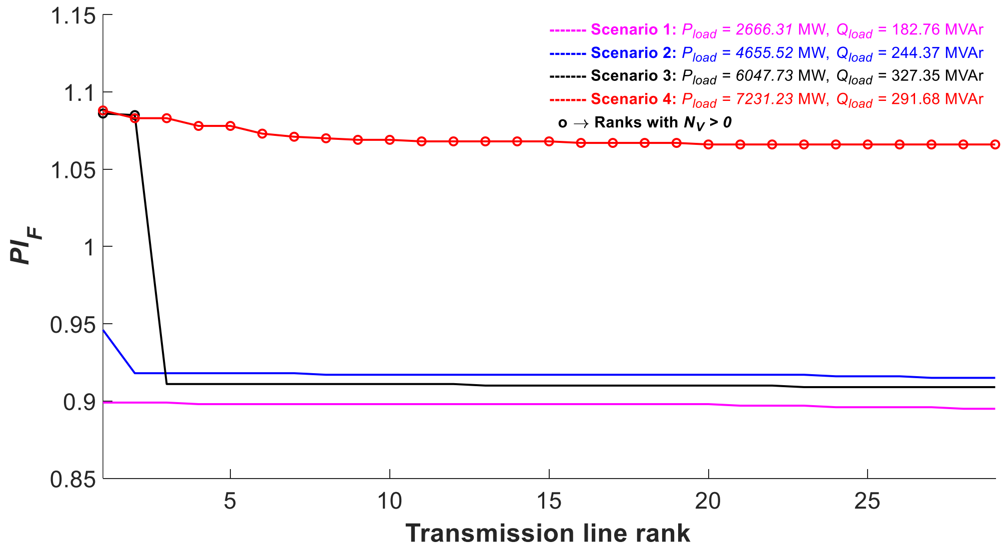

Figure 4.16 Comparison of the PI_F Index Transmission Line Contingencies Under Different Loading Scenarios

The ranks of each transmission line contingencies under different loading scenarios based on the PI_V and PI_F indices are summarized in Tables 4.9 and 4.10 respectively. It can be observed that the ranks vary with the load on the operating utility as well as with the performance index used for analysis. For example, Ln 1 is identified as the most critical line for scenario 1 based on the PI_V index, whereas it is the least critical line for scenario 2 and 3 based on the same index. The same line is ranked 27th relative to the other lines based on the PI_F index for scenario 1.

Table 4.9 List of PI_V Based Rank of the 29 Transmission Line Contingencies Under Different Loading Scenarios

Transmission line name	PI_V based rank			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Ln 1	1	29	29	26
Ln 2	3	24	27	28
Ln 3	4	25	28	29
Ln 4	21	12	12	11
Ln 5	14	20	21	27
Ln 6	19	13	13	10
Ln 7	18	17	17	17
Ln 8	29	2	2	2
Ln 9	11	5	11	13
Ln 10	22	6	5	5
Ln 11	23	8	7	8
Ln 12	20	14	9	12
Ln 13	13	19	16	18
Ln 14	12	21	18	19
Ln 15	15	18	20	20
Ln 16	5	28	26	23
Ln 17	9	22	22	21
Ln 18	6	26	24	24
Ln 19	10	23	23	22
Ln 20	7	27	25	25
Ln 21	8	11	10	7
Ln 22	16	15	14	14
Ln 23	17	16	15	15
Ln 24	2	10	19	16
Ln 25	28	1	1	1
Ln 26	26	4	3	3
Ln 27	27	3	4	4
Ln 28	25	7	8	9
Ln 29	24	9	6	6

Table 4.10 List of PI_F Based Rank of the 29 Transmission Line Contingencies Under Different Loading Scenarios

Transmission line name	PI_F based rank			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Ln 1	27	27	29	29
Ln 2	2	4	6	26
Ln 3	3	5	7	27
Ln 4	25	25	25	13
Ln 5	20	20	16	28
Ln 6	23	24	28	12
Ln 7	21	22	22	18
Ln 8	24	1	26	4
Ln 9	1	2	4	20
Ln 10	15	7	13	8
Ln 11	4	3	5	11
Ln 12	10	6	3	14
Ln 13	17	21	1	2
Ln 14	13	19	2	3
Ln 15	22	23	21	19
Ln 16	7	11	10	23
Ln 17	8	12	11	21
Ln 18	5	8	8	24
Ln 19	9	13	12	22
Ln 20	6	9	9	25
Ln 21	29	28	24	9
Ln 22	11	14	18	16
Ln 23	12	15	19	17
Ln 24	18	16	15	7
Ln 25	28	29	23	1
Ln 26	26	26	27	5
Ln 27	19	17	17	6
Ln 28	14	10	14	15
Ln 29	16	18	20	10

The ranks of the transmission line contingencies relative to each other based on the PI_F and PI_V performance indices for different loading scenarios are consolidated using the ranking index defined by (4.8). The values of weights W_1, W_2, W_3, and W_4 used here are 0.33, 0.25, 0.17, and 0.25 respectively. The value of k is set to be 100. The results are shown in Table 4.11.

Table 4.11 List of PI_V and PI_F Based Ranks of the Transmission Line Contingencies Using the R_F Index

PI_V based			PI_F based		
Rank	Transmission line name	R_F	Rank	Transmission line name	R_F
1	Ln 25	68.179	1	Ln 9	51
2	Ln 1	35.410	2	Ln 8	33.279
3	Ln 8	34.638	3	Ln 13	32.632
4	Ln 26	21.519	4	Ln 25	27.780
5	Ln 24	21.457	5	Ln 2	26.545
6	Ln 27	20.056	6	Ln 11	22.256
7	Ln 10	14.067	7	Ln 14	20.688
8	Ln 2	13.564	8	Ln 3	19.354
9	Ln 21	11.669	9	Ln 12	14.919
10	Ln 9	11.469	10	Ln 18	12.892
11	Ln 29	11.153	11	Ln 20	11.167
12	Ln 3	10.719	12	Ln 10	10.204
13	Ln 11	10.113	13	Ln 16	9.7740
14	Ln 28	9.794	14	Ln 17	8.9440
15	Ln 16	9.234	15	Ln 27	8.3740
16	Ln 18	8.212	16	Ln 19	8.1430
17	Ln 6	7.468	17	Ln 24	8.101
18	Ln 12	7.408	18	Ln 26	7.860
19	Ln 4	7.344	19	Ln 28	7.738
20	Ln 20	7.320	20	Ln 22	7.293
21	Ln 17	6.766	21	Ln 29	6.801
22	Ln 22	6.729	22	Ln 23	6.782
23	Ln 13	6.306	23	Ln 21	5.517
24	Ln 23	6.304	24	Ln 6	5.167
25	Ln 19	6.262	25	Ln 4	4.923
26	Ln 14	6.201	26	Ln 7	4.869
27	Ln 7	5.775	27	Ln 5	4.855
28	Ln 15	5.689	28	Ln 15	4.712
29	Ln 5	5.343	29	Ln 1	3.596

From Table 4.11, it can be observed that considering the impact of the transmission line contingencies under four different loading scenarios, Ln 25 and Ln 9 are identified as the most critical transmission lines based on the PI_V and PI_F indices respectively.

4.5 Simulation Results for 500 kV Circuit Breaker Contingencies

The relay protection in a power system network is responsible for sensing the faults and tripping the circuit breakers to isolate the faulted circuit or equipment. The relays are coordinated in such a way that the circuit breaker(s) closest to the fault are tripped to clear the fault with minimum impact on the rest of the power system network. This requires the circuit breakers to operate in time and interrupt or clear the fault current. However, occasionally circuit breakers may fail to operate as desired. Hence, the fault may persist in the system and can damage other transmission assets if not cleared in time. According to [36], breaker failures are mainly categorized as failure to clear and failure to trip. In failure to clear scenarios, the breaker contacts open but the arc inside the breaker's contact chambers is not extinguished completely. Therefore, the fault current continues to flow and the fault is not cleared. However, in failure to trip situations, the breaker's contacts fail to open after a trip signal is initiated by the protective relay. The reason for this malfunction could be incorrect circuit wiring or a mechanical problem in the breaker itself. Such a condition is termed as a '*stuck breaker*' [36].

During a breaker failure situation, backup protection known as a *breaker failure protection* (BFP) is activated where other circuit breakers are tripped to isolate the sources contributing to the fault [36]. A BFP will disconnect all the circuit breakers and/or equipment that are connected directly to the faulty circuit breaker to avoid feeding the fault current from other sources. Hence, a BFP usually trips more than one circuit breakers when activated. This may result in loss of additional transmission elements like transformers, transmission lines, generators, shunt devices, and/or loads depending upon the substation configuration.

In this study, the criticality of the 500 kV circuit breakers is analyzed in terms of their impact on the rest of the power system network when a breaker fails to trip or when it suffers from a stuck breaker situation. To simulate a stuck breaker contingency, a list is prepared consisting of all the circuit breakers and transmission elements that would be required to trip under the failure to trip situation of that breaker. However, it is to be noted that the faulty breaker stays in service while simulating the stuck breaker scenario. A sub-station with breaker-and-a-half bus configuration is shown in Fig. 4.17. For illustrative purpose, the list of circuit breakers and transmission equipment that will trip due to the stuck breaker contingencies of breakers CB 1, CB 2, CB 3, and CB 9 of Fig. 4.17 is given in Table 4.12.

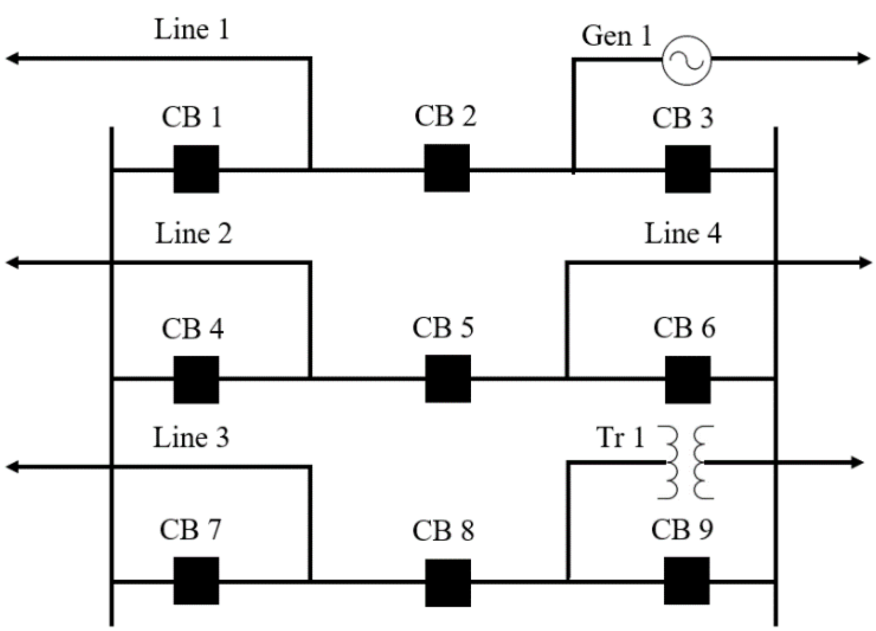

Figure 4.17 Breaker-and-a-Half Substation Configuration

Table 4.12 Illustration of Stuck Breaker Contingencies

Stuck breaker	Tripped circuit breakers	Tripped transmission equipment
CB 1	CB 2 CB 4 CB 7	Line 1
CB 2	CB 1 CB 3	Line 1 Gen 1
CB 3	CB 2 CB 6 CB 9	Gen 1
CB 9	CB 3 CB 6 CB 8	Tr 1

From Table 4.12, it can be noted that a stuck breaker contingency may even result in the loss of more than one transmission element in a substation as in the case of CB 2. This can have a severe impact on the rest of the system. The stuck breaker contingency for each one of the 112 circuit breakers identified in the contingency list is simulated in PSLF.

An EPCL code in conjunction with a Matlab script is used to automate the simulation, store the results and eventually calculate the performance indices PI_V and PI_F for each circuit breaker failure scenario. The value of performance indices PI_V, PI_F and N_V for the stuck breaker contingencies under scenario 1 (light load case) are given in Tables E.1-E.2 of Appendix E. A comparison between the values of these performance indices for scenario 1 is shown in Fig. 4.18.

