VOLTAGE INSTABILITY ANALYSIS FOR ELECTRICAL POWER SYSTEM USING VOLTAGE STABILITY INDEX

AMAR HAKIMI BIN BAHAR

B.ENG (HONS.) ELECTRICAL ENGINEERING (POWER SYSTEM)

UNIVERSITI MALAYSIA PAHANG

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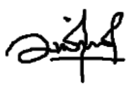

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SENIOR LECTURER
DEPARTMENT OF ELECTRICAL ENGINEERING
COLLEGE OF ENGINEERING
UNIVERSITI MALAYSIA PAHANG
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AMAR HAKIMI BIN BAHAR

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ABSTRAK

Peningkatan fenomena ketidakstabilan voltan sejak beberapa dekad yang lalu sehingga sekarang amat membimbangkan. Peningkatan permintaan kuasa dan kekurangan sumber kuasa telah menyebabkan sistem untuk beroperasi pada kapasiti maksimumnya. Apabila sistem bekerja pada hadnya, situasi ini akan membawa kepada masalah kestabilan voltan seperti voltan runtuh. Oleh itu, mengenal pasti kawasan lemah kestabilan voltan adalah penting bagi mengelak voltan runtuh. Kertas ini akan membentangkan kajian mengenai analisis ketidakstabilan voltan dengan menggunakan indeks yang telah dibangunkan sebelumnya iaitu indeks kestabilan voltan pantas (FVSI) sebagai indeks utama. Indeks kestabilan garis (Lmn) juga digunakan untuk menentukan kejadian ketidakstabilan voltan. Analisi ketidakstabilan voltan boleh ditentukan dengan banyak cara. Salah satunya dengan meningkatkan beban pada bas terpilih. Beban akan di naikkan sehingga bas tersebut mencapai tahap kebolehmuatan yang maksimum. Pada saat ini, sistem akan mengalami penurunan voltan secara tiba-tiba dalam waktu yang sama bacaan index akan mencapai kepada 1 dan sistem dianggap akan mengalami voltan runtuh. Dalam kertas kajian ini juga, putusan garisan akan dilakukan untuk melihat nilai voltan dan nilai indeks FVSI. Putusan garisan akan mempengaruhi keadaan kestabilan voltan. Kedua-dua analisis ini akan dikaji pada data bas sistem IEEE-30 dan data bas sistem IEEE-69 dan projek ini dijalankan sepenuhnya di perisian MATLAB.

ABSTRACT

The rise of voltage instability phenomena from the past few decades until now is worrying. The increases of power demand and limited power sources make the system to operate at its maximum limit of capacity. When the system is working at its limit, this situation can lead to voltage stability problems such as voltage collapse. Hence, it is important to identify the voltage stability weak areas to avoid the voltage collapse. This paper will present the study of voltage instability analysis using pre-developed voltage stability index, Fast Voltage Stability Index (FVSI) as the main index. The Line Stability Index (Lmn) is also will be use to determine voltage instability activity. Voltage instability analysis can be done with many ways. One of it by increase the load at selected bus. The loading will be injected until the bus reach its maximum loadability. At this point, the system will experience a sudden voltage drop as the index reaching to 1 and the system is now considered as voltage collapse. In this paper, the line outage will be carrying out to observe the voltage and Fast Voltage Stability Index values. The line outage most likely will affect the voltage condition of the system. Both of analysis will be test on IEEE-30 bus system and IEEE-69 bus system and this project will fully work on MATLAB software.

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LIST OF SYMBOLS

r_{ij}	Line reactance
P_G	Injected real power from the system
V_j	Target value for index calculation
V_i	Sending End Voltage
P_i	Sending End Real Power
Q_i	Receiving End Reactive Power
V_1	Voltage at sending bus
V_2	Voltage at receiving bus
P_1	Active power at sending bus
P_2	Active power at receiving bus
Q_1	Reactive power at sending bus
Q_2	Reactive power at receiving bus
Z_l	Line Impedance
X_l	Line Resistance
S_1	Apparent power at sending bus
S_2	Apparent power at receiving bus

$\boldsymbol{\delta_1}$ Angle at sending bus

$\boldsymbol{\delta_2}$ Angle at receiving bus

$\boldsymbol{\delta}$ $\delta = \delta_1 - \delta_2$

Angle difference.

$\boldsymbol{V_s}$ Voltage Sending

$\boldsymbol{Q_r}$ Less receiving end power

LIST OF ABBREVIATIONS

FVSI	Fast Voltage Stability Index
Lmn	Line Stability Index
PV	Real Power-Voltage
QV	Reactive Power-Voltage
VSM	Voltage Stability Margin
FACTS	Flexible Alternating Current Transmission System
PSI	Power Stability Index
VDI	Voltage Derivation Index
LQP	Line Stability Factor
NSLI	Novel Line Stability Index

CHAPTER 1

INTRODUCTION

1.1 Project Background

Voltage stability is an ability for the voltage to maintain at its equilibrium state at normal condition and to regain equilibrium of voltage condition after a disturbance. Voltage instability is a stability problem that may manifest under heavy loading conditions. In certain cases, the instability can occur when the uncontrolled system voltage is damaged over a large size of power system network and fails to maintain the voltage at the buses in the system. Voltage instability has become a big concern in the electrical power systems because of being one of the reasons for power blackouts. There are many factors that can lead to voltage instability. One of it because of the increasing global electricity demand each year with a few factors that contribute at rising demand, for example the increase of world population. The world population increase from 5.3 billion in 1990 to 7.9 billion in 2021 which mean the population is increase by 50% for the past 30 years. The world's electricity consumption increased by 125% from 1990 to 2018 shows the power demand increase as the population growth increase. With insufficient power supply, voltage instability might occur. Thus, it is important to tackle this issue. In order to stop or avoid voltage instability, voltage instability analysis is a must. From the analysis, we know what the causes, and how to prevent voltage instability from occur. One way to determine voltage instability is by using voltage stability index. From the analysis, weak line can be detected. Weak line can contribute to voltage instability due to its less loadbility range. For this project, the voltage instability analysis will be test on IEEE 30 Bus RTS and IEEE 69 Bus RTS test system.

1.2 Problem Statement

- The voltage collapse and line overload can be prevented if we know the loadability of each bus Because of the uncertainty load demand was increase every year, the voltage stability can be happened in the power system. By knowing the limit of the buses, we can improve the power system network.

- There are more than twenty different types of indexes for voltage stability index. Thus, it is important to choose the right and suitable index to analyse the voltage instability.

1.3 Objective

- To determine weak line in the system network when it received an increase load at loaded bus by using pre-develop voltage stability index.

- To monitor the performance of voltage stability index and voltage profile in order to determine congested line.

1.4 Scope of Work

Firstly, this analysis presented the pre-developed voltage stability index, main index is Fast Voltage Stability Index (FVSI) and second index is Line Stability Index (Lmn) to determine the weak line at certain bus. Basically, this study will show the effect of increased loading (Qd) at selected bus. The voltage is expected to be drop after reaching its maximum loadability of the bus. This analysis is tested on IEEE 30-Bus Reliability Test System (RTS) and IEEE 69-Bus Reliability Test System (RTS). The effect of increased loading on selected bus was investigated.

Secondly, an analysis to observe the behaviour of the voltage and (FVSI) before and after the system experience contingencies which is line outages. This analysis is also tested on IEEE 30-Bus Reliability Test System and IEEE 69-Bus Reliability Test System.