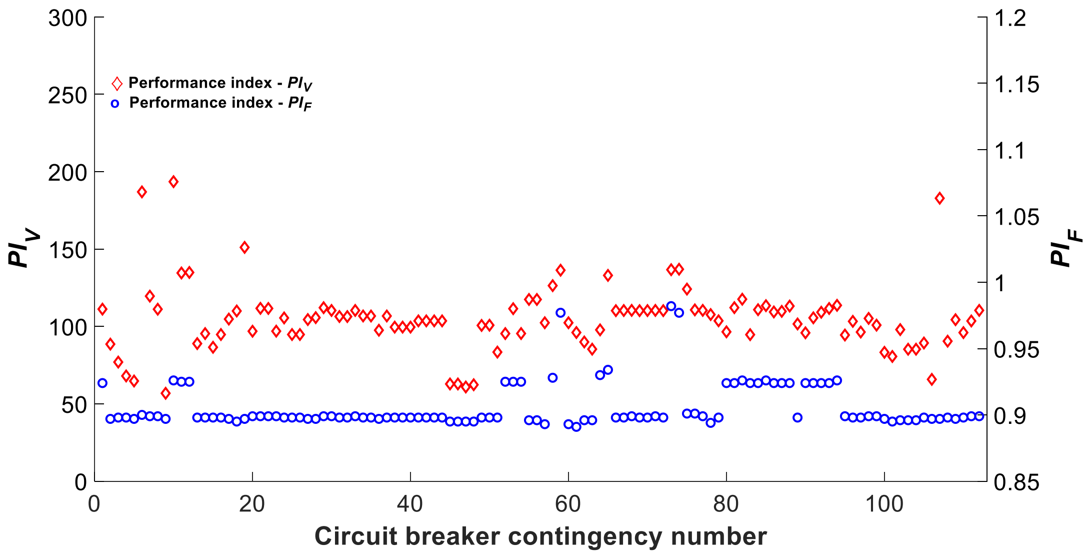

Figure 4.18 Comparison of PI_V and PI_F Indices for Circuit Breaker Contingencies of Scenario 1

The observations from the simulation results of the stuck breaker contingencies under scenario 1 are discussed below:

- From the values of PI_F and N_V, it can be observed that none of the stuck breaker contingency results in any branch overload in the power system network of the operating utility. The value of N_V is zero for all the contingencies under study.
- Cb 73 (PI_F = 0.982) is identified as the most critical circuit breaker relative to the others based on the PI_F performance index. Although, no branch limit violations are observed for Cb 73 contingency, the value of PI_F is very close to unity even for a light load condition. The activation of BFP following the stuck breaker contingency of Cb 73 results in the tripping of two additional circuit breakers and the loss of a generator in the power system network of the operating utility.
- The PI_F value for the top 30 circuit breakers contingencies is observed to be greater than or equal to 0.9. It can be observed that this value is higher than the top ranked transformer and transmission line contingencies. Hence, in general, the impact of

the critical circuit breaker contingencies is more severe than the impact of the transformer and transmission line contingencies.

- Cb 10 (PI_V = 193.561) is identified as the most critical circuit breaker relative to the others based on the PI_V performance index.

Figs. 4.19 and 4.20 show the system wide bus voltage deviation plot for the most critical circuit breaker Cb 10 and the least critical circuit breaker Cb 9 under scenario 1. It can be observed that the bus voltages are not significantly affected upon failure of these breakers. This is evident from the value of the average voltage deviation ΔV_{avg}. The value of ΔV_{avg} is observed to be 0.016 and 0.007 for Cb 10 and Cb 9 respectively which is below the threshold value. In general, the value of ΔV_{avg} for other circuit breaker contingencies lies between 0.007 and 0.016. Hence, from the point of view of system bus voltages, the stuck breaker contingencies do not have any severe impact on the power system network of the operating utility under scenario 1.

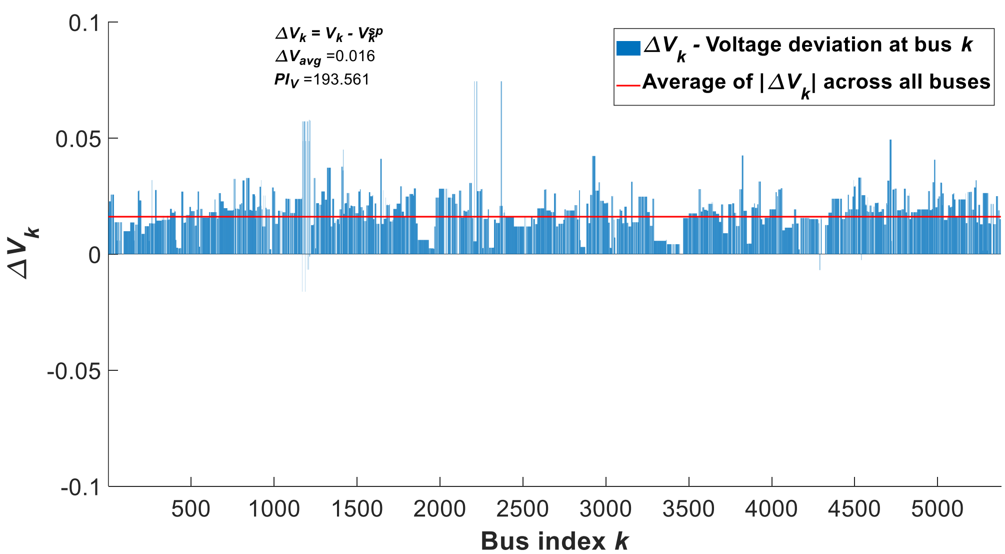

Figure 4.19 Scenario 1: Bus Voltage Deviation Plot for Most Critical Circuit Breaker Cb 10 Contingency Based on PI_V

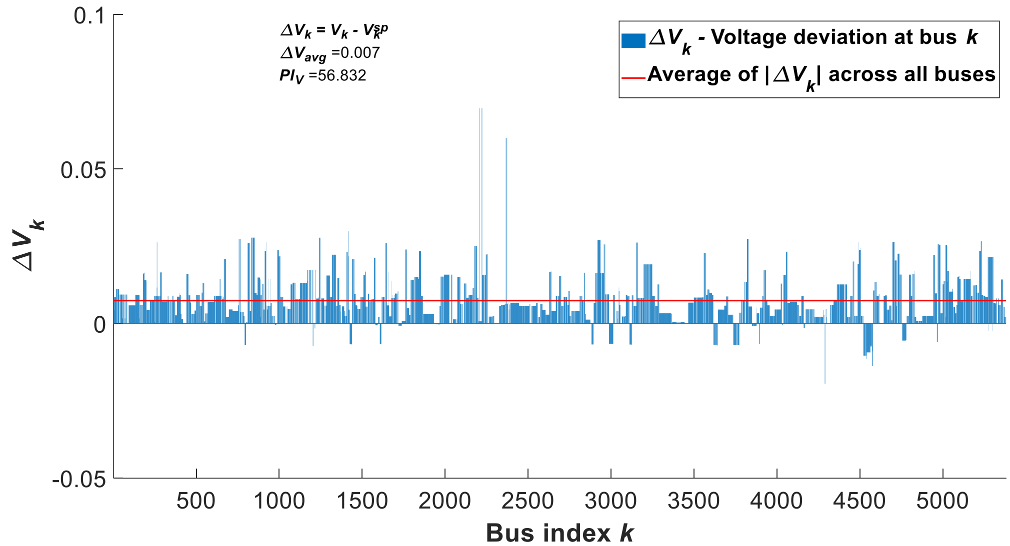

Figure 4.20 Scenario 1: Bus Voltage Deviation Plot for Least Critical Circuit Breaker Cb 9 Contingency Based on PI_V

The simulation results for the 500 kV stuck breaker contingencies under scenario 2,3, and 4 are given in Tables E.3-E.8 of Appendix E. A comparison of the values of PI_V and PI_F performance indices for contingencies under scenario 4 is shown in Fig. 4.21. Each breaker failure contingency under scenario 4 results in at least two branch limit violations ($N_V \geq 2$) in the power system network of the operating utility. Several circuit breaker contingencies even result in four branch limit violations. These contingencies are shown in Fig. 4.21. These observations imply that a stuck breaker contingency under the summer peak load case, irrespective of its rank, will impact the rest of the power system network significantly in terms of branch overloads. Cb 107 (PI_F = 1.174, N_V = 6) is identified as the most critical circuit breaker for scenario 4 (summer peak load case) based on the PI_F index. A total of six branch limit violations are observed in the network during Cb 107 contingency. The PI_F value of 1.174 for this breaker indicates that the maximum overloaded branch will be operating at 117.4 % of its rated limit.

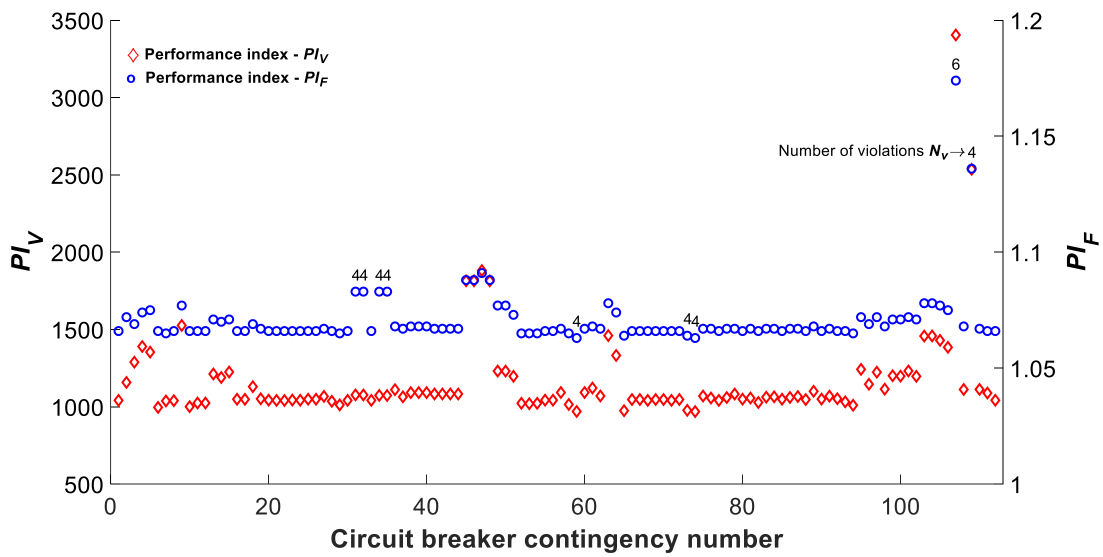

Figure 4.21 Comparison of PI_V and PI_F Indices for Circuit Breaker Contingencies of Scenario 4

Cb 107 is identified as the most critical circuit breaker for scenario 4 based on the PI_V performance index. The value of PI_V index for this circuit breaker is 3404.958 which is very high compared to the PI_V values of the top ranked circuit breakers under relatively light load cases. The bus voltage deviation plot for Cb 107 circuit breaker contingency is shown in Fig. 4.22. This plot indicates severe under-voltage across all the buses in the power system network of the operating utility. The average voltage deviation ΔV_{avg} is observed to be 0.066 for Cb 107 circuit breaker contingency which is higher than the threshold value. The voltage deviation plot for the least critical circuit breaker Cb 74 based on the PI_V index, is shown in Fig. 4.23. Although the system wide voltage profile show under-voltage across most of the buses, the impact is not that severe. This is evident from the lower value of ΔV_{avg} = 0.038 for Cb 74 circuit breaker contingency under scenario 4.

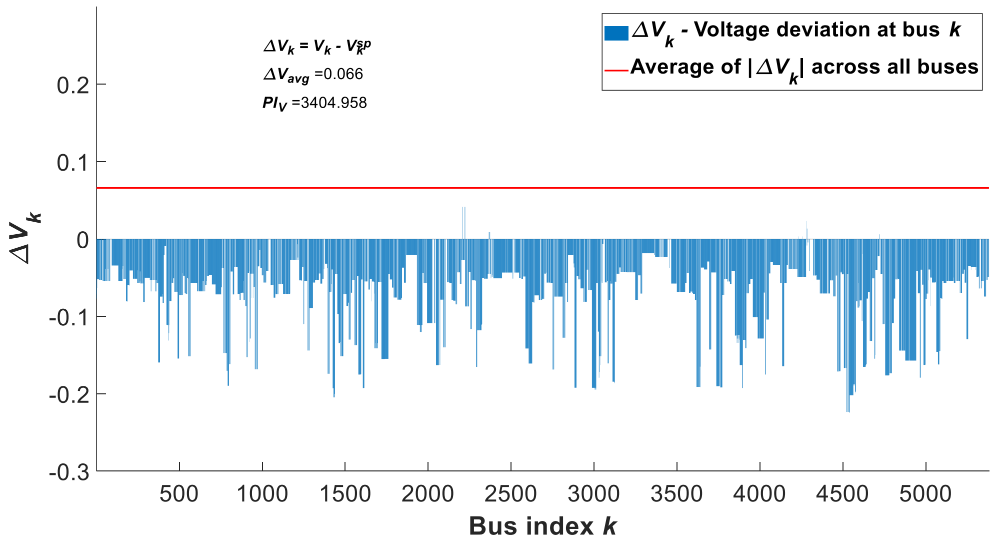

Figure 4.22 Scenario 4: Bus Voltage Deviation Plot for Most Critical Circuit Breaker Cb 107 Contingency Based on PI_V

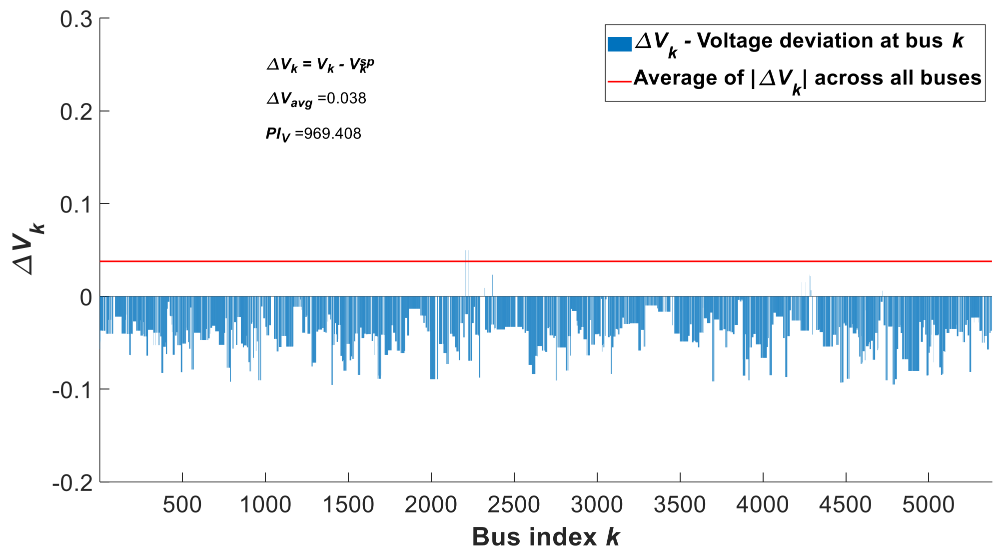

Figure 4.23 Scenario 4: Bus Voltage Deviation Plot for Most Critical Circuit Breaker Cb 74 Contingency Based on PI_V

The comparison of PI_V and PI_F values for circuit breaker contingencies of similar ranks under various loading scenarios is shown in Figs. 4.24 and 4.25 respectively.

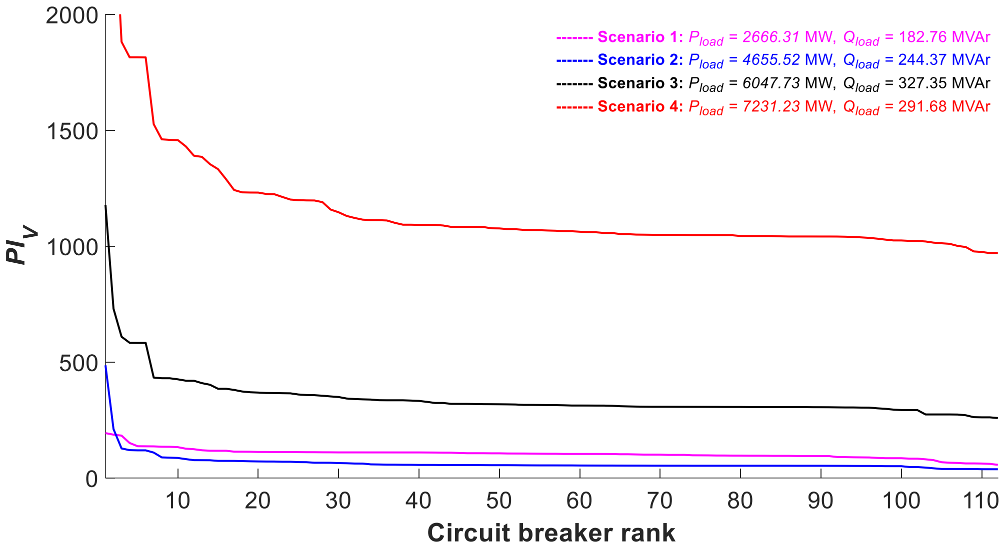

Figure 4.24 Comparison of the PI_V Index Circuit Breaker Contingencies Under Different Loading Scenarios

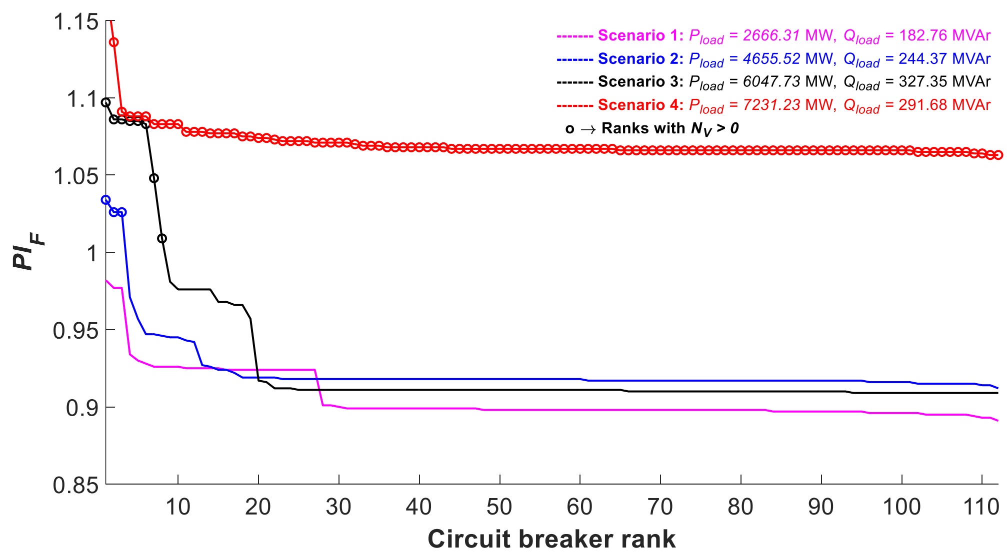

Figure 4.25 Comparison of the PI_F Index Circuit Breaker Contingencies Under Different Loading Scenarios

The ranks of each circuit breaker contingency under different loading scenarios based on the PI_V and PI_F indices are summarized in Tables E.9-E.14. The ranks of the circuit breaker contingencies relative to each other based on the PI_F and PI_V performance indices for different loading scenarios are consolidated using the ranking index R_F defined by (4.8). The values of weights W_1, W_2, W_3, and W_4 used here are 0.33, 0.25, 0.17, and 0.25 respectively. The value of k is set to be 100. As discussed earlier, the ranking of the contingencies using R_F accounts for all four loading scenarios in the proportion of the values W_1 to W_4. Table 4.13 shows the results of ranking the circuit breaker contingencies using PI_V and PI_F based on the ranking index R_F. For the illustrative purpose, the list for top 35 circuit breaker contingencies is shown here. A complete list is given in Tables E.15-E17 of Appendix E. Cb 107 and Cb 73 are identified as the most critical circuit breakers based on the PI_V and PI_F performance indices respectively using the final ranking index R_F.

Table 4.13 List of PI_V and PI_F Based Top 35 Circuit Breaker Contingencies Using R_F

PI_V based			PI_F based		
Rank	Circuit breaker name	R_F	Rank	Circuit breaker name	R_F
1	Cb 107	78	1	Cb 73	60.118
2	Cb 109	34.079	2	Cb 74	30.223
3	Cb 10	33.632	3	Cb 107	29.088
4	Cb 47	22.631	4	Cb 58	28.981
5	Cb 6	17.124	5	Cb 59	20.503
6	Cb 48	14.967	6	Cb 109	15.531
7	Cb 45	14.956	7	Cb 32	12.830
8	Cb 46	12.303	8	Cb 65	10.917
9	Cb 19	9.056	9	Cb 31	9.561
10	Cb 9	8.652	10	Cb 64	9.463
11	Cb 74	7.345	11	Cb 47	9.052
12	Cb 106	7.137	12	Cb 94	8.031
13	Cb 104	6.580	13	Cb 35	7.825
14	Cb 73	6.297	14	Cb 82	7.631
15	Cb 5	6.294	15	Cb 10	7.498
16	Cb 4	6.203	16	Cb 6	7.205
17	Cb 63	6.175	17	Cb 45	6.985
18	Cb 3	6.041	18	Cb 34	6.709
19	Cb 103	6.032	19	Cb 85	6.626
20	Cb 105	5.494	20	Cb 9	6.485
21	Cb 59	5.474	21	Cb 106	6.005
22	Cb 64	4.801	22	Cb 46	5.728
23	Cb 12	4.787	23	Cb 48	4.888
24	Cb 11	4.335	24	Cb 63	4.801
25	Cb 75	4.335	25	Cb 4	4.767
26	Cb 49	4.193	26	Cb 53	4.718
27	Cb 95	4.167	27	Cb 54	4.348
28	Cb 65	4.127	28	Cb 52	4.190
29	Cb 101	3.979	29	Cb 11	4.036
30	Cb 50	3.907	30	Cb 12	3.829
31	Cb 15	3.784	31	Cb 76	3.669
32	Cb 7	3.750	32	Cb 75	3.600
33	Cb 97	3.715	33	Cb 99	3.587
34	Cb 58	3.634	34	Cb 88	3.563
35	Cb 13	3.476	35	Cb 1	3.371

CHAPTER 5: CONCLUSIONS AND FUTURE RECOMMENDATIONS

5.1 Main Conclusions

The study in this thesis analyzes the failure impact of the 500 kV transformers, transmission lines and circuit breakers on the power system network of the operating utility. The severity of the impact is quantified in terms of two system wide performance indices namely PI_F and PI_V. The ranks of the 500 kV transmission assets obtained using these performance indices highlight the critical transmission equipment in each category. The analysis was carried out for four different loading scenarios of the operating utility under study.

It is observed that the values of PI_V and PI_F performance indices tend to saturate for the contingencies at lower ranks irrespective of the loading scenario under consideration. However, these values differ from each other for critical contingencies located at the top of the ranking list. The performance index PI_V defined by (4.1), provides a better perspective of the voltage deviations occurring in the power system network following a contingency. The most critical contingencies, especially under high loading scenarios (scenario 3 and 4), result in large voltage deviations at the buses in the power system network. In case of the circuit breaker Cb 107 contingency for scenario 4, the value of PI_V is observed to be ~ 3405 which is quite high. The average voltage deviation for this contingency is found to be 0.066 p.u. which is greater than the recommended threshold value of 0.05 p.u. for the 500 kV buses. On the other hand, the contingency corresponding to the least critical circuit breaker, Cb 74 (PI_V = 969.4), results in lesser voltage deviations (ΔV_{avg} = 0.038). Hence, the PI_V index can be effectively used to identify the critical assets from the large set of transmission elements based on the severity of their failure impact on the system voltage profile. The PI_F index ranks the contingencies relative to each other based on the maximum branch overload in the power system network following a contingency.

It is observed that the criticality of the transmission assets varies with the loading conditions. For example, Tr 35 is identified as the most critical transformer for scenario 4 (summer peak load case). The same transformer is ranked at 27^{th} position (out of 35 transformers under study) for scenario 1 (light load case). Similar trends are observed in the ranking list of transmission lines and circuit breakers as well. The ranks of the transmission assets are also found to vary with the performance index used to quantify the impact of the failure on the rest of the power system network. Transmission line Ln 1 is identified as the most critical transmission line under operating conditions corresponding to scenario 1 based on the PI_V index. The same line is ranked at 27^{th} position (out of 29 transmission line under study) for the same scenario using the PI_F index.

Since the rank of a transmission asset relative to the others varies with the loading scenario, a ranking index R_F is used to consolidate the ranks under different loading scenarios. The ranking list of the transmission assets obtained using the index R_F can be used to prioritize long term maintenance and investment decisions for the critical assets. This index considers different loading scenarios to which the utility is subjected to over a period of one year. Similarly, the short term maintenance strategies can be designed based on the ranking list obtained for the scenario which most closely resembles the system loading. That system loading is at the time when the maintenance of the transmission assets is planned.

In general, the impact of breaker failure contingencies on the power system network of the operating utility is found to be more severe than the transformer or transmission line contingencies. This can be observed from the values of the PI_V and PI_F performance indices for the circuit breakers, transformers and transmission lines located at top of the ranking lists under any scenario. The values of these performance indices are always higher for the circuit breaker contingencies. Such an observation is a result of the fact that a stuck breaker contingency results in the loss of additional circuit breakers along with other transmission elements. The simulation and analysis of breaker failure contingencies is carried out using the node breaker model. Several critical circuit breakers are identified whose failure could have a detrimental impact on the system. This is the advantage of using the node breaker model over the traditional bus branch model.

5.2 Recommendations for Future Work

Below are the recommendations for the future work that can be carried out by the operating utility on its power system network:

- The ranking of the transmission assets at 230 kV can be carried out in a manner similar to the 500 kV transmission assets, to identify the critical elements relative to each other at 230 kV level. The study can also be extended for the assets at distribution level.
- Protective relays as well as instrumentation transformers play an important role in ensuring that the system senses and clears the faults immediately. Such elements can be analyzed to quantify the impact of their failure and rank them relative to each other to identify the critical ones.

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APPENDIX A

CONTINGENCY LIST OF 500 kV CIRCUIT BREAKERS

The list of circuit breakers identified for contingency analysis and ranking as per criteria described in section 3.2 are given in Tables A.1-A.3.