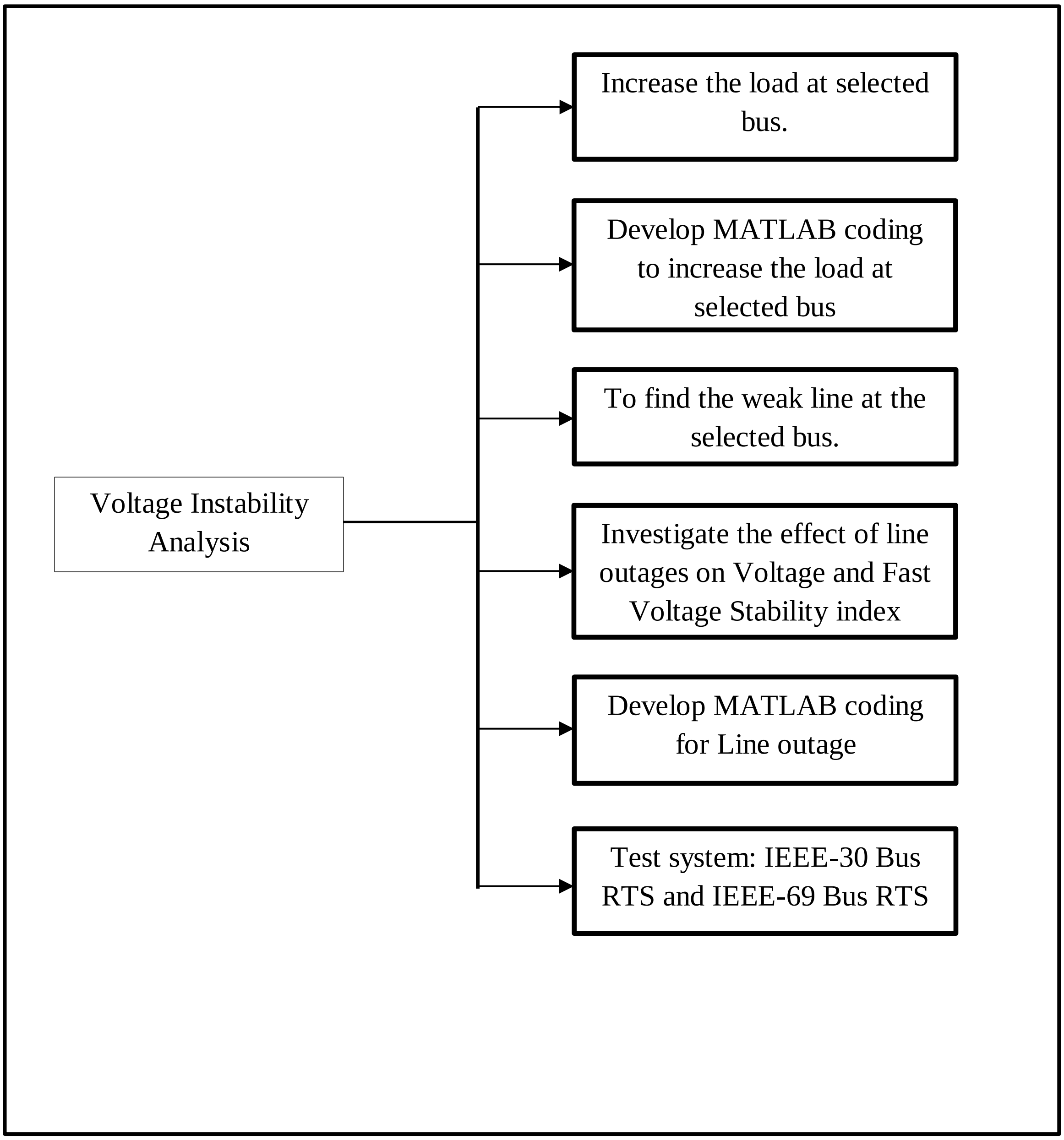

Figure 1.4: Overall Research Framework of Voltage Instability Analysis

1.5 Thesis Outline

This thesis is divided into five different chapter. The background of the subject of this thesis is presented in Chapter one. Subsequently, the concerned associated with the subject are clarified briefly. The priorities of the analysis are outline based on the problem statement. Firsts, to provide an outline of this whole project, the scale of the work is presented.

Chapter two presents the literature review of the related studies of this research. All important aspects such as voltage instability definition, cause of voltage instability, voltage stability index definition and type of voltage stability index will report in details under this chapter.

Chapter three will explain on the methodology to investigate the voltage instability analysis by using voltage stability index as indicator. This chapter will demonstrate how to include this methodology in both test system, IEEE 30 bus RTS and IEEE 69 Bus RTS. In this chapter also introduce the cases study for this project.

Chapter four will summaries all of the data and analysis perform during the analysis. The entire set of result was documented, displayed and discussed in further details in this chapter.

Lastly, chapter five will summarize all of the study findings, conclusion and recommendation for future research to establish a more practical approach to this endeavour.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter presents a literature analysis of prior articles on related works and covers both paper works and related research. This chapter start with understand what is the power system and how it works before continue to the explaining the voltage instability. Voltage instability analysis is very common now adays due to increases of voltage stability problem. This chapter also contain the voltage stability index which is an index to determine voltage condition at a certain bus. Voltage stability analysis have a lot of way to be determine. Voltage stability index is one of them. Another way we can use to determine voltage instability are by using PV-QV curve or Voltage Stability Margin (VSM) and Modal Analysis.

2.2 Introduction to Power System.

Power system is a network that provide the electricity from the source to the consumer. There are few components in the power system which is main component and support component. As seen in figure 2.2.1, the main component consists of generation, transmission, distribution and load while the support component consists of measuring & monitoring system and protection system [1]. The provided electrical power from producing stations to the loads is borne by the long transmission lines. A stable power system without any problem can provide the customers with efficient, optimized electricity and sufficient power.

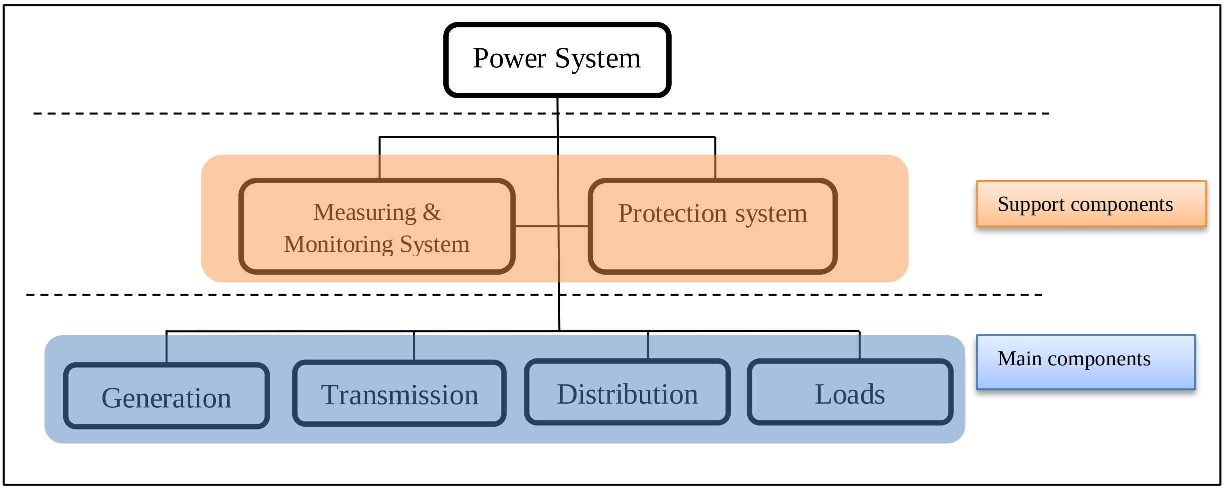

Figure 2.2.1: Component of Electrical Power System.

Figure 2.2.2 shows the elements of the electrical power structure. The power plant will produce and generate the power source and then the transformer will step-up and step-down for transmission. The transmission line will transfer the power to the substations before the power going to distribution transformer for step-down the power. The step-down power will reach to the consumer with appropriate value of power that suitable to the need of the customers.

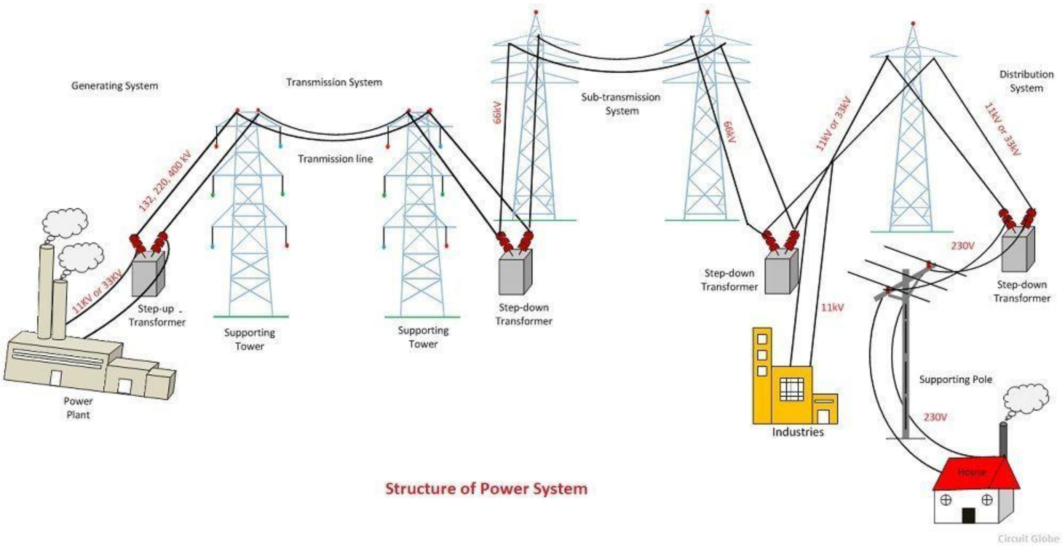

Figure 2.2.2: Structure of Power System[2].

The evolution of power grid interconnection for the past few decades makes the power system to becoming bigger and more complex. A large power grid obviously have more advantages but it also experience some hidden problem like disturbance in power system effecting the whole system behaviour which can lead to system collapse and blackout if cannot be handled correctly[3].

It is important for a power system network to maintain its fundamental requirement to ensure the electricity supply to the customers without problems. A voltage magnitude range in a power system must be in the specific range at each bus. Reactive power and voltage magnitude are interplay thing since the desired voltage profile can be maintain by receiving a support from reactive power. Too high and too low voltages can lead Electrical Power system losses, overheating of the equipment such as motor and voltage collapse [4]. If this condition is not treated correctly, it will lead a huge catastrophe to the system.

2.3 Voltage Instability

The development of complex interconnection in transmission in power system and the increase of load demand has force the grid to operate close to the limit of its stability range. Operating in the range of stability limit is very dangerous and need to constantly monitor the voltage stability to avoid voltage collapse which can result in blackout event in power system [5]. The power transfer in a transmission network is closely related to voltage drops between the generation and consumption points. Usually, in steady state operating condition, the voltage drop is in the range of a few percent of nominal voltage and it is important for an operator and power system planner to maintain the system below heavy stress conditions.

Voltage instability is recognized as a big treat in the system operation as big as thermal overload and angle instability. The producing of new transmission and power generation is getting more difficult and often delayed due to the complexity of the system to build. As the increase number of building of remote power plant and increase of electrical distance between generation and load and yet the number of voltage control point remain the same is also a factor that will contribute to voltage instability. In order to support voltage profile to give larger power transfer, the heavy using of shunt compensation is needed but this will closing the gap between instability point to normal values[6].

Voltage instability can happen if these few factors and characteristic is within the condition of the system. Firstly, the high reactive power consumption at heavy load. Secondly, generating station are too far from the load centres. Next, difference in transmission of reactive power under heavy loads and also due to improper location of Flexible Alternating Current Transmission System (FACTS) controller in the system network. Lastly, the poor coordination between multiple Flexible Alternating Current Transmission System (FACTS) controller itself that will lead to voltage instability.

Voltage instability can result in loss of load in area, transmission line tripping and the worst part to have voltage collapse within the system. Basically, voltage instability can be prevent by a specific placement of FACTS controller, the co-ordination of multiple FACTS controllers, Installation of synchronous condenser and the placement of series and shunt [7].

Working on voltage stability analysis on the system also can help to prevent the system from voltage instability. Voltage stability analysis can be categories into two which is dynamic and static. The static voltage analysis is fixed because it is conducted by assuming the system operating in stable condition and usually the analysis is done by researcher to learn the behaviour of the voltage instability by simulation while dynamic voltage analysis is based on real time condition and it deal with non-linear load which is hard to model them compare to static voltage analysis [8].

Voltage instability analysis for this research is in the static category because the analysis will be carryout through simulation on MATLAB software. Voltage instability can be determined by using voltage stability index.

2.4 Voltage Stability Index

Voltage stability index is a function to situate the current operation of the power system and predict the nature of the system. Voltage stability index also help to evaluate a long-term development trend within pre-defined condition. Sayed Shah Danish classified voltage stability index into 2 categories in his research [9].

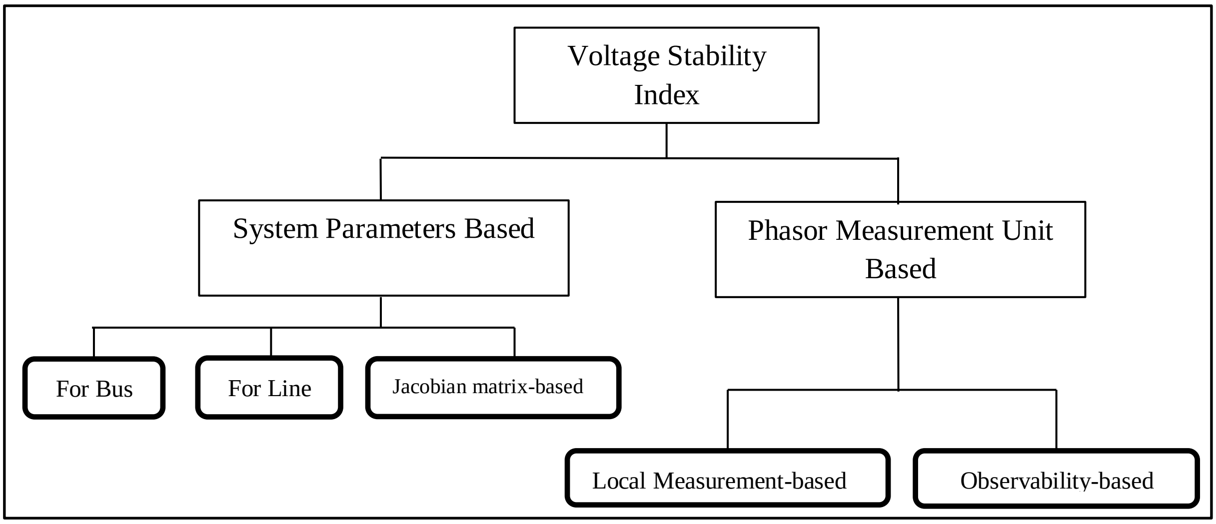

Figure 2.4.1: A classification of Voltage Stability Index.

Based on the figure 2.4.1, voltage stability index is classified into two categories; i) System Parameter Based and ii) Phasor Measurement Unit based. System parameter based have three different indexes for three different conditions. The first index for bus which is the index is more suitable to use on bus contingency while doing analysis of voltage stability. For line, it is an index that more suitable to analyse voltage stability with line problem and lastly Jacobian matrix based is an index that analyse the voltage stability using Jacobian matrix. Phasor Measurement Unit based have two class-based which is local measurement based and observability based.

Example of index's formula from each type of voltage stability index type;

- For Bus type:

Power Stability Index (PSI)

$$PSI = \frac{4r_{ij}(P_L - P_G)}{[\ |V_i|cos(\theta - \delta)]^2} \leq 1 \quad (1)$$

Where r_{ij} is the line resistances, P_L is the real power at load bus, P_G is the injected real power from the system. According to M. Aman, the PSI is proposed for the optimum placement of the Distributed Generation (DG) at the critical sensitive bus close to voltage collapse. PSI is proposed based on a 2-bus system that have less than the unity margin for a stable operation of voltage[10].

Voltage Deviation Index (VDI)

$$\mathrm{VDI_j} = |1 - \mathrm{V_j}| \quad (2)$$

$$VDI_T = \sum_{j=1}^{N} |1 - V_j| \quad (3)$$

Where N is number of buses under study and Vj is the target value for index calculation. Voltage Deviation Index (VDI) is defined as an absolute value for bus voltage deviation compared to 1 per unit (p.u). The index is generalized in terms of an N-bus system based on the sum of N voltage deviations. Equation (2) was calculated separately for each bus in all systems and generalized in equation (3)[11].

- For line type:

Line Stability Factor (LQP)

$$LQP = 4\left(\frac{X}{V_i^2}\right)\left(\frac{X}{V_i^2}P_i^2 + Q_j\right) \quad (4)$$

Where; Vi is the sending end voltage, Pi is the sending end real, Qi is the receiving end reactive power, X is line reactance. Line Stability Factor (LQP) is an index that proposed based on the equation of power flow in single line network and the highest index for Line Stability Factor (LQP) is 1 that indicate the voltage system is already instable.

Novel Line Stability Index (NLSI)

$$NLSI_{ij} = \frac{R_{ij}P_j + X_{ij}Q_j}{0.25V_i^2} \quad 5$$

Where Vi is the voltage sending bus, Pj is active power at the receiving end bus and Qj is the reactive power at the receiving end bus, Rij and Xij are the line resistance and line reactance between sending and receiving end buses respectively. The Novel Line Stability Index (NLSI) in Equation (5) is a derivation formula from load flow of 2-bus equation. Yazdanpanah claimed that it is effective for determined point of voltage collapse, weak bus, and critical line identification in interconnected system [12]. NLSI also indicate 1 as the index of voltage instability of the system.

Aside from voltage stability index, voltage instability analysis also can be carryout using Voltage Stability Margin (VSM) and modal analysis. Voltage Stability Margin (VSM) consist of two main components which are Real power-voltage (PV) and Reactive power-voltage (QV). VSM can be determined by obtained both Real power-Voltage (PV) curve and Reactive power-Voltage (QV) that had been generated from a series of power flow. The load at the system is increased at each iteration until it reached the maximum limit of the system when the system not able to run the power flow anymore. The PV and QV values is plotted with the increased load value to show the margin between PV and QV curve. Figure 2.4.2 shows how the result of PV and QV will be and how to determine the margin [13].

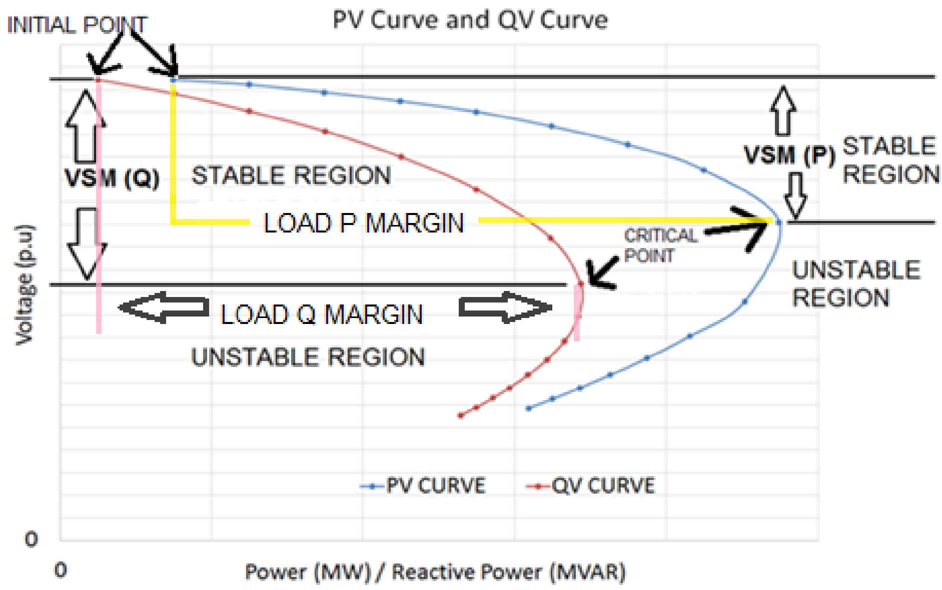

Figure 2.4.2: The PV curve and QV curve.

$$VSM = \frac{V_{initial} - V_{critical}}{V_{critical}} \qquad 6$$

Voltage Stability Margin also can be determine using the above Equation (6). V initial is voltage of bus during normal operating condition and V critical is the voltage of bus at voltage collapse point. Voltage Stability Margin is suitable to apply for small power system only because it got to take a lot of time if VSM is apply on large power system. Modal analysis in other hand is suitable for large power system.