Table A.1 List of 500 kV Circuit Breakers from Cb 1 to Cb 34 for Contingency Analysis and Ranking

Circuit breaker name	From bus number	To bus number
Cb 1	99487	99486
Cb 2	99762	99757
Cb 3	99760	99764
Cb 4	99761	99765
Cb 5	99773	99772
Cb 6	100270	100262
Cb 7	100279	100258
Cb 8	100280	100259
Cb 9	100273	100269
Cb 10	100276	100271
Cb 11	100267	100263
Cb 12	100246	100250
Cb 13	100459	100460
Cb 14	100468	100467
Cb 15	100461	100462
Cb 16	100986	100966
Cb 17	100984	100954
Cb 18	100949	100950
Cb 19	101004	100957
Cb 20	100981	100958
Cb 21	100998	100999
Cb 22	101001	101002
Cb 23	101009	101005
Cb 24	100978	100965
Cb 25	100991	100983
Cb 26	100947	100955
Cb 27	100970	100952
Cb 28	100988	100961
Cb 29	100959	100960
Cb 30	100968	100969
Cb 31	100980	100962
Cb 32	100974	100951
Cb 33	100971	100956
Cb 34	100967	100953

Table A.2 List of 500 kV Circuit Breakers from Cb 35 to Cb 75 for Contingency Analysis and Ranking

Circuit breaker name	From bus number	To bus number
Cb 35	100997	100996
Cb 36	100990	100964
Cb 37	100977	100975
Cb 38	100993	100994
Cb 39	101294	101281
Cb 40	101292	101291
Cb 41	101287	101288
Cb 42	101290	101289
Cb 43	101297	101285
Cb 44	101282	101295
Cb 45	101300	101284
Cb 46	101299	101298
Cb 47	101446	101443
Cb 48	101449	101450
Cb 49	101440	101439
Cb 50	101447	101448
Cb 51	101454	101453
Cb 52	102129	102131
Cb 53	102130	102132
Cb 54	102128	102133
Cb 55	102431	102437
Cb 56	102436	102438
Cb 57	102408	102418
Cb 58	102394	102384
Cb 59	102395	102404
Cb 60	102398	102421
Cb 61	102402	102423
Cb 62	102392	102386
Cb 63	102380	102383
Cb 64	102401	102397
Cb 65	102416	102417
Cb 66	102400	102411
Cb 67	102403	102414
Cb 68	102389	102407
Cb 69	102381	102415
Cb 70	102382	102412
Cb 71	102434	102432
Cb 72	102405	102406
Cb 73	102396	102420
Cb 74	102409	102426
Cb 75	102393	102413

Table A.3 List of 500 kV Circuit Breakers from Cb 76 to Cb 112 for Contingency Analysis and Ranking

Circuit breaker name	From bus number	To bus number
Cb 76	102388	102424
Cb 77	102399	102425
Cb 78	102489	102486
Cb 79	102498	102496
Cb 80	102502	102499
Cb 81	102506	102503
Cb 82	102511	102512
Cb 83	102510	102507
Cb 84	102516	102513
Cb 85	102517	102518
Cb 86	102522	102521
Cb 87	102449	102446
Cb 88	102452	102453
Cb 89	102455	102454
Cb 90	102458	102456
Cb 91	102461	102462
Cb 92	102464	102463
Cb 93	102468	102465
Cb 94	102471	102472
Cb 95	102734	102735
Cb 96	102731	102733
Cb 97	102727	102729
Cb 98	102724	102726
Cb 99	102740	102739
Cb 100	102770	102771
Cb 101	102762	102763
Cb 102	102765	102766
Cb 103	103150	103151
Cb 104	103153	103149
Cb 105	103146	103155
Cb 106	103605	103602
Cb 107	103611	103607
Cb 108	103608	103603
Cb 109	103609	103606
Cb 110	103798	103792
Cb 111	103793	103790
Cb 112	103795	103796

APPENDIX B

EPCL CODE TO SIMULATE TRANSFORMER CONTINGENCIES

```
$file="6047_KJ.sav"
@return=getf($file)
gosub initialize
@ntran=casepar[0].ntran
@ngen=casepar[0].ngen
@nbus=casepar[0].nbus
@nbrsec=casepar[0].nbrsec
$file1="tran_list.txt"
$file2="tran_fail_busvolts.txt"
$file3="tran_fail_flows.txt"
$file4="tran_fail_genx.txt"
@ret=openlog($file1)
@ret=openlog($file2)
@ret=openlog($file3)
@ret=openlog($file4)
@count=0
for @tran_num = 0 to @ntran-1
      /*
      @tran_num=5979
      */
      @fbus_ind=tran[@tran_num].ifrom
      @tbus_ind=tran[@tran_num].ito
      @tbus1_ind=tran[@tran_num].itert
      @flag1=0;
      @flag2=0;
      if((busd[@fbus_ind].basekv=500) or (busd[@tbus_ind].basekv=500))
            @flag1=1
      endif
      if(@tbus1_ind!=-1)
            if(busd[@tbus1_ind].basekv=500)
                  @flag2=1
            endif
      endif
      /*checking for utility owned 500 KV transformers*/
      if((tran[@tran_num].nown=33) and (@flag1 or @flag2))
            if(tran[@tran_num].st=1)
                  @count=@count+1
                  tran[@tran_num].st=0
                  gosub gen_resch
                  /*soln argument is 0 for non-flat start*/
                  solpar[0].itnrvl=0
                  solpar[0].itnrmx=25
                  solpar[0].tolnr=1
                  @return=soln("0")
                  if(@return=-2)
                        @return=getf($file)
                        tran[@tran_num].st=0
                        gosub gen_resch
                        solpar[0].itnrvl=6
                        solpar[0].itnrmx=75
                        solpar[0].tolnr=1
                        @return=soln("0")
                  elseif(@return=-3)
                        @return=getf($file)
                        tran[@tran_num].st=0
                        gosub gen_resch
                        busd[9247].type=0
```

```
                    @return=soln("0")
                endif
                @ret=flowcalc("1")
                @equip_no=@tran_num
                gosub flows
                logprint($file3,"endofcase<")
                @return=getf($file)
            endif
        endif
next
logterm("ALL CASES EVALUATED")
close($file1)
close($file2)
close($file3)

/* subroutine to initialize unit transformers to their respective gen-
erators index */
subroutine initialize
    dim #tr_gen[6560]
    dim #gen_pr[55]
    for @i=0 to @ntran-1
        #tr_gen[@i]=0
    next
    #tr_gen[5927]=3508
    #tr_gen[5977]=3529
    #tr_gen[5978]=3530
    #tr_gen[5979]=3531
    #tr_gen[5986]=275
    #tr_gen[5987]=276
    #tr_gen[5988]=277
    #tr_gen[5990]=3532
    #tr_gen[5993]=3555
    #tr_gen[5994]=3556
    #tr_gen[5995]=3557
    #tr_gen[5996]=3558
    #tr_gen[5997]=3559
    #tr_gen[5998]=3560
    #tr_gen[5999]=3535
    #tr_gen[6000]=3536
    #tr_gen[6001]=3537
    #gen_pr[0]=275
    #gen_pr[1]=276
    #gen_pr[2]=277
    #gen_pr[3]=3529
    #gen_pr[4]=3530
    #gen_pr[5]=3531
    #gen_pr[6]=3508
    #gen_pr[7]=3507
    #gen_pr[8]=3578
    #gen_pr[9]=3577
    #gen_pr[10]=3541
    #gen_pr[11]=3544
    #gen_pr[12]=3542
    #gen_pr[13]=3543
    #gen_pr[14]=3545
    #gen_pr[15]=3524
    #gen_pr[16]=3525
```

```
      #gen_pr[17]=3526
      #gen_pr[18]=3535
      #gen_pr[19]=3536
      #gen_pr[20]=3537
      #gen_pr[21]=3519
      #gen_pr[22]=3522
      #gen_pr[23]=260
      #gen_pr[24]=261
      #gen_pr[25]=1225
      #gen_pr[26]=1226
      #gen_pr[27]=1227
      #gen_pr[28]=1160
      #gen_pr[29]=1161
      #gen_pr[30]=1162
      #gen_pr[31]=1243
      #gen_pr[32]=1246
      #gen_pr[33]=3546
      #gen_pr[34]=3547
      #gen_pr[35]=3548
      #gen_pr[36]=3549
      #gen_pr[37]=3495
      #gen_pr[38]=3499
      #gen_pr[39]=3500
      #gen_pr[40]=3501
      #gen_pr[41]=3502
      #gen_pr[42]=3503
      #gen_pr[43]=3504
      #gen_pr[44]=3505
      #gen_pr[45]=3506
      #gen_pr[46]=3496
      #gen_pr[47]=3497
      #gen_pr[48]=3498
      #gen_pr[49]=3489
      #gen_pr[50]=3490
      #gen_pr[51]=3491
      #gen_pr[52]=3520
      #gen_pr[53]=3521
      #gen_pr[54]=3523
return
/*subroutine to reschedule the generation in case of loss of a genera-
tor */
subroutine gen_resch
      if(#tr_gen[@tran_num]!=0)
            @gen_indx=#tr_gen[@tran_num]
            @delp=gens[@gen_indx].pgen
            gens[@gen_indx].st=0
            gens[@gen_indx].pgen=0
            for @j=0 to 51
                  if(#gen_pr[@j]!=@gen_indx)
                        @indx=#gen_pr[@j]
                        if(@indx!=3507)
                              @buff=gens[@indx].pmax-gens[@indx].pgen
                              if((@buff>0) and (@buff<@delp))

      gens[@indx].pgen=gens[@indx].pgen+@buff
                                    if(gens[@indx].st=0)
                                          gens[@indx].st=1
```

```
                                          gosub swtch_brkrs
                                    endif
                                    @delp=@delp-@buff

                              elseif(@buff>@delp)

      gens[@indx].pgen=gens[@indx].pgen+@delp
                                    if(gens[@indx].st=0)
                                          gens[@indx].st=1
                                          gosub swtch_brkrs
                                    endif
                                    @delp=0

                              endif
                              if(@delp=0)
                                    quitfor
                              endif
                        endif
                  endif
            next
      endif
return

/*subroutine to switch breakers to bring a newly switched generator in
service */
subroutine swtch_brkrs
      if(@indx=3507)
            brkr[96199].st=1
            tran[5926].st=1
            brkr[96197].st=1
            brkr[96211].st=1
            brkr[96178].st=1
            brkr[96207].st=1
            brkr[96179].st=1
            brkr[96208].st=1
            brkr[96108].st=1
            brkr[96177].st=1
            brkr[96180].st=1
      elseif(@indx=3577)
            brkr[100890].st=1
      elseif(@indx=3541)
            brkr[99144].st=1
      elseif(@indx=3542)
            brkr[99146].st=1
      elseif(@indx=260)
            brkr[6764].st=1
      elseif(@indx=261)
            brkr[6765].st=1
      elseif(@indx=1161)
            brkr[33294].st=1
      elseif(@indx=1243)
       brkr[35324].st=1
      elseif(@indx=1246)
            brkr[35325].st=1
      elseif(@indx=3546)
            brkr[99140].st=1
            brkr[99092].st=1
```

```
        elseif(@indx=3547)
              brkr[99141].st=1
        elseif(@indx=3548)
              brkr[99142].st=1
              brkr[99097].st=1
        elseif(@indx=3549)
              brkr[99143].st=1
              brkr[99088].st=1
              tran[6032].st=1
              brkr[99082].st=1
              brkr[99134].st=1
        elseif(@indx=3495)
              brkr[96034].st=1
        elseif(@indx=3499)
              brkr[96038].st=1
        elseif(@indx=3500)
              brkr[96039].st=1
        elseif(@indx=3501)
              brkr[96040].st=1
        elseif(@indx=3502)
              brkr[96041].st=1
        elseif(@indx=3503)
              brkr[96042].st=1
        elseif(@indx=3504)
              brkr[96043].st=1
        elseif(@indx=3505)
              brkr[96044].st=1
        elseif(@indx=3506)
              brkr[96045].st=1
        elseif(@indx=3496)
              brkr[96035].st=1
        elseif(@indx=3497)
              brkr[96036].st=1
        elseif(@indx=3498)
              brkr[96037].st=1
        elseif(@indx=3489)
              brkr[95214].st=1
        elseif(@indx=3490)
              brkr[95215].st=1
        elseif(@indx=3491)
              brkr[95216].st=1
        elseif(@indx=3520)
              brkr[97387].st=1
        elseif(@indx=3521)
              brkr[97388].st=1
        elseif(@indx=3523)
              tran[5963].st=1
              brkr[97384].st=1
              brkr[97429].st=1
        endif
return
```

APPENDIX C

MATLAB SCRIPT TO CALCULATE PERFORMANCE INDICES

C.1 Code Structure

The entire code is divided into seven subroutines that perform different tasks individually. A summary of the subroutines along with their respective functions is given in Table C.1. The run sequence of the Matlab code is shown in Fig. C.1.

Table C.1 Summary of Matlab Subroutines and Their Functions

Subroutine name	Function
sav_dat.m	Invokes 'read_' subroutines to read the `.txt` files containing power flow study results and the contingency lists. Saves the read data.
read_list.m	Reads the `.txt` files containing contingency lists for transformers, transmission lines, and circuit breakers.
read_flows.m	Reads the `.txt` files containing branches flows for each transformer, transmission line, and circuit breaker contingency simulated in PSLF.
read_volts.m	Reads the `.txt` files containing bus voltages for each transformer, transmission line and circuit breaker contingency simulated in PSLF.
main.m	Calls the 'piflowindx.m' and 'pivindx.m' subroutines to compute flow based and voltage based performance indices and displays the ranking results.
piflowindx.m	Calculates the flow based performance index (PI_F) for a given contingency.
pivindx.m	Calculates the voltage based performance index (PI_V) for a given contingency.

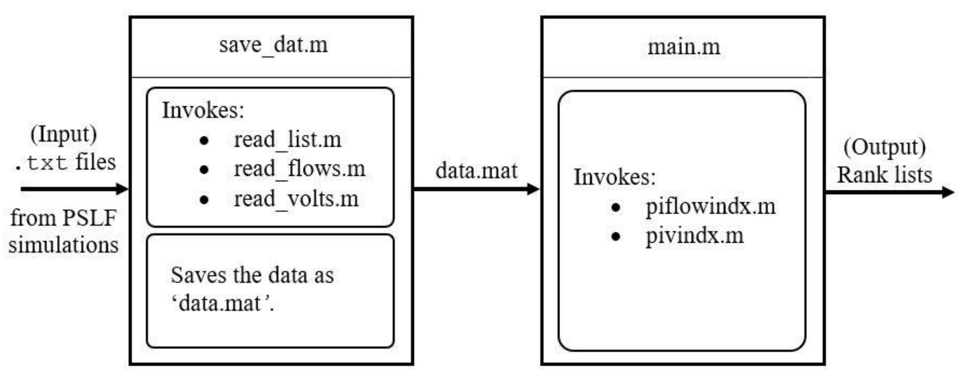

Figure C.1 Run Sequence for the Matlab Code

C.2 Matlab Subroutines

save_dat.m

```
clear all;
format long;

filename="Contingency list.xlsx";
% Writes the contingency list in an excel file
[tran_list]=read_list("tran_list.txt");
writetable(tran_list,filename,'Sheet','Transformers list');
[line_list]=read_list("line_list.txt");
writetable(line_list,filename,'Sheet','Lines list');
[cb_list]=read_list("cb_list.txt");
writetable(cb_list,filename,'Sheet','Circuit breakers list');

% Reading flows
[base_flows]=read_flows("base_flows.txt",0);
[tran_fail_flows,num_tran_cases]=read_flows("tran_fail_flows.txt",1);
[line_fail_flows,num_line_cases]=read_flows("line_fail_flows.txt",1);
[cb_fail_flows,num_cb_cases]=read_flows("cb_fail_flows.txt",1);

% Reading volts
[base_volts]=read_volts("base_busvolts.txt",0);
[tran_fail_busvolts]=read_volts("tran_fail_busvolts.txt",1);
[line_fail_busvolts]=read_volts("line_fail_busvolts.txt",1);
[cb_fail_busvolts]=read_volts("cb_fail_busvolts.txt",1);
save('data_raw');
```

read_list.m

```
function[list]=read_list(filename);
line=0;
fid=fopen(filename);
while ~feof(fid)
    tline=fgetl(fid);
    line=line+1;
    data(line,:)=textscan(tline,'%d%d%s%s%s%d%d%d%d%d%f%f');
end
list=cell2table(data);
```

read_flows.m

```
function[flows,total_cases]=read_flows(filename,flag);
if(flag==0)
    fprintf("Reading base flows....");
else
    fprintf("Reading cases flows....");
end
fid=fopen(filename);
line=0;
casenum=1;
while ~feof(fid)
```

```
    tline=fgetl(fid);
    while(~strcmp(tline,'endofcase'))
        line=line+1;
        if(line>3)
            data(line-3,:)=textscan(tline,'%d%d%d%d%s%2c%f%f%f%f%f');
        end
        tline=fgetl(fid);
    end
    if(flag==1)
        flows(casenum).dat=cell2table(data);
        casenum=casenum+1;
    else
        flows(1).dat=cell2table(data);
    end
    line=0;
end
total_cases=casenum-1;
fprintf("Completed\n");
```

read_volts.m

```
function[volts]=read_volts(filename,flag);
if(flag==0)
    fprintf("Reading base voltages....");
else
    fprintf("Reading cases voltages....");
end
fid=fopen(filename);
line=0;
casenum=1;
while ~feof(fid)
    tline=fgetl(fid);
    while(~strcmp(tline,'endofcase'))
        line=line+1;
        if(line>4)
            data(line-4,:)=textscan(tline,'%d%d%d%14c%f%f%f%f%f%f');
        end
        tline=fgetl(fid);
    end
    if(flag==1)
        volts(casenum).dat=cell2table(data);
        casenum=casenum+1;
    else
        volts(1).dat=cell2table(data);
    end
    line=0;
end
total_cases=casenum-1;
fprintf("Completed\n");
```

main.m

```
clear all;
format long;
load('data_raw');
```

```
fprintf("Ranking transformers on PIF....\n");
[pif1_tran_ranks,pif2_tran_ranks,load_mat]=piflowindx(num_tran_cases,tr
an_fail_flows);
fprintf("Ranking lines on PIF....\n");
[pif1_line_ranks
pif2_line_ranks]=piflowindx(num_line_cases,line_fail_flows);
fprintf("Ranking circuit breakers on PIF....\n");
[pif1_cb_ranks,pif2_cb_ranks]=piflowindx(num_cb_cases,cb_fail_flows);
fprintf("Ranking transformers on PIV....\n");
[piv1_tran_ranks,piv2_tran_ranks,delv_tran]=pivindx(num_tran_cases,tran
_fail_busvolts);
fprintf("Ranking lines on PIV....\n");
[piv1_line_ranks,piv2_line_ranks,delv_line]=pivindx(num_line_cases,line
_fail_busvolts);
fprintf("Ranking circuit breakers on PIV....\n");
[piv1_cb_ranks,piv2_cb_ranks,delv_cb]=pivindx(num_cb_cases,cb_fail_busv
olts);
save('results');
```

piflowindx.m

```
function[pif1 pif2 load_mat]=ranking(num_cases,flows)
Wi=1;
n=1;
for i=1:num_cases
    pif2(i,2)=0;
    violations=0;
    for j=1:size(flows(i).dat,1)
        if(flows(i).dat{j,11}==0)
            ratio(j)=0.666;
        else
            if(strcmp(cell2mat(flows(i).dat{j,5}),'LINE')==1)
                ratio(j)=flows(i).dat{j,10}/flows(i).dat{j,11};
            else
                ratio(j)=flows(i).dat{j,9}/flows(i).dat{j,11};
            end
        end
        if(ratio(j)>1)
            violations=violations+1;
        end
        load_mat(j,i)=ratio(j)*100;

        pif2(i,1)=i;
        pif2(i,2)=pif2(i,2)+(0.5*Wi/n)*ratio(j)^(2*n);
    end
    pif2(i,2)=pif2(i,2)/2;
    pif1(i,1)=i;
    [pif1(i,2) pif1(i,3)]=max(ratio);
    pif1(i,4)=violations;
end
pif1=sortrows(pif1,2,'descend');
pif2=sortrows(pif2,2,'descend');
```

pivindx.m

```
function[piv1,piv2,del]=pivindx(num_cases,volts);
n=1;
for case_num=1:num_cases
    piv1(case_num,1:2)=0;
    piv2(case_num,1:2)=0;
    count=0;
    for bus_num=1:size(volts(case_num).dat,1)
        if(volts(case_num).dat{bus_num,3}~=0)
            count=count+1;
            vi=volts(case_num).dat{bus_num,6};
            vsp=volts(case_num).dat{bus_num,8};
            if(vsp==0)
                vsp=1.1;
            end
            del(case_num).vi(count,1)=abs(vi-vsp);
            del(case_num).vi(count,2)=bus_num;
            Wvi=1;
            if(volts(case_num).dat{bus_num,5}>=500)
                del_vi=0.05;
            else
                del_vi=0.075;
            end
            piv1(case_num,1)=case_num;
            piv1(case_num,2)=piv1(case_num,2)+(0.5*Wvi/n)*((abs(vi-
vsp))/del_vi)^(2*n);
            piv2(case_num,1)=case_num;
            piv2(case_num,2)=piv2(case_num,2)+abs(vi-vsp);
        end
    end
    piv2(case_num,2)=piv2(case_num,2)/size(volts(case_num).dat,1);
end
piv1=sortrows(piv1,2,'descend');
piv2=sortrows(piv2,2,'descend');
```

APPENDIX D

SIMULATION RESULTS OF CONTINGENCIES UNDER SCENARIOS 2 AND 3

D.1 A Listing of PI_V and PI_F Indices for Transformer Contingencies of Scenario 2 and 3

The values of PI_V, PI_F, and N_V for each one of the 35 transformer contingencies corresponding to scenario 2 are listed in Table D.1. Fig. D.1 shows the comparison of the PI_V and PI_F indices for transformer contingencies of scenario 2. The values of PI_V, PI_F, and N_V for each one of the 35 transformer contingencies corresponding to scenario 3 are listed in Table D.2. Fig. D.2 shows the comparison of the PI_V and PI_F indices for transformer contingencies of scenario 3.

Table D.1 List of PI_V and PI_F Indices for Transformer Contingencies of Scenario 2 (P_{load} = 4655.52 MW, Q_{load} = 244.38 MVAr)

Transformer name	PI_V	PI_F	N_V
Tr 1	52.641	0.918	0
Tr 2	55.588	0.918	0
Tr 3	55.588	0.918	0
Tr 4	52.490	0.918	0
Tr 5	51.088	0.942	0
Tr 6	50.771	0.919	0
Tr 7	46.978	0.918	0
Tr 8	54.574	0.918	0
Tr 9	68.131	0.918	0
Tr 10	68.126	0.918	0
Tr 11	54.329	0.917	0
Tr 12	54.181	0.917	0
Tr 13	38.751	0.919	0
Tr 14	38.617	0.919	0
Tr 15	38.758	0.919	0
Tr 16	37.832	1.026	2
Tr 17	38.267	0.924	0
Tr 18	37.780	1.026	2

Transformer name	PI_V	PI_F	N_V
Tr 19	53.888	0.918	0
Tr 20	51.721	0.918	0
Tr 21	52.350	0.918	0
Tr 22	52.641	0.918	0
Tr 23	52.359	0.918	0
Tr 24	52.879	0.918	0
Tr 25	52.787	0.918	0
Tr 26	52.558	0.918	0
Tr 27	52.613	0.918	0
Tr 28	52.677	0.918	0
Tr 29	52.746	0.918	0
Tr 30	52.746	0.918	0
Tr 31	53.933	0.918	0
Tr 32	53.933	0.918	0
Tr 33	53.909	0.918	0
Tr 34	53.991	0.918	0
Tr 35	171.93	0.918	0

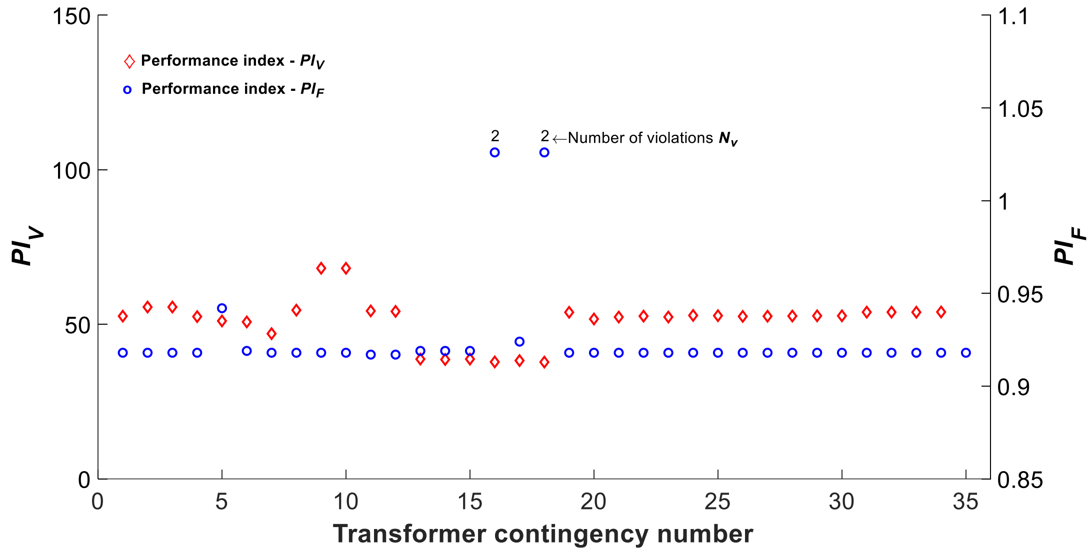

Figure D.1 Comparison of PI_V and PI_F Indices for Transformer Contingencies of Loading Scenario 2

Table D.2 List of PI_V and PI_F Indices for Transformer Contingencies for Scenario 3 (P_{load} = 6047.73 MW, Q_{load} = 327.35 MVAr)

Transformer	PI_V	PI_F	N_V
Tr 1	305.225	0.911	0
Tr 2	325.295	0.911	0
Tr 3	325.294	0.911	0
Tr 4	304.633	0.911	0
Tr 5	300.236	0.939	0
Tr 6	299.131	0.916	0
Tr 7	292.496	0.911	0
Tr 8	315.235	0.911	0
Tr 9	354.579	0.910	0
Tr 10	354.696	0.910	0
Tr 11	319.589	1.086	2
Tr 12	318.185	1.085	2
Tr 13	306.780	0.910	0
Tr 14	305.751	0.910	0
Tr 15	306.693	0.910	0
Tr 16	314.866	0.966	0
Tr 17	318.277	0.912	0
Tr 18	314.240	0.966	0

Transformer	PI_V	PI_F	N_V
Tr 19	312.708	0.910	0
Tr 20	300.431	0.911	0
Tr 21	303.565	0.911	0
Tr 22	305.241	0.911	0
Tr 23	304.618	0.911	0
Tr 24	307.035	0.911	0
Tr 25	306.553	0.911	0
Tr 26	301.570	0.911	0
Tr 27	302.055	0.911	0
Tr 28	295.319	0.911	0
Tr 29	305.307	0.911	0
Tr 30	305.307	0.911	0
Tr 31	312.642	0.911	0
Tr 32	312.642	0.911	0
Tr 33	312.503	0.911	0
Tr 34	312.968	0.911	0
Tr 35	592.830	0.910	0

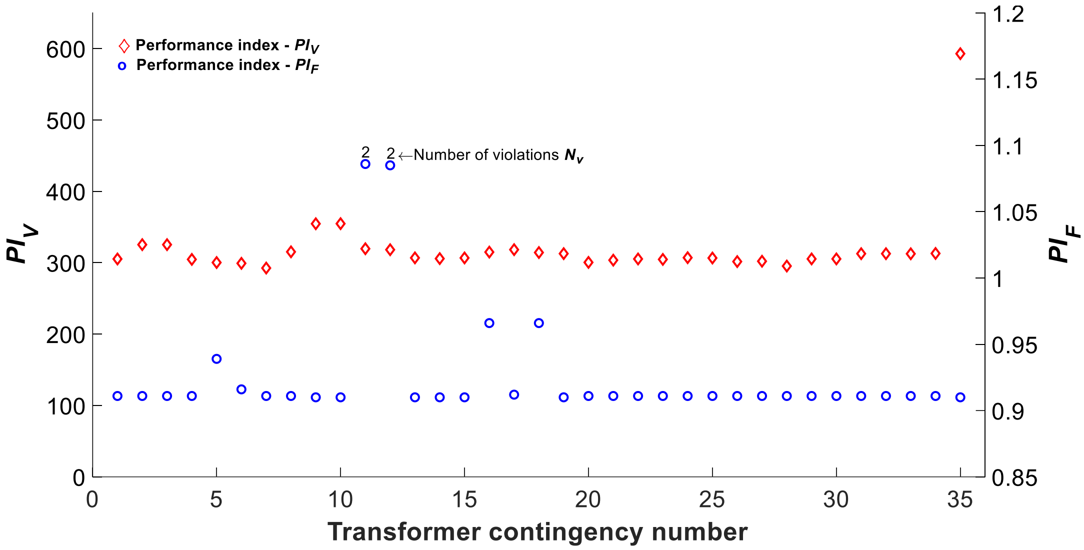

Figure D.2 Comparison of PI_V and PI_F Indices for Transformer Contingencies of Loading Scenario 3

D.2 A Listing of PI_V and PI_F Indices for Transmission Line Contingencies of Scenario 2

The values of PI_V, PI_F, and N_V for each one of the 29 transmission line contingencies corresponding to scenario 2 are listed in Table D.3. Fig. D.3 shows the comparison of the PI_V and PI_F indices for transformer contingencies of scenario 2. The values of PI_V, PI_F, and N_V for each one of the 29 transmission line contingencies corresponding to scenario 3 are listed in Table D.4. Fig. D.4 shows the comparison of the PI_V and PI_F indices for transformer contingencies of scenario 3.