Modal analysis is a method that computes the smallest eigenvalue and associated eigenvector of the reduced Jacobian matrix of the power system based on stable state or steady state system model. The eigenvalues are associated with a mode of voltage and reactive power variation. The system will be considered as stable for the voltage if the eigenvalues are positive while the system will be considered as unstable if the eigenvalues is negative. If the eigenvalue is zero, that value indicate that the system is on the borderline of voltage instability. The potential voltage collapse situation of a stable system is predicted by evaluate the minimum positive value of eigenvalues. The magnitude of every minimum eigenvalue can give a measure to show how close the system from voltage collapse moment. The weakest bus is determined by using bus participation factor in order to prevent the voltage collapse situation.

2.5 Summary

The introduction to power system are explained detail in this chapter. Next, the definition of voltage instability and what cause the system to experience voltage instability is presented. Lastly, the voltage stability index, voltage stability margin and modal analysis is also been review in this chapter including its formula.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter will address the Voltage Stability Index that will be used for voltage instability analysis. Two selected indexes from Voltage Stability Index will be use in the project. The selected index will be explained in details in this chapter including the flowchart and formula derivation. In this study, there will be four case study to be carryout for voltage instability analysis. These four cases study will be test on IEEE 30 Bus Reliability Test System (RTS) and IEEE 69 Bus Reliability Test System. Lastly, this chapter will discuss the implementation of MATLAB software and coding.

3.2 Voltage Stability Index

In previous chapter, the voltage stability index is already explained but for this chapter, the chosen index of Voltage Stability Index will be explained and how it will be used in this project. To carry out the voltage instability analysis, Fast Voltage Stability Index (FVSI) is chosen as the main index that to help to detect the instability in the voltage system. FVSI was broadly actualized as a rule concerning voltage stability and checking because its reliance on reactive power instead of real power. The FVSI formula is derived by obtaining the current equation through a line in a 2-bus system.

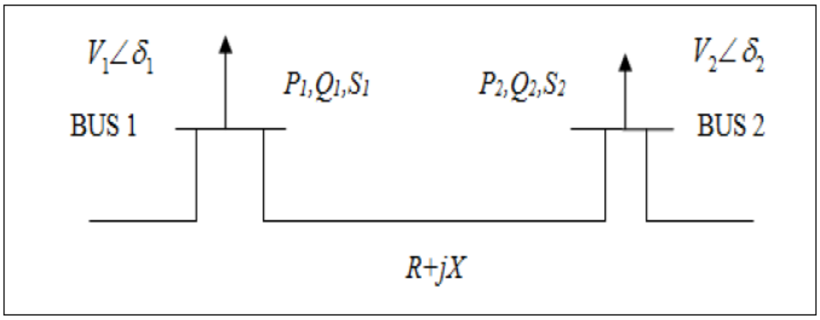

Figure 3.2.1: 2-bus model representation

The line impedance is denoted by $Z = R + jX$ and the current flowing through the line is given by

$$I = \frac{V_1\angle\delta_1 - V_2\angle\delta_2}{R + jX} \quad 7$$

V_1 is taken as the reference; thus, its phase angle is set to zero. The apparent power at bus 2 is written as:

$$S_2 = V_2 I_2^* \quad 8$$

And by rearrange this equation, we get:

$$I = \left(\frac{S_2}{V_2}\right)^* = \frac{P_2 - jQ_2}{V_2\angle - \delta} \quad 9$$

From Equation (8) and (9), we get:

$$\frac{V_1\angle 0 - V_2\angle\theta}{R + jX} = \frac{P_2 - jQ_2}{V_2\angle - \delta} \quad 10$$

$$V_1V_2\angle - \delta - V_2^2\angle 0 = (R + jX)(P_2 - jQ_2) \quad 11$$

Separating the real and imaginary parts yield:

$$V_2^2 - \left(\frac{R}{X}\sin\delta + \cos\delta\right)V_1V_2 + \left(X + \frac{R^2}{X}\right)Q_2 = 0 \quad 12$$

The roots for V_2 will be:

$$V_2 = \frac{\left[\left(\frac{R}{X}\sin\delta + \cos\delta\right)V_1\right]^2 - 4\left(X + \frac{R^2}{X}\right)Q_2}{2} \quad 13$$

To obtain real roots for V2, the discriminant must be more than or equal to zero.

$$\left[\left(\frac{R}{X}\sin\delta + \cos\delta\right)V_1\right]^2 - 4\left(X + \frac{R^2}{X}\right)Q_2 \geq 0 \quad (14)$$

$$\frac{4Z^2Q_2X}{V_1^2(R\sin\delta + X\cos\delta)^2} \leq 1 \quad (15)$$

Since δ is normally too small,

$$\delta \approx 0 \rightarrow R\sin\delta \approx 0, \qquad X\ \cos\delta \approx X \quad (16)$$

FVSI final formula:

$$FVSI = \frac{4Z_l^2Q_r}{V_s^2X_l} \quad (17)$$

Symbol	Name	Symbol	Name
$\boldsymbol{V_1}$	Voltage at sending bus	S_1	Apparent power at sending bus
$\boldsymbol{V_2}$	Voltage at receiving bus	S_2	Apparent power at receiving bus
$\boldsymbol{P_1}$	Active power at sending bus	δ_1	Angle at sending bus
$\boldsymbol{P_2}$	Active power at receiving bus	δ_2	Angle at receiving bus
$\boldsymbol{Q_1}$	Reactive power at sending bus	δ	$\delta = \delta_1 - \delta_2$ Angle difference.
$\boldsymbol{Q_2}$	Reactive power at receiving bus	V_s	Voltage Sending
$\boldsymbol{Z_l}$	Line Impedance	Q_r	Less receiving end power

X_l	Line Resistance		

Table 3.2.1: The symbols and its name from 2-bus model and formula

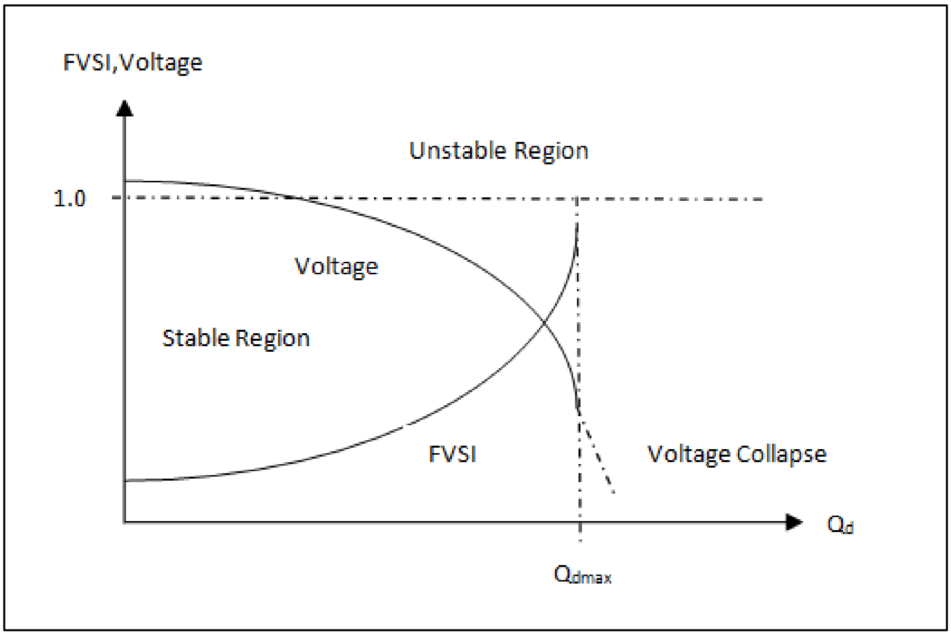

Figure 3.2.2: A graph of FVSI and Voltage Versus Reactive Loading to Determine the Voltage Collapse.

Figure 3.2.2 shows the behaviour of FVSI index and voltage profile with respect to reactive power loading variation. As the reactive power increase, the FVSI values also increase while the voltage value is opposite to FVSI. When the reactive power loading is at the maximum value, the index value of FVSI normally closes to one and the power system voltage going close to Voltage Collapse region.

Two indexes of Voltage stability index will be used to carry out this project, one is Fast Voltage Stability Index (FVSI) and the second index is Line Stability Index (L_{mn}). The purpose of Line Stability Index (L_{mn}) is to determine the point of voltage instability, the weakest bus in the system and the critical line referred to a bus. When the index value closed to unity, it indicate the respective line is closed to entering its instability phase [14]. Mohavemmietal had derived a Line Stability Index based on concept of a power transmission in a single line model. For this project, the Line Stability Index (L_{mn}) formula used is given as:

$$L_{mn} = \frac{4Q_r X}{[|V_s| \sin(\theta - \delta)\ ]} \leq 1.00 \qquad 18$$

Where:

X = Line Reactance, Q_r= Reactive power at the receiving end, V_s= Sending end voltage, θ =Line impedance angle, δ=The angle between the supply voltage and the receiving voltage.