Table D.3 List of PI_V and PI_F Indices for Transmission Line Contingencies for Scenario 2 (P_{load} = 4655.52 MW, Q_{load} = 244.38 MVAr)

Transmission line name	PI_V	PI_F	N_V
Ln 1	50.926	0.915	
Ln 2	52.769	0.918	0
Ln 3	52.769	0.918	0
Ln 4	57.296	0.916	0
Ln 5	54.309	0.917	0
Ln 6	56.486	0.916	0
Ln 7	55.037	0.917	0
Ln 8	118.98	0.946	0
Ln 9	67.078	0.918	0
Ln 10	65.717	0.918	0
Ln 11	62.204	0.918	0
Ln 12	56.15	0.918	0
Ln 13	54.355	0.917	0
Ln 14	54.207	0.917	0
Ln 15	54.706	0.917	0

Transmission line name	PI_V	PI_F	N_V
Ln 16	52.754	0.917	0
Ln 17	52.947	0.917	0
Ln 18	52.756	0.917	0
Ln 19	52.947	0.917	0
Ln 20	52.756	0.917	0
Ln 21	57.513	0.915	0
Ln 22	55.604	0.917	0
Ln 23	55.604	0.917	0
Ln 24	58.927	0.917	0
Ln 25	119.06	0.915	0
Ln 26	76.861	0.916	0
Ln 27	79.398	0.917	0
Ln 28	63.702	0.917	0
Ln 29	62.083	0.917	0

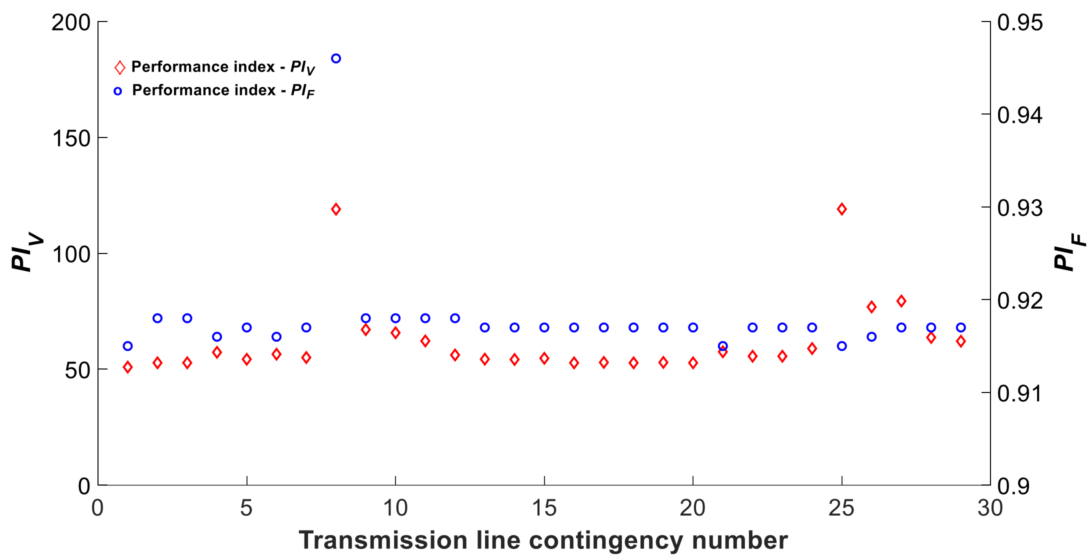

Figure D.3 Comparison of PI_V and PI_F Indices for Transmission Line Contingencies of Loading Scenario 2

Table D.4 List of PI_V and PI_F Indices for Transmission Line Contingencies for Scenario 3 (P_{load} = 6047.73 MW, Q_{load} = 327.35 MVAr)

Transmission line name	PI_V	PI_F	N_V
Ln 1	304.429	0.909	0
Ln 2	305.751	0.911	0
Ln 3	305.751	0.911	0
Ln 4	327.991	0.909	0
Ln 5	312.777	0.910	0
Ln 6	325.530	0.909	0
Ln 7	318.678	0.910	0
Ln 8	508.887	0.909	0
Ln 9	332.603	0.911	0
Ln 10	365.919	0.910	0
Ln 11	345.917	0.911	0
Ln 12	335.285	0.911	0
Ln 13	319.812	1.086	2
Ln 14	318.396	1.085	2
Ln 15	315.450	0.910	0

Transmission line name	PI_V	PI_F	N_V
Ln 16	306.423	0.911	0
Ln 17	307.355	0.911	0
Ln 18	306.445	0.911	0
Ln 19	307.355	0.911	0
Ln 20	306.445	0.911	0
Ln 21	334.309	0.909	0
Ln 22	321.719	0.910	0
Ln 23	321.719	0.910	0
Ln 24	315.650	0.910	0
Ln 25	581.638	0.909	0
Ln 26	420.475	0.909	0
Ln 27	400.690	0.910	0
Ln 28	339.665	0.910	0
Ln 29	352.956	0.910	0

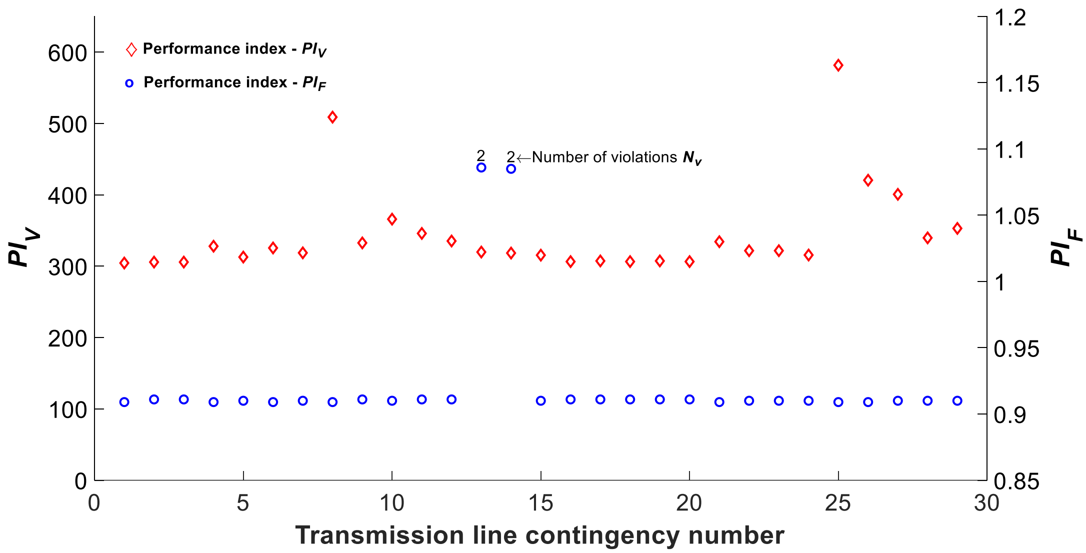

Figure D.4 Comparison of PI_V and PI_F Indices for Transmission Line Contingencies of Loading Scenario 3

APPENDIX E

SIMULATION RESULTS OF CIRCUIT BREAKER CONTINGENCIES FOR DIFFERENT SCENARIOS

Table E.1 List of PI_V and PI_F Indices for Circuit Breaker Contingencies from Cb 1 to Cb 72 Under Scenario 1 (P_{load} = 2666.31 MW, Q_{load} = 182.76 MVAr)

Circuit breaker name	PI_V	PI_F	N_V
1	111.199	0.924	0
2	88.580	0.897	0
3	76.987	0.898	0
4	68.026	0.898	0
5	64.763	0.897	0
6	186.956	0.900	0
7	119.590	0.899	0
8	111.144	0.899	0
9	56.832	0.897	0
10	193.561	0.926	0
11	134.559	0.925	0
12	134.899	0.925	0
13	88.936	0.898	0
14	95.402	0.898	0
15	86.555	0.898	0
16	94.796	0.898	0
17	104.769	0.897	0
18	110.007	0.895	0
19	151.101	0.897	0
20	96.916	0.899	0
21	111.705	0.899	0
22	111.643	0.899	0
23	96.967	0.899	0
24	105.511	0.898	0
25	94.801	0.898	0
26	94.801	0.898	0
27	104.463	0.897	0
28	105.713	0.897	0
29	112.127	0.899	0
30	110.350	0.899	0
31	106.427	0.898	0
32	106.400	0.898	0
33	110.350	0.899	0
34	106.786	0.898	0
35	106.759	0.898	0
36	97.562	0.897	0

Circuit breaker name	PI_V	PI_F	N_V
37	106.775	0.898	0
38	99.575	0.898	0
39	99.577	0.898	0
40	99.577	0.898	0
41	103.608	0.898	0
42	103.608	0.898	0
43	103.608	0.898	0
44	103.608	0.898	0
45	62.848	0.895	0
46	62.848	0.895	0
47	60.899	0.895	0
48	62.343	0.895	0
49	100.675	0.898	0
50	100.810	0.898	0
51	83.442	0.898	0
52	95.409	0.925	0
53	111.492	0.925	0
54	95.442	0.925	0
55	117.443	0.896	0
56	117.443	0.896	0
57	102.397	0.893	0
58	126.378	0.928	0
59	136.347	0.977	0
60	102.397	0.893	0
61	96.087	0.891	0
62	89.978	0.896	0
63	85.338	0.896	0
64	97.791	0.930	0
65	133.008	0.934	0
66	110.222	0.898	0
67	110.304	0.898	0
68	110.400	0.899	0
69	110.219	0.898	0
70	110.275	0.898	0
71	110.375	0.899	0
72	110.219	0.898	0

Table E.2 List of PI_V and PI_F Indices for Circuit Breaker Contingencies from Cb 73 to Cb 112 Under Scenario 1 (P_{load} = 2666.31 MW, Q_{load} = 182.76 MVAr)

Circuit breaker name	PI_V	PI_F	N_V
73	136.675	0.982	0
74	136.973	0.977	0
75	124.154	0.901	0
76	110.712	0.901	0
77	110.400	0.899	0
78	107.694	0.894	0
79	103.660	0.898	0
80	96.537	0.924	0
81	112.163	0.924	0
82	117.614	0.926	0
83	94.712	0.924	0
84	110.832	0.924	0
85	113.447	0.926	0
86	109.381	0.924	0
87	109.760	0.924	0
88	113.180	0.924	0
89	101.617	0.898	0
90	95.896	0.924	0
91	105.585	0.924	0
92	109.191	0.924	0

Circuit breaker name	PI_V	PI_F	N_V
93	111.626	0.924	0
94	113.657	0.926	0
95	94.472	0.899	0
96	103.302	0.898	0
97	96.391	0.898	0
98	105.214	0.899	0
99	100.859	0.899	0
100	83.284	0.897	0
101	80.620	0.895	0
102	97.969	0.896	0
103	85.286	0.896	0
104	85.300	0.896	0
105	89.309	0.898	0
106	65.818	0.897	0
107	182.863	0.897	0
108	90.487	0.898	0
109	104.372	0.897	0
110	96.039	0.898	0
111	103.547	0.899	0
112	110.397	0.899	0

Table E.3 List of PI_V and PI_F Indices for Circuit Breaker Contingencies from Cb 1 to Cb 76 for Scenario 2 (P_{load} = 4655.52 MW, Q_{load} = 244.38 MVAr)