In power system, the voltage will be unstable if the load on the reactive power increase and exceeds the maximum level. Thus, by using pre-developed FVSI and L_{mn} of voltage stability index during voltage instability assessment, we will able to obtain an estimate maximum of the load on the stage before the voltage is not stable. Maximum loadability or known as maximum permissible load is an important point to indicate power system strength. The level of loadability of determine whether a power system network is in safe region or not. The higher the value of the loadability, the more the system can add load to a particular bus load.

3.2.1 Algorithm for Maximum Permissible Load Identification

The identification of weak line at the chosen load buses in a system can be conducted by performing load flow along with the computation of FVSI and Lmn values. The power flow process is conducted repeatedly for various loading conditions at all the chosen loaded bus. The result from load flow allows us to determine the voltage collapse point. The flowchart in Figure 3.2.1.1 and Figure 3.2.1.2 will represent the process of weak line identification as follows:

Fast Voltage Stability Index flowchart:

1. Select the load bus.
2. Set the loading condition at selected load bus.
3. Run the load flow programming using the Newton-Raphson method for the base case.
4. Gradually increase the reactive power loading at the chosen load bus until the FVSI value close to 1.000.
5. Rank top 5 lines with high FVSI values.
6. Choose another load bus and repeat step (1) to (5).
7. Identify Qdmax for every load bus.

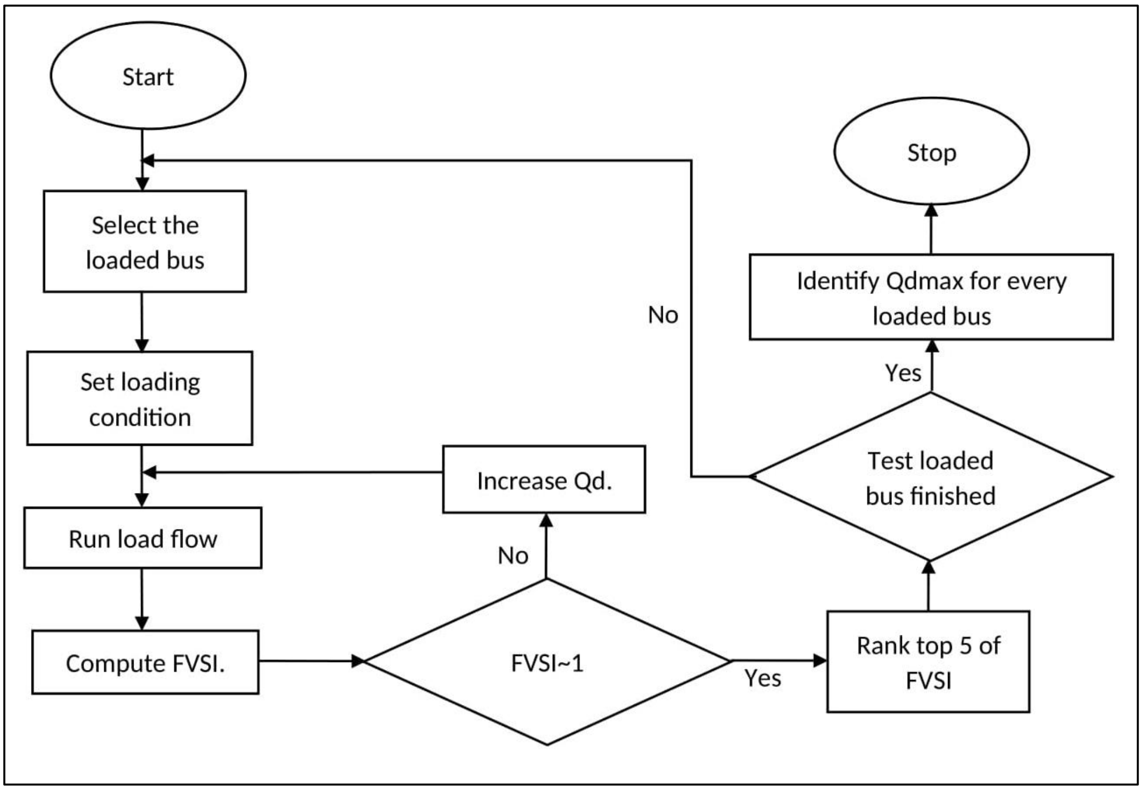

Figure 3.2.1.1: Flowchart for Weak Line Identification using FVSI.

Line Stability Index (Lmn) flowchart:

1. Select the load bus.
2. Set the loading condition at selected load bus.
3. Run the load flow programming using the Newton-Raphson method for the base case.
4. Gradually increase the reactive power loading at the chosen load bus until the Lmn value close to 1.000.
5. Rank top 5 lines with high Lmn values.
6. Choose another load bus and repeat step (1) to (5).
7. Identify Qdmax for every load bus.

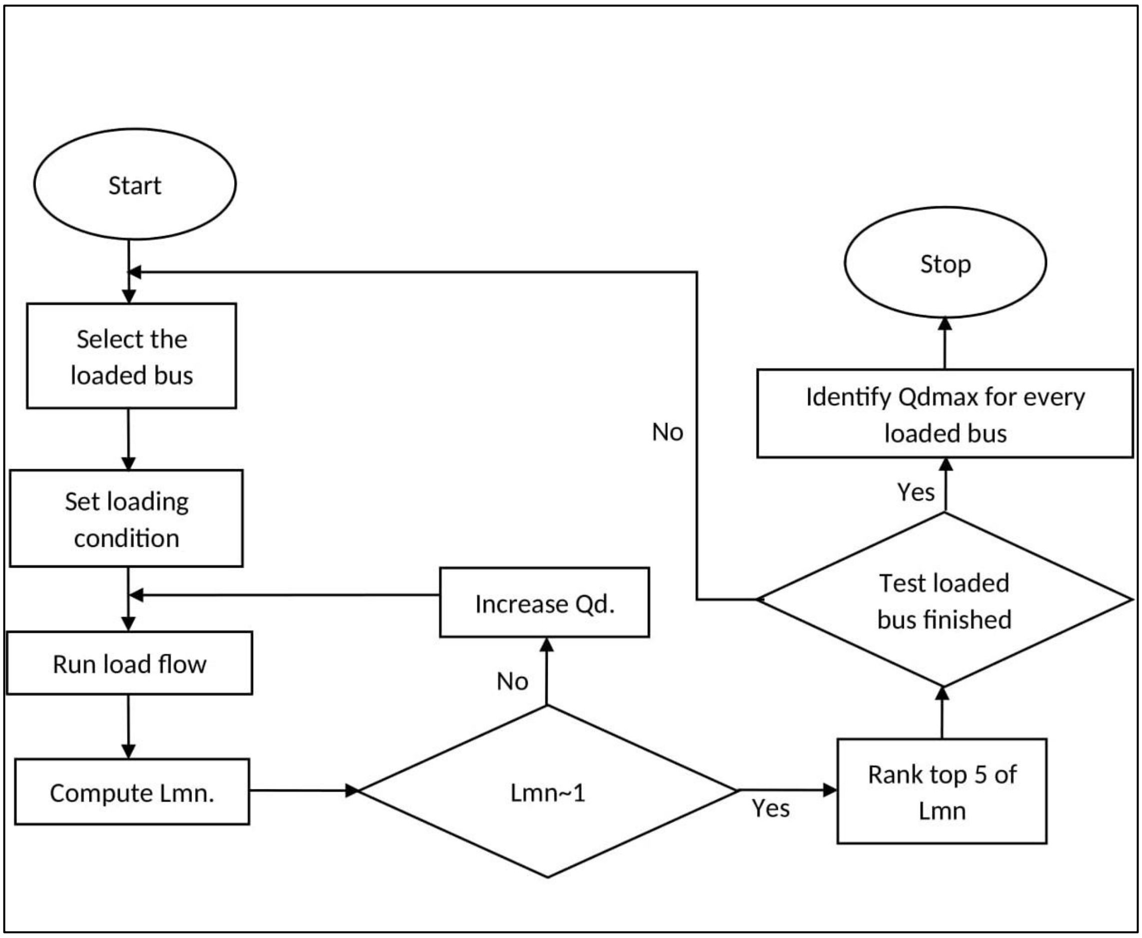

Figure 3.2.1.2: Flowchart for Weak Line Identification using Lmn.

3.3 Cases Study

This project is about voltage instability analysis. Thus, there are a few types of tests that can be run for analysis the data of voltage instability. Voltage instability analysis can be determined through the effect of these contingencies:

Voltage Instability Analysis –

- Increase in loading at the loaded bus
- The action of tap changing transformers to the system.
- Power system loads with recovery dynamics.
- Line tripping or line outages analysis.
- Generator outage analysis[15].

This research will carry out the voltage instability analysis by increase the loading at loaded bus and line outages at the bus line. Thus, this project will have four cases study.

Case Study 1: The analysis of voltage instability by increase the loading at the selected load bus within IEEE 30 Bus Reliability Test System (RTS).

Case Study 2: The analysis of voltage instability by line outage the selected line bus within IEEE 30 Bus Reliability Test System (RTS).

Case Study 3: The analysis of voltage instability by increase the loading at the selected load bus within IEEE 69 Bus Reliability Test System (RTS).

Case Study 4: The analysis of voltage instability by line outage the selected line bus within IEEE 69 Bus Reliability Test System (RTS).

3.4 Test System

For this project, two test systems is chosen to be test for analysis of voltage instability. The first test system is IEEE 30-Bus Reliability Test System (RTS). This system consists of 6 generating units that already labelled as G-1, G-2, G-5, G-8, G-11, and G-13 with 41 transmission line and 30 buses. The data for IEEE 30-Bus Reliability Test System (RTS) available in Appendix 1.

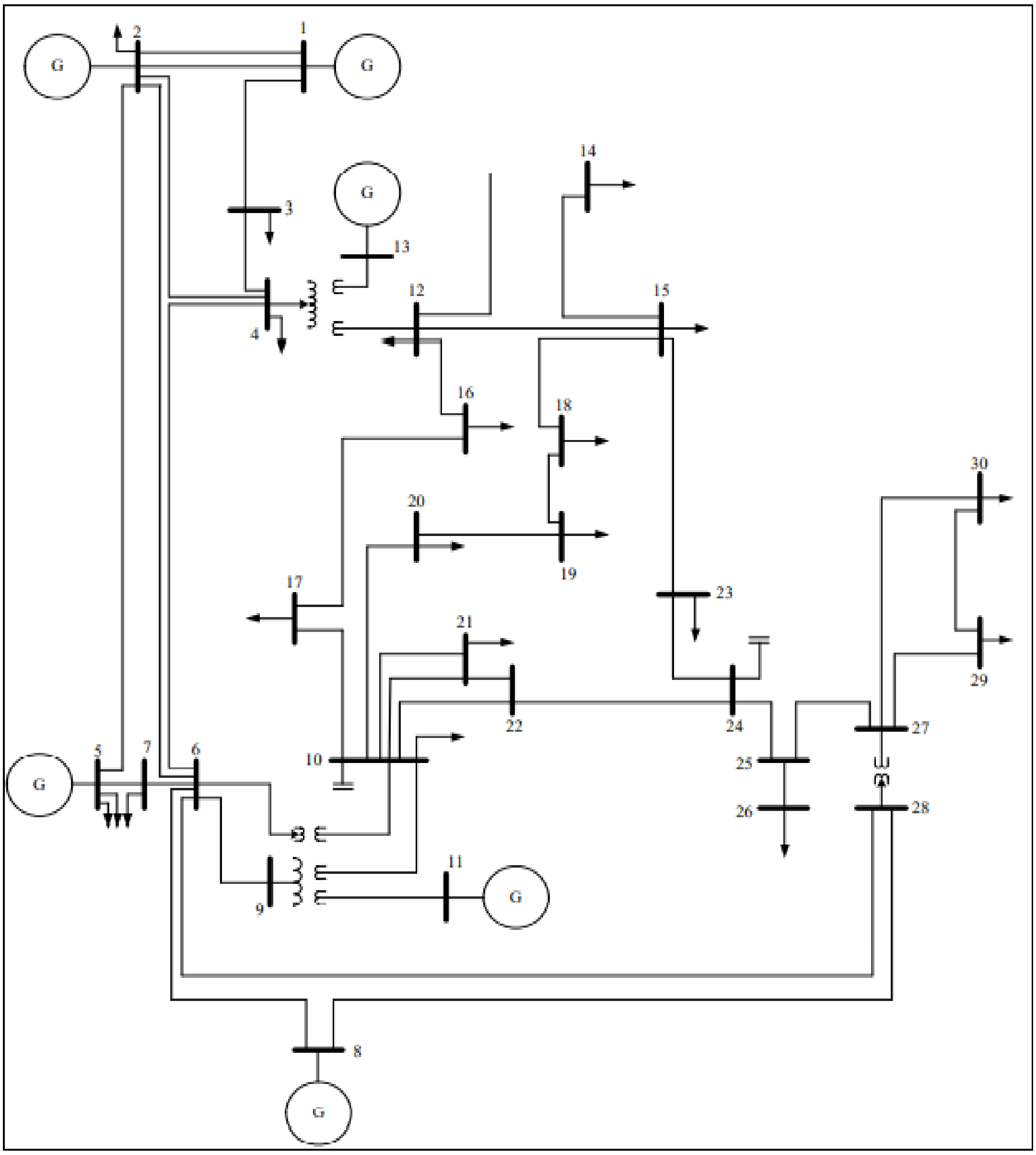

Figure 3.4.1: IEEE 30-Bus Reliability Test System (RTS)

IEEE 69-Bus Reliability Test System (RTS) is the second test bus that will be used in this project. This test system only has one generating unit. This test system also has 69 buses with 68 transmission lines. The data for IEEE 69-Bus Reliability Test System also available in Appendix 1.

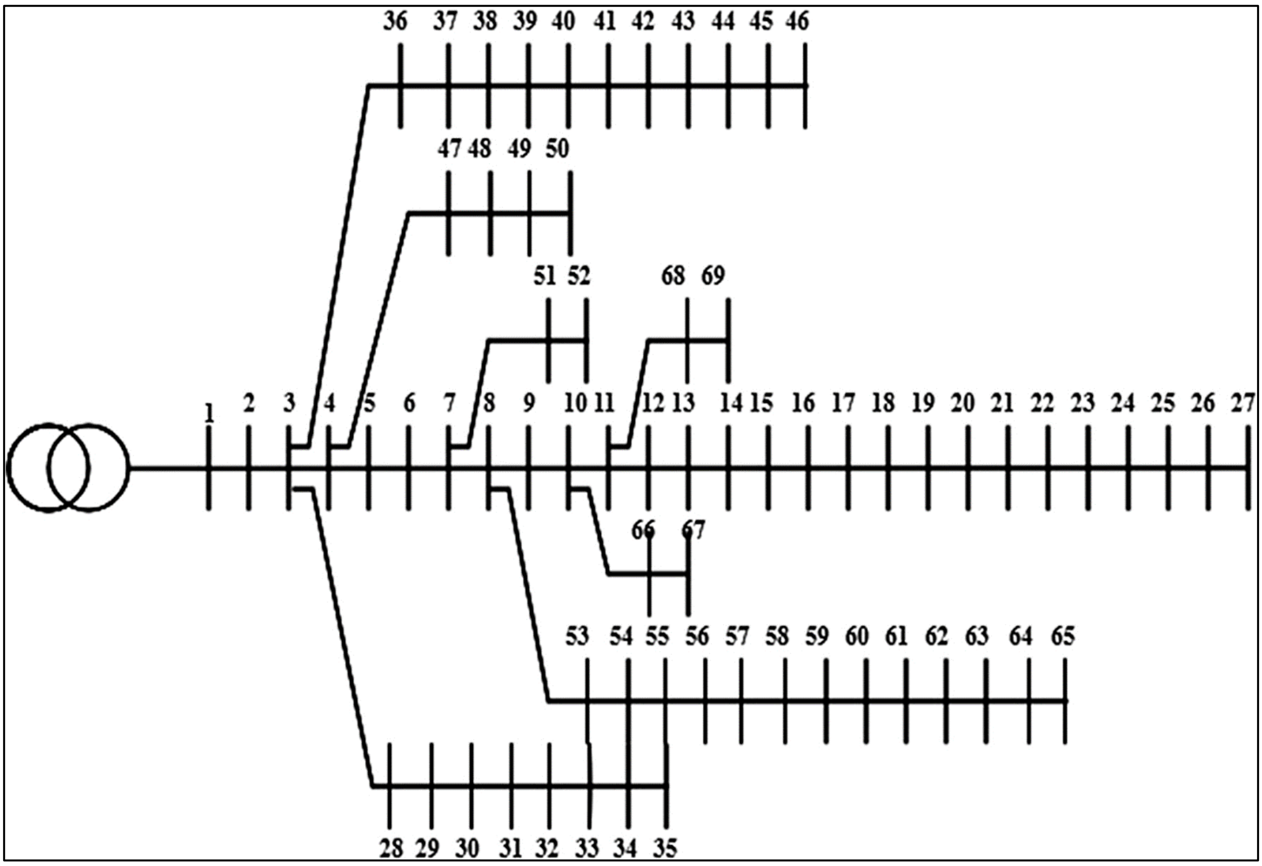

Figure 3.4.2: IEEE 69-Bus Reliability Test System (RTS).

3.5 Coding Software.

The programming codes for this project are developed by using MATLAB R2020a as well as for the simulation purpose. This project consists of three major coding that will be used according to case study. The three major coding are Main_coding, Index_Coding, and Base_coding. For case study 1 and case study 3, Main_coding and Index_Coding will be used while case study 2 and case study 4 are using Base_coding and Index_Coding. Main_coding is a programme to increase the loading at the selected bus load, Base_coding to determine base value of voltage and index and Index_Coding is programme to determine index value for both FVSI and Lmn.