Circuit breaker name	PI_V	PI_F	N_V	Circuit breaker name	PI_V	PI_F	N_V
1	52.641	0.918	0	39	56.263	0.918	0
2	71.452	0.917	0	40	56.263	0.918	0
3	81.395	0.917	0	41	55.708	0.917	0
4	88.823	0.917	0	42	55.708	0.917	0
5	86.378	0.917	0	43	55.708	0.917	0
6	41.798	0.957	0	44	55.708	0.917	0
7	57.510	0.918	0	45	119.25	0.915	0
8	52.490	0.918	0	46	119.25	0.915	0
9	109.61	0.927	0	47	127.45	0.915	0
10	44.858	0.946	0	48	120.13	0.915	0
11	47.244	0.918	0	49	73.848	0.917	0
12	47.113	0.918	0	50	73.606	0.917	0
13	70.004	0.918	0	51	68.089	0.918	0
14	65.828	0.918	0	52	38.743	0.919	0
15	71.078	0.917	0	53	38.565	0.919	0
16	52.947	0.917	0	54	38.749	0.919	0
17	54.494	0.917	0	55	50.909	0.915	0
18	57.373	0.915	0	56	50.909	0.915	0
19	50.988	0.916	0	57	55.195	0.914	0
20	51.856	0.918	0	58	38.789	0.971	0
21	52.640	0.918	0	59	37.787	1.026	2
22	52.640	0.918	0	60	55.195	0.914	0
23	51.856	0.918	0	61	58.280	0.912	0
24	54.305	0.917	0	62	55.378	0.916	0
25	52.947	0.917	0	63	76.848	0.916	0
26	52.947	0.917	0	64	52.023	0.922	0
27	54.703	0.917	0	65	38.829	0.924	0
28	55.011	0.924	0	66	52.751	0.917	0
29	53.022	0.926	0	67	52.734	0.917	0
30	52.769	0.918	0	68	52.751	0.918	0
31	54.352	0.917	0	69	52.753	0.917	0
32	54.351	0.917	0	70	52.751	0.917	0
33	52.769	0.918	0	71	52.767	0.918	0
34	54.204	0.917	0	72	52.753	0.917	0
35	54.204	0.917	0	73	37.878	1.034	2
36	56.901	0.917	0	74	37.734	1.026	2
37	53.699	0.917	0	75	58.793	0.919	0
38	56.150	0.918	0	76	52.248	0.919	0

Table E.4 List of PI_V and PI_F Indices for Circuit Breaker Contingencies from Cb 77 to Cb 112 for Scenario 2 (P_{load} = 4655.52 MW, Q_{load} = 244.38 MVAr)

Circuit breaker name	PI_V	PI_F	N_V	Circuit breaker name	PI_V	PI_F	N_V
77	52.751	0.918	0	95	72.830	0.918	0
78	53.859	0.918	0	96	62.349	0.917	0
79	55.569	0.917	0	97	72.017	0.918	0
80	52.741	0.918	0	98	62.181	0.918	0
81	53.035	0.918	0	99	70.080	0.918	0
82	51.396	0.942	0	100	65.839	0.917	0
83	53.779	0.918	0	101	70.949	0.915	0
84	53.477	0.918	0	102	64.210	0.916	0
85	52.769	0.943	0	103	76.515	0.916	0
86	53.366	0.918	0	104	76.703	0.916	0
87	53.640	0.918	0	105	73.758	0.917	0
88	52.379	0.918	0	106	87.699	0.947	0
89	56.790	0.917	0	107	486.01	0.947	0
90	53.254	0.918	0	108	63.570	0.917	0
91	55.178	0.917	0	109	210.99	0.945	0
92	53.637	0.918	0	110	68.368	0.918	0
93	53.315	0.918	0	111	65.602	0.918	0
94	52.636	0.945	0	112	52.771	0.918	0

Table E.5 List of PI_V and PI_F Indices for Circuit Breaker Contingencies from Cb 1 to Cb 76 for Scenario 3 (P_{load} = 6047.73 MW, Q_{load} = 327.35 MVAr)

Circuit breaker name	PI_V	PI_F	N_V	Circuit breaker name	PI_V	PI_F	N_V
1	305.225	0.911	0	39	335.146	0.911	0
2	351.808	0.910	0	40	335.146	0.911	0
3	430.126	0.910	0	41	274.094	0.976	0
4	360.144	1.083	1	42	274.094	0.976	0
5	425.595	0.910	0	43	274.094	0.976	0
6	258.457	0.917	0	44	274.094	0.976	0
7	308.031	0.911	0	45	582.867	0.909	0
8	304.630	0.911	0	46	582.867	0.909	0
9	402.186	1.048	1	47	609.353	0.909	0
10	262.305	0.916	0	48	583.371	0.909	0
11	292.916	0.911	0	49	365.613	0.910	0
12	292.759	0.911	0	50	365.170	0.910	0
13	379.904	0.911	0	51	354.777	0.910	0
14	366.684	0.910	0	52	306.778	0.910	0
15	384.912	0.910	0	53	305.746	0.910	0
16	307.177	0.911	0	54	306.690	0.910	0
17	314.389	0.910	0	55	304.235	0.909	0
18	333.976	0.909	0	56	304.235	0.909	0
19	294.946	0.909	0	57	323.521	0.909	0
20	303.548	0.911	0	58	270.616	1.097	1
21	305.172	0.911	0	59	314.820	0.966	0
22	305.016	0.911	0	60	323.521	0.909	0
23	303.656	0.911	0	61	335.417	0.909	0
24	312.571	0.910	0	62	317.005	0.909	0
25	307.191	0.911	0	63	357.171	1.009	1
26	307.191	0.911	0	64	433.191	0.910	0
27	315.230	0.910	0	65	318.805	0.912	0
28	317.590	0.910	0	66	306.306	0.911	0
29	307.588	0.911	0	67	306.270	0.911	0
30	305.591	0.911	0	68	305.539	0.911	0
31	319.695	1.086	2	69	261.613	0.968	0
32	319.562	1.086	2	70	306.346	0.911	0
33	305.591	0.911	0	71	305.590	0.911	0
34	318.283	1.085	2	72	261.613	0.968	0
35	318.155	1.085	2	73	317.904	0.981	0
36	340.454	0.911	0	74	314.194	0.966	0
37	312.497	0.910	0	75	319.857	0.912	0
38	335.159	0.911	0	76	306.847	0.912	0

Table E.6 List of PI_V and PI_F Indices for Circuit Breaker Contingencies from Cb 77 to Cb 112 for Scenario 3 (P_{load} = 6047.73 MW, Q_{load} = 327.35 MVAr)

Circuit breaker name	PI_V	PI_F	N_V	Circuit breaker name	PI_V	PI_F	N_V
77	305.539	0.911	0	95	373.099	0.911	0
78	312.346	0.910	0	96	349.240	0.910	0
79	273.697	0.976	0	97	368.470	0.911	0
80	307.047	0.911	0	98	338.304	0.911	0
81	309.566	0.911	0	99	357.774	0.911	0
82	298.414	0.911	0	100	369.814	0.910	0
83	312.296	0.910	0	101	384.915	0.909	0
84	312.575	0.910	0	102	366.219	0.909	0
85	306.569	0.911	0	103	419.481	0.909	0
86	311.510	0.910	0	104	419.679	0.909	0
87	313.526	0.910	0	105	409.152	0.910	0
88	305.862	0.911	0	106	430.212	0.909	0
89	328.352	0.910	0	107	1178.09	0.909	0
90	306.940	0.911	0	108	339.202	0.910	0
91	315.349	0.910	0	109	730.144	0.909	0
92	308.756	0.911	0	110	342.766	0.911	0
93	300.560	0.911	0	111	332.406	0.911	0
94	293.002	0.957	0	112	305.745	0.911	0

Table E.7 List of PI_V and PI_F Indices for Circuit Breaker Contingencies from Cb 1 to Cb 76 for Scenario 4 (P_{load} = 7231.23 MW, Q_{load} = 291.68 MVAr)

Circuit breaker name	PI_V	PI_F	N_V	Circuit breaker name	PI_V	PI_F	N_V
1	1041.682	1.066	2	39	1091.734	1.068	2
2	1157.871	1.072	2	40	1091.734	1.068	2
3	1288.734	1.069	2	41	1083.118	1.067	2
4	1390.067	1.074	2	42	1083.118	1.067	2
5	1353.652	1.075	2	43	1083.118	1.067	2
6	996.2910	1.066	2	44	1083.118	1.067	2
7	1037.855	1.065	2	45	1814.773	1.088	2
8	1039.737	1.066	2	46	1814.773	1.088	2
9	1526.181	1.077	2	47	1881.436	1.091	2
10	1001.007	1.066	2	48	1814.258	1.088	2
11	1024.654	1.066	2	49	1231.272	1.077	2
12	1024.557	1.066	2	50	1231.049	1.077	2
13	1212.258	1.071	2	51	1197.290	1.073	2
14	1189.685	1.070	2	52	1022.795	1.065	2
15	1225.039	1.071	2	53	1020.177	1.065	2
16	1048.959	1.066	2	54	1022.576	1.065	2
17	1048.519	1.066	2	55	1043.071	1.066	2
18	1130.282	1.069	2	56	1043.071	1.066	2
19	1051.726	1.067	2	57	1092.546	1.067	2
20	1043.251	1.066	2	58	1015.177	1.065	2
21	1041.469	1.066	2	59	970.0530	1.063	4
22	1040.827	1.066	2	60	1092.546	1.067	2
23	1043.726	1.066	2	61	1121.492	1.068	2
24	1042.538	1.066	2	62	1070.226	1.067	2
25	1049.015	1.066	2	63	1460.752	1.078	2
26	1049.015	1.066	2	64	1332.155	1.074	2
27	1067.529	1.067	2	65	974.9550	1.064	2
28	1035.732	1.066	2	66	1047.181	1.066	2
29	1012.481	1.065	2	67	1047.162	1.066	2
30	1041.721	1.066	2	68	1041.613	1.066	2
31	1076.985	1.083	4	69	1047.145	1.066	2
32	1076.519	1.083	4	70	1047.224	1.066	2
33	1041.721	1.066	2	71	1041.704	1.066	2
34	1073.567	1.083	4	72	1047.145	1.066	2
35	1073.112	1.083	4	73	977.3150	1.064	4
36	1110.679	1.068	2	74	969.4080	1.063	4
37	1064.362	1.067	2	75	1069.613	1.067	2
38	1091.731	1.068	2	76	1056.897	1.067	2

Table E.8 List of PI_V and PI_F Indices for Circuit Breaker Contingencies from Cb 77 to Cb 112 for Scenario 4 (P_{load} = 7231.23 MW, Q_{load} = 291.68 MVAr)

Circuit breaker name	PI_V	PI_F	N_V
77	1041.613	1.066	2
78	1059.945	1.067	2
79	1082.655	1.067	2
80	1049.563	1.066	2
81	1056.823	1.067	2
82	1028.244	1.066	2
83	1062.253	1.067	2
84	1064.686	1.067	2
85	1049.110	1.066	2
86	1060.591	1.067	2
87	1066.607	1.067	2
88	1046.960	1.066	2
89	1100.528	1.068	2
90	1049.894	1.066	2
91	1068.801	1.067	2
92	1052.417	1.066	2
93	1032.316	1.066	2
94	1010.067	1.065	2

Circuit breaker name	PI_V	PI_F	N_V
95	1242.145	1.072	2
96	1146.104	1.069	2
97	1224.025	1.072	2
98	1114.252	1.068	2
99	1201.001	1.071	2
100	1198.372	1.071	2
101	1232.011	1.072	2
102	1196.994	1.071	2
103	1457.541	1.078	2
104	1458.307	1.078	2
105	1430.038	1.077	2
106	1385.033	1.075	2
107	3404.958	1.174	6
108	1112.133	1.068	2
109	2535.890	1.136	4
110	1112.512	1.067	2
111	1089.087	1.066	2
112	1042.325	1.066	2

Table E.9 List of PI_V Based Rank of the 112 Circuit Breaker Contingencies from Cb 1 to Cb 40 Under Different Loading Scenarios

Circuit breaker name	PI_V based rank			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Cb 1	26	87	89	89
Cb 2	96	20	29	29
Cb 3	104	11	9	16
Cb 4	105	8	25	12
Cb 5	107	10	10	14
Cb 6	2	104	112	108
Cb 7	13	36	67	95
Cb 8	27	91	92	94
Cb 9	112	7	14	7
Cb 10	1	103	109	107
Cb 11	9	101	101	99
Cb 12	8	102	102	100
Cb 13	95	24	17	23
Cb 14	86	28	21	28
Cb 15	97	21	16	21
Cb 16	89	73	71	72
Cb 17	55	54	56	73
Cb 18	41	37	39	31
Cb 19	4	98	99	66
Cb 20	78	96	96	81
Cb 21	22	88	90	92
Cb 22	23	89	91	93
Cb 23	77	95	95	80
Cb 24	53	57	60	84
Cb 25	87	71	69	70
Cb 26	88	72	70	71
Cb 27	56	53	54	56
Cb 28	51	52	51	96
Cb 29	21	70	68	105
Cb 30	34	75	84	86
Cb 31	49	55	45	49
Cb 32	50	56	46	50
Cb 33	35	76	85	87
Cb 34	46	58	48	51
Cb 35	48	59	49	52
Cb 36	76	38	32	36
Cb 37	47	62	61	59
Cb 38	73	42	36	42
Cb 39	71	40	37	40
Cb 40	72	41	38	41

Table E.10 List of PI_V Based Rank of the 112 Circuit Breaker Contingencies from Cb 41 to Cb 80 Under Different Loading Scenarios

Circuit breaker name	PI_V based rank			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Cb 41	59	43	103	44
Cb 42	60	44	104	45
Cb 43	61	45	105	46
Cb 44	62	46	106	47
Cb 45	108	5	5	4
Cb 46	109	6	6	5
Cb 47	111	3	3	3
Cb 48	110	4	4	6
Cb 49	70	15	23	19
Cb 50	69	17	24	20
Cb 51	101	26	28	26
Cb 52	85	108	75	101
Cb 53	25	109	82	103
Cb 54	84	107	76	102
Cb 55	15	99	93	82
Cb 56	16	100	94	83
Cb 57	65	49	42	38
Cb 58	11	106	108	104
Cb 59	7	111	55	111
Cb 60	66	50	43	39
Cb 61	81	35	35	32
Cb 62	93	48	52	53
Cb 63	98	12	27	8
Cb 64	75	94	7	15
Cb 65	10	105	47	110
Cb 66	38	84	79	75
Cb 67	36	86	80	76
Cb 68	30	82	87	90
Cb 69	39	79	110	77
Cb 70	37	81	78	74
Cb 71	33	78	86	88
Cb 72	40	80	111	78
Cb 73	6	110	50	109
Cb 74	5	112	57	112
Cb 75	12	34	44	54
Cb 76	29	93	74	63
Cb 77	31	83	88	91
Cb 78	45	60	62	62
Cb 79	58	47	107	48
Cb 80	79	85	72	68