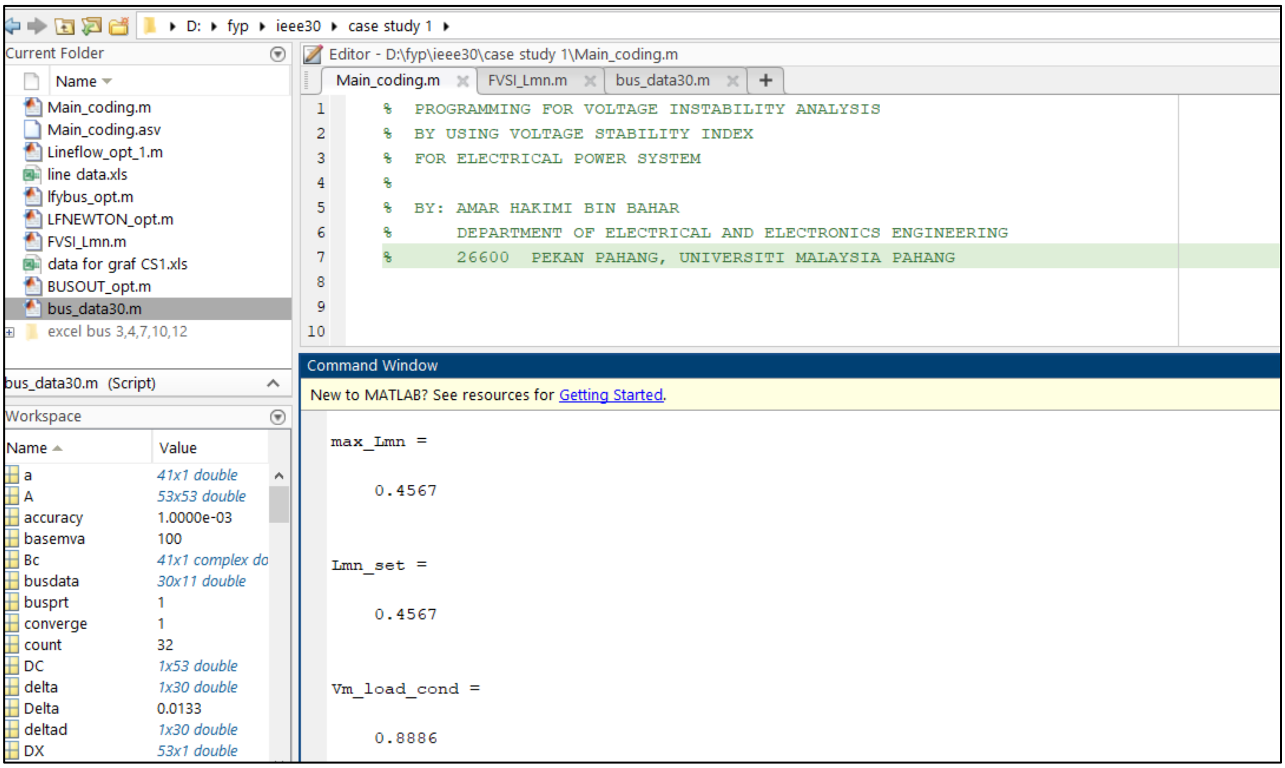

Figure 3.5.1: MATLAB R2020a

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the result, description of data and analysis of data of the voltage instability analysis studies. Here, the result will be present following from case study one until case study four. From the result, we will understand more about voltage instability according to the case study. All the tests will conduct on both IEEE 30 Bus Reliability Test System (RTS) and IEEE 69 Bus Reliability Test System (RTS).

4.2 Case Study 1: The analysis of voltage instability by increase the loading at the selected load bus within IEEE 30 Bus Reliability Test System (RTS).

In this case study, the results are tabulated into table to study the effect of increasing loading at selected bus to the voltage condition and index value. The result will be arranged from raw result to analysis data.

Loading (MVAr)	**FVSI**	**Lmn**	**Voltage (p.u)**
152	0.42418	0.42948	0.90151
153	0.42563	0.43095	0.90080
154	0.42708	0.43242	0.90009
155	0.42853	0.43390	0.89938

156	0.42999	0.43538	0.89867
157	0.43145	0.43687	0.89796
158	0.43292	0.43837	0.89724
159	0.43440	0.43986	0.89652

Table 4.2.1: Result when the loading is increase at bus 3 at IEEE 30 Bus RTS.

Table 4.2.1 is the overall result when the loading is test at bus 3 by increase the loading until the voltage collapse. Next, from the data above, the details analysis about voltage instability will be conducted which is to determine the weak line that connected to tested bus.

Loading, Qd (MVAr)	**Voltage (p.u)**	**Line 2**		**Line 4**	
		FVSI	Lmn	FVSI	Lmn
152	0.9015	0.38619	0.41558	0.21196	0.2197
153	0.9008	0.38832	0.41782	0.21390	0.2217
154	0.9001	0.39045	0.42007	0.21585	0.2237
155	0.8994	0.39257	0.42231	0.21781	0.2237
156	0.8987	0.39469	0.42456	0.21978	0.2258
157	0.8980	0.39682	0.42680	0.22176	0.2279

Table 4.2.2: The result of weak line at bus 3 at IEEE 30 Bus RTS.

Table 4.2.2 shows the result of voltage instability analysis in order to determine weak line at bus 3. From the result, shows that as the loading (Qd) is increase, the voltage value become decrease. For bus 3, the maximum loadability (Qdmax) or the maximum permissible load that this bus can carry is 154 MVAr. This is due to the result of voltage value, 0.9001, indicate the minimum value of voltage for the system to be considered in steady state or in a stable condition. Since the test bus is bus 3, the line that connected to bus 3 is line 2 and line 4. Line 2 is a connection from bus 2 to bus 3 while line 4 is a connection from bus 3 to bus 4. Weak line that connected to bus 3 is determined by the value of its index. From both line, line 2 have the highest value for both index Fast Voltage Stability Index (FVSI) and Line Stability Index (Lmn) indicate that line 2 is the weakest line among these two lines.

Loading, Qd (MVAr)	**FVSI**	**Lmn**	**Voltage (p.u)**
195	0.51896	0.52621	0.90090
196	0.52080	0.52808	0.90046
197	0.52264	0.52996	0.90002
198	0.52448	0.53185	0.89958
199	0.52633	0.53373	0.89914
200	0.52819	0.53563	0.89870
201	0.53005	0.53753	0.89826
202	0.53192	0.53943	0.89782

Table 4.2.3: Result when the loading is increase at bus 4 at IEEE 30 Bus RTS.

Table 4.2.3 is the overall result when the loading is test at bus 4 by increase the loading until the voltage collapse. Next, from the data above, the details analysis about voltage instability will be conducted which is to determine the weak line at the bus 4.

Loading,Qd (MVAr)	**Voltage (p.u)**	**Line 3**		**Line 4**		**Line 7**	
		FVSI	Lmn	FVSI	Lmn	FVSI	Lmn
195	0.9009	0.28389	0.29728	0.07869	0.08028	0.25138	0.25903
196	0.9005	0.28545	0.29889	0.07906	0.08065	0.25295	0.26067
197	0.9000	0.28701	0.30050	0.07942	0.08103	0.25452	0.26231
198	0.8996	0.29013	0.30372	0.08016	0.08177	0.25768	0.26581
199	0.8991	0.28857	0.30211	0.07979	0.08139	0.25610	0.26396
200	0.8987	0.29168	0.30533	0.08053	0.08215	0.25927	0.26726

Table 4.2.4: The result of weak line at bus 4 at IEEE 30 Bus RTS.

Table 4.2.4 shows the result of voltage instability analysis in order to determine weak line at bus 3. From the result, as the loading (Qd) is increased the voltage value is also decrease. For bus 4, the maximum loadability (Qdmax) for this bus can afford is 197 MVAr. This is because of the voltage value which is 0.9000, indicate the minimum value of voltage for the system to be considered in steady state or in a stable condition. Since the test bus is bus 4, the line that connected to bus 4 is line 3, line 4 and line 7. Line 3 is a connection from bus 2 to bus 4, line 4 is a connection from bus 3 to bus 4, and line 7 is a connection from bus 4 to bus 6. Weak line that connected to bus 4 is determined by the value of its index. From all three lines, line 3 have the highest index value for both index Fast Voltage Stability Index (FVSI) and Line Stability Index (Lmn) indicate that line 3 is the weakest line among these two lines.

4.3 Case Study 2: The analysis of voltage instability by line outage the selected line bus within IEEE 30 Bus Reliability Test System (RTS).

In this case study, the results are tabulated into table to study the effect of line outage to the voltage stability condition at the test IEEE 30 Bus (RTS). In this case study, the value for Voltage base and Fast Voltage Stability Index is determined first. After that, the line outage is performed and the value for voltage and Fast Voltage Stability Index is compared. The result will be arranged from raw result to analysis data. For this case study, there are two result that will be explain, the first is line outage at line 1 and the second is line outage at line 2.