Table E.11 List of PI_V Based Rank of the 112 Circuit Breaker Contingencies from Cb 81 to Cb 112 Under Different Loading Scenarios

Circuit breaker name	PI_V based rank			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Cb 81	20	69	65	64
Cb 82	14	97	98	98
Cb 83	90	61	63	60
Cb 84	28	65	59	58
Cb 85	18	77	77	69
Cb 86	43	66	64	61
Cb 87	42	63	58	57
Cb 88	19	92	81	79
Cb 89	67	39	41	37
Cb 90	83	68	73	67
Cb 91	52	51	53	55
Cb 92	44	64	66	65
Cb 93	24	67	97	97
Cb 94	17	90	100	106
Cb 95	91	18	18	17
Cb 96	64	32	30	30
Cb 97	80	19	20	22
Cb 98	54	33	34	33
Cb 99	68	23	26	24
Cb 100	102	27	19	25
Cb 101	103	22	15	18
Cb 102	74	30	22	27
Cb 103	100	14	12	10
Cb 104	99	13	11	9
Cb 105	94	16	13	11
Cb 106	106	9	8	13
Cb 107	3	1	1	1
Cb 108	92	31	33	35
Cb 109	57	2	2	2
Cb 110	82	25	31	34
Cb 111	63	29	40	43
Cb 112	32	74	83	85

Table E.12 List of PI_F Based Rank of the 112 Circuit Breaker Contingencies from Cb 1 to Cb 40 Under Different Loading Scenarios

Circuit breaker name	PI_F based rank			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Cb 1	18	32	36	88
Cb 2	86	92	86	23
Cb 3	72	74	82	33
Cb 4	82	89	6	20
Cb 5	92	93	90	18
Cb 6	30	5	20	98
Cb 7	31	26	30	102
Cb 8	40	37	42	92
Cb 9	95	13	7	14
Cb 10	10	8	21	95
Cb 11	14	27	34	99
Cb 12	15	28	35	100
Cb 13	50	46	65	28
Cb 14	69	60	75	32
Cb 15	80	73	80	27
Cb 16	73	69	62	67
Cb 17	87	94	83	78
Cb 18	106	105	101	35
Cb 19	94	96	102	56
Cb 20	37	24	32	80
Cb 21	35	33	37	89
Cb 22	36	34	38	90
Cb 23	38	25	33	81
Cb 24	79	83	81	91
Cb 25	74	70	63	68
Cb 26	75	71	64	69
Cb 27	88	95	85	54
Cb 28	85	16	89	96
Cb 29	34	14	61	106
Cb 30	44	41	49	82
Cb 31	70	84	3	8
Cb 32	71	85	2	7
Cb 33	45	42	50	83
Cb 34	66	81	5	10
Cb 35	67	82	4	9
Cb 36	84	80	57	36
Cb 37	57	68	79	57
Cb 38	58	49	25	40
Cb 39	59	50	26	41
Cb 40	60	51	27	42

Table E.13 List of PI_F Based Rank of the 112 Circuit Breaker Contingencies from Cb 41 to Cb 80 Under Different Loading Scenarios

Circuit breaker name	PI_F based rank			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Cb 41	61	75	10	46
Cb 42	62	76	11	47
Cb 43	63	77	12	48
Cb 44	64	78	13	49
Cb 45	103	106	95	4
Cb 46	104	107	96	5
Cb 47	107	109	94	3
Cb 48	105	108	97	6
Cb 49	81	90	92	17
Cb 50	83	91	93	16
Cb 51	54	59	72	22
Cb 52	13	21	78	103
Cb 53	11	20	74	105
Cb 54	12	22	77	104
Cb 55	101	103	110	93
Cb 56	102	104	111	94
Cb 57	110	110	103	44
Cb 58	6	4	1	108
Cb 59	3	3	18	111
Cb 60	111	111	104	45
Cb 61	112	112	98	37
Cb 62	96	97	112	52
Cb 63	97	99	8	12
Cb 64	5	17	84	21
Cb 65	4	15	22	110
Cb 66	56	67	58	72
Cb 67	55	65	56	76
Cb 68	41	38	43	86
Cb 69	52	62	15	73
Cb 70	51	61	53	75
Cb 71	43	40	46	85
Cb 72	53	63	16	74
Cb 73	1	1	9	109
Cb 74	2	2	17	112
Cb 75	28	19	24	63
Cb 76	29	18	23	62
Cb 77	42	39	44	87
Cb 78	109	58	68	61
Cb 79	65	79	14	50
Cb 80	24	36	52	71

Table E.14 List of PI_F Based Rank of the 112 Circuit Breaker Contingencies from Cb 81 to Cb 112 Under Different Loading Scenarios

Circuit breaker name	PI_F based rank			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Cb 81	17	45	60	64
Cb 82	7	12	29	101
Cb 83	26	57	67	59
Cb 84	20	53	69	58
Cb 85	9	11	47	77
Cb 86	22	54	66	60
Cb 87	21	55	70	55
Cb 88	16	31	45	79
Cb 89	78	86	88	39
Cb 90	25	47	51	70
Cb 91	27	72	71	53
Cb 92	23	56	55	66
Cb 93	19	48	31	97
Cb 94	8	9	19	107
Cb 95	33	29	41	24
Cb 96	77	87	87	34
Cb 97	49	44	54	25
Cb 98	47	30	40	38
Cb 99	32	23	28	29
Cb 100	91	88	91	31
Cb 101	108	102	99	26
Cb 102	100	101	100	30
Cb 103	98	98	107	11
Cb 104	99	100	108	13
Cb 105	76	64	76	15
Cb 106	90	6	109	19
Cb 107	93	7	105	1
Cb 108	68	66	73	43
Cb 109	89	10	106	2
Cb 110	48	52	59	51
Cb 111	39	35	39	65
Cb 112	46	43	48	84

Table E.15 List of PI_V and PI_F Based Ranking List of Circuit Breaker Contingencies from Rank 1 to 39 Using the R_F Index

PI_V based		
Rank	Circuit breaker name	R_F
1	Cb 107	78
2	Cb 109	34.079
3	Cb 10	33.632
4	Cb 47	22.631
5	Cb 6	17.124
6	Cb 48	14.967
7	Cb 45	14.956
8	Cb 46	12.303
9	Cb 19	9.056
10	Cb 9	8.652
11	Cb 74	7.345
12	Cb 106	7.137
13	Cb 104	6.580
14	Cb 73	6.297
15	Cb 5	6.294
16	Cb 4	6.203
17	Cb 63	6.175
18	Cb 3	6.041
19	Cb 103	6.032
20	Cb 105	5.494
21	Cb 59	5.474
22	Cb 64	4.801
23	Cb 12	4.787
24	Cb 11	4.335
25	Cb 75	4.335
26	Cb 49	4.193
27	Cb 95	4.167
28	Cb 65	4.127
29	Cb 101	3.979
30	Cb 50	3.907
31	Cb 15	3.784
32	Cb 7	3.750
33	Cb 97	3.715
34	Cb 58	3.634
35	Cb 13	3.476
36	Cb 99	3.268
37	Cb 100	3.144
38	Cb 82	3.043
39	Cb 2	3.042

PI_F based		
Rank	Circuit breaker name	R_F
1	Cb 73	60.118
2	Cb 74	30.223
3	Cb 107	29.088
4	Cb 58	28.981
5	Cb 59	20.503
6	Cb 109	15.531
7	Cb 32	12.830
8	Cb 65	10.917
9	Cb 31	9.561
10	Cb 64	9.463
11	Cb 47	9.052
12	Cb 94	8.031
13	Cb 35	7.825
14	Cb 82	7.631
15	Cb 10	7.498
16	Cb 6	7.205
17	Cb 45	6.985
18	Cb 34	6.709
19	Cb 85	6.626
20	Cb 9	6.485
21	Cb 106	6.005
22	Cb 46	5.728
23	Cb 48	4.888
24	Cb 63	4.801
25	Cb 4	4.767
26	Cb 53	4.718
27	Cb 54	4.348
28	Cb 52	4.190
29	Cb 11	4.036
30	Cb 12	3.829
31	Cb 76	3.669
32	Cb 75	3.600
33	Cb 99	3.587
34	Cb 88	3.563
35	Cb 1	3.371
36	Cb 95	3.318
37	Cb 29	3.271
38	Cb 81	3.171
39	Cb 41	3.118

Table E.16 List of PI_V and PI_F Based Ranks of Circuit Breaker Contingencies from Rank 40 to 78 Using the R_F Index

PI_V based			PI_F based		
Rank	Circuit breaker name	R_F	Rank	Circuit breaker name	R_F
40	Cb 14	2.979	40	Cb 93	3.064
41	Cb 102	2.978	41	Cb 103	3.023
42	Cb 55	2.940	42	Cb 42	2.939
43	Cb 51	2.857	43	Cb 7	2.838
44	Cb 56	2.795	44	Cb 84	2.799
45	Cb 85	2.741	45	Cb 43	2.786
46	Cb 18	2.723	46	Cb 20	2.777
47	Cb 96	2.697	47	Cb 80	2.748
48	Cb 110	2.686	48	Cb 87	2.723
49	Cb 81	2.664	49	Cb 105	2.715
50	Cb 98	2.626	50	Cb 23	2.692
51	Cb 94	2.625	51	Cb 104	2.664
52	Cb 88	2.535	52	Cb 44	2.654
53	Cb 29	2.417	53	Cb 86	2.637
54	Cb 108	2.395	54	Cb 98	2.618
55	Cb 111	2.392	55	Cb 92	2.569
56	Cb 61	2.389	56	Cb 97	2.556
57	Cb 36	2.318	57	Cb 90	2.542
58	Cb 84	2.282	58	Cb 79	2.538
59	Cb 21	2.245	59	Cb 69	2.514
60	Cb 89	2.224	60	Cb 21	2.441
61	Cb 93	2.181	61	Cb 72	2.420
62	Cb 39	2.174	62	Cb 50	2.418
63	Cb 22	2.171	63	Cb 51	2.407
64	Cb 40	2.125	64	Cb 28	2.402
65	Cb 38	2.115	65	Cb 83	2.385
66	Cb 57	2.081	66	Cb 38	2.384
67	Cb 60	2.036	67	Cb 111	2.381
68	Cb 76	2.033	68	Cb 22	2.377
69	Cb 1	2.028	69	Cb 13	2.358
70	Cb 31	2.016	70	Cb 49	2.341
71	Cb 53	1.999	71	Cb 39	2.323
72	Cb 34	1.993	72	Cb 91	2.281
73	Cb 32	1.976	73	Cb 40	2.265
74	Cb 8	1.948	74	Cb 5	2.205
75	Cb 35	1.939	75	Cb 8	2.177
76	Cb 87	1.914	76	Cb 68	2.149
77	Cb 91	1.900	77	Cb 77	2.100
78	Cb 68	1.878	78	Cb 71	2.056

Table E.17 List of PI_V and PI_F Based Ranks of Circuit Breaker Contingencies from Rank 79 to 112 Using the R_F Index

PI_V based		
Rank	Circuit breaker name	R_F
79	Cb 41	1.874
80	Cb 112	1.868
81	Cb 42	1.837
82	Cb 77	1.834
83	Cb 78	1.827
84	Cb 27	1.822
85	Cb 86	1.822
86	Cb 37	1.808
87	Cb 43	1.802
88	Cb 71	1.802
89	Cb 30	1.797
90	Cb 92	1.783
91	Cb 79	1.781
92	Cb 44	1.768
93	Cb 33	1.759
94	Cb 70	1.756
95	Cb 67	1.749
96	Cb 28	1.722
97	Cb 66	1.715
98	Cb 17	1.709
99	Cb 62	1.674
100	Cb 24	1.642
101	Cb 69	1.642
102	Cb 72	1.611
103	Cb 83	1.463
104	Cb 90	1.371
105	Cb 25	1.335
106	Cb 26	1.317
107	Cb 80	1.316
108	Cb 16	1.300
109	Cb 23	1.183
110	Cb 20	1.169
111	Cb 54	1.095
112	Cb 52	1.094

PI_F based		
Rank	Circuit breaker name	R_F
79	Cb 30	2.012
80	Cb 33	1.970
81	Cb 112	1.951
82	Cb 110	1.947
83	Cb 2	1.940
84	Cb 14	1.903
85	Cb 15	1.893
86	Cb 3	1.761
87	Cb 70	1.711
88	Cb 36	1.698
89	Cb 101	1.684
90	Cb 108	1.678
91	Cb 96	1.647
92	Cb 100	1.640
93	Cb 67	1.617
94	Cb 66	1.603
95	Cb 37	1.600
96	Cb 102	1.581
97	Cb 89	1.548
98	Cb 16	1.462
99	Cb 25	1.441
100	Cb 18	1.432
101	Cb 26	1.420
102	Cb 78	1.394
103	Cb 61	1.367
104	Cb 27	1.301
105	Cb 57	1.261
106	Cb 60	1.242
107	Cb 62	1.234
108	Cb 19	1.225
109	Cb 24	1.204
110	Cb 17	1.171
111	Cb 55	0.993
112	Cb 56	0.983