Line data	FVSI Base	FVSI line outage	Voltage Base (p.u)	Voltage line outage (p.u)
1	0.08079	1.00000	1.06000	0.00000
2	0.03228	0.59997	1.06000	1.06000
3	0.00480	0.30597	1.04300	0.99300
4	0.00888	0.23040	1.02247	0.93466
5	0.06616	0.00038	1.04300	0.99300
6	0.04193	0.16170	1.04300	0.99300
7	0.03374	0.18056	1.01403	0.93935
8	0.05563	0.13956	1.01000	0.96000
9	0.00549	0.05851	1.01325	0.95586
10	0.00135	0.03589	1.01325	0.95586
11	0.18447	0.30133	1.01325	0.95586
12	0.18641	0.27466	1.01325	0.95586
13	0.09841	0.24891	1.05661	1.02194
14	0.00360	0.02643	1.05661	1.02194
15	0.21311	0.43357	1.01403	0.93935
16	0.03840	0.14507	1.06091	1.02508
17	0.02143	0.02071	1.06091	1.02508
18	0.02917	0.02986	1.06091	1.02508
19	0.01480	0.01089	1.06091	1.02508
20	0.00502	0.00203	1.04710	1.01021
21	0.00092	0.00634	1.05133	1.01293
22	0.00848	0.00418	1.04342	1.00501
23	0.00035	0.00348	1.03553	0.99582
24	0.01112	0.01365	1.03397	0.99366
25	0.03781	0.04547	1.05526	1.01478
26	0.02058	0.02453	1.05526	1.01478
27	0.00980	0.01288	1.05526	1.01478
28	0.01217	0.01620	1.05526	1.01478
29	0.00320	0.00421	1.04779	1.00659
30	0.01703	0.01770	1.04342	1.00501
31	0.04359	0.05767	1.04729	1.00594
32	0.00295	0.00188	1.03514	0.99432
33	0.04165	0.06196	1.03245	0.98890
34	0.04806	0.05316	1.02638	0.97589
35	0.00131	0.01197	1.02638	0.97589
36	0.08503	0.09464	1.01216	0.95673
37	0.03010	0.03374	1.03107	0.97679
38	0.03948	0.04394	1.03107	0.97679
39	0.01230	0.01381	1.01139	0.95589
40	0.00769	0.01773	1.01000	0.96000
41	0.00888	0.01794	1.01325	0.95586

Table 4.3.1: The result of Voltage and FVSI before and after line outage at line 1 at IEEE 30 Bus RTS.

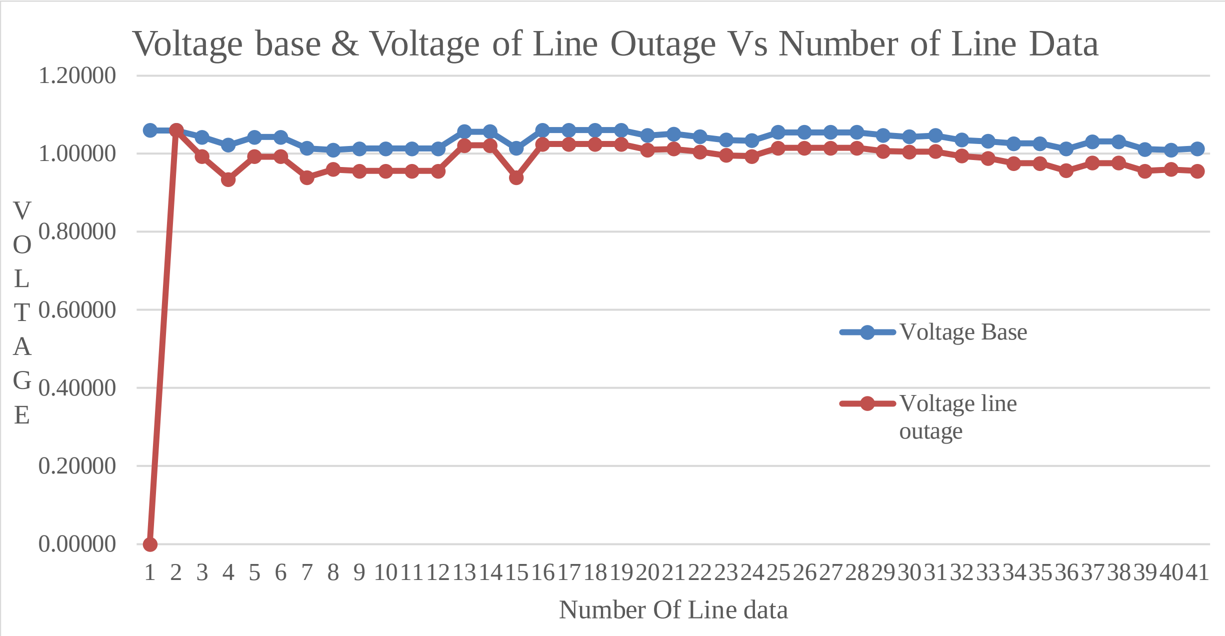

Figure 4.3.1: The graph shows the comparison of voltage value before and after line outage.

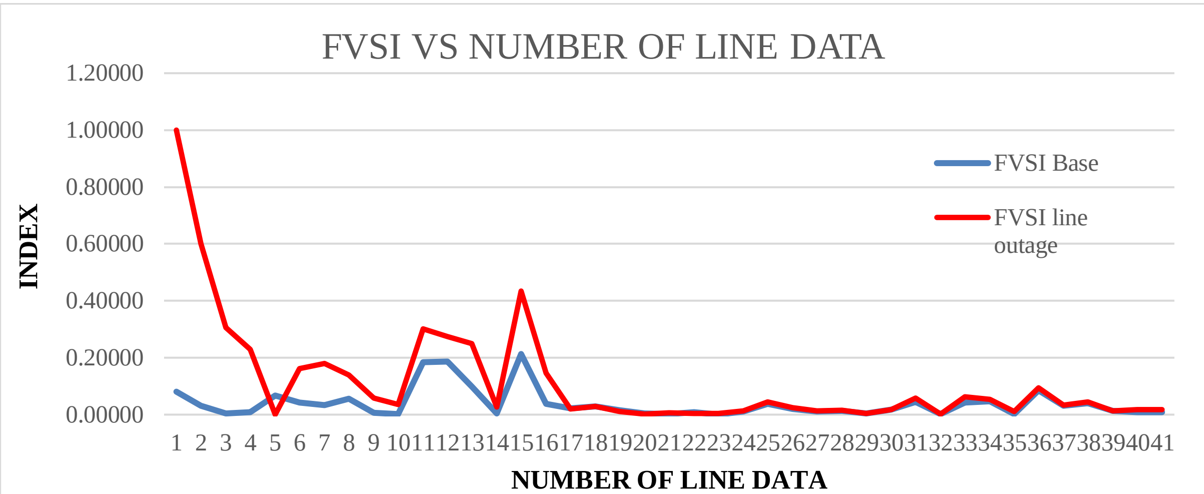

Figure 4.3.2: The graph of comparison for FVSI index before and after line outage.

Table 4.3.1 shows the overall value of voltage and Fast Voltage Stability Index before and after line outage at line 1. At figure 4.3.1, the voltage base and voltage line outage at line one shows a different where the voltage base is much higher than voltage line outage at line one. The voltage line outage at line one start from zero at line 1 and at line 2 the voltage base and voltage line outage are same. Before the rest of voltage line outage value decrease and shows a gap between them until line 41. Figure 4.3.2 shows the differences between FVSI base and FVSI line outage value. At the beginning, line one, the FVSI value is equal to one indicate that line 1 is not stable and it is a weak line. This is due to the line outage. Unlike voltage, the FVSI value is going down slowly toward the stable value of index at line 5 and remain slightly higher than FVSI base value until line 41.

Line data	FVSI Base	FVSI line outage	Voltage Base	Voltage line outage
1	0.08079	0.09105	1.06000	1.06000
2	0.03228	1.00000	1.06000	0.00000
3	0.00480	0.09258	1.04300	1.02300
4	0.00888	0.00139	1.02247	0.98558
5	0.06616	0.11849	1.04300	1.02300
6	0.04193	0.13778	1.04300	1.02300
7	0.03374	0.03470	1.01403	0.98621
8	0.05563	0.04011	1.01000	0.99000
9	0.00549	0.00657	1.01325	0.99025
10	0.00135	0.01490	1.01325	0.99025
11	0.18447	0.23491	1.01325	0.99025
12	0.18641	0.23362	1.01325	0.99025
13	0.09841	0.15199	1.05661	1.04374
14	0.00360	0.00719	1.05661	1.04374
15	0.21311	0.28829	1.01403	0.98621
16	0.03840	0.08733	1.06091	1.04858
17	0.02143	0.02506	1.06091	1.04858
18	0.02917	0.03533	1.06091	1.04858
19	0.01480	0.02256	1.06091	1.04858
20	0.00502	0.00967	1.04710	1.03419
21	0.00092	0.00620	1.05133	1.03838
22	0.00848	0.01342	1.04342	1.03038
23	0.00035	0.00252	1.03553	1.02205
24	0.01112	0.00991	1.03397	1.02028
25	0.03781	0.03456	1.05526	1.04139
26	0.02058	0.01811	1.05526	1.04139
27	0.00980	0.01050	1.05526	1.04139
28	0.01217	0.01306	1.05526	1.04139
29	0.00320	0.00343	1.04779	1.03363
30	0.01703	0.02446	1.04342	1.03038
31	0.04359	0.04666	1.04729	1.03307
32	0.00295	0.01252	1.03514	1.02110
33	0.04165	0.05839	1.03245	1.01715
34	0.04806	0.04981	1.02638	1.00820

35	0.00131	0.01085	1.02638	1.00820
36	0.08503	0.09742	1.01216	0.99002
37	0.03010	0.03136	1.03107	1.01124
38	0.03948	0.04103	1.03107	1.01124
39	0.01230	0.01283	1.01139	0.99114
40	0.00769	0.00154	1.01000	0.99000
41	0.00888	0.01329	1.01325	0.99025

Table 4.3.2: The result of Voltage and FVSI before and after line outage at line 2 at IEEE 30 Bus RTS.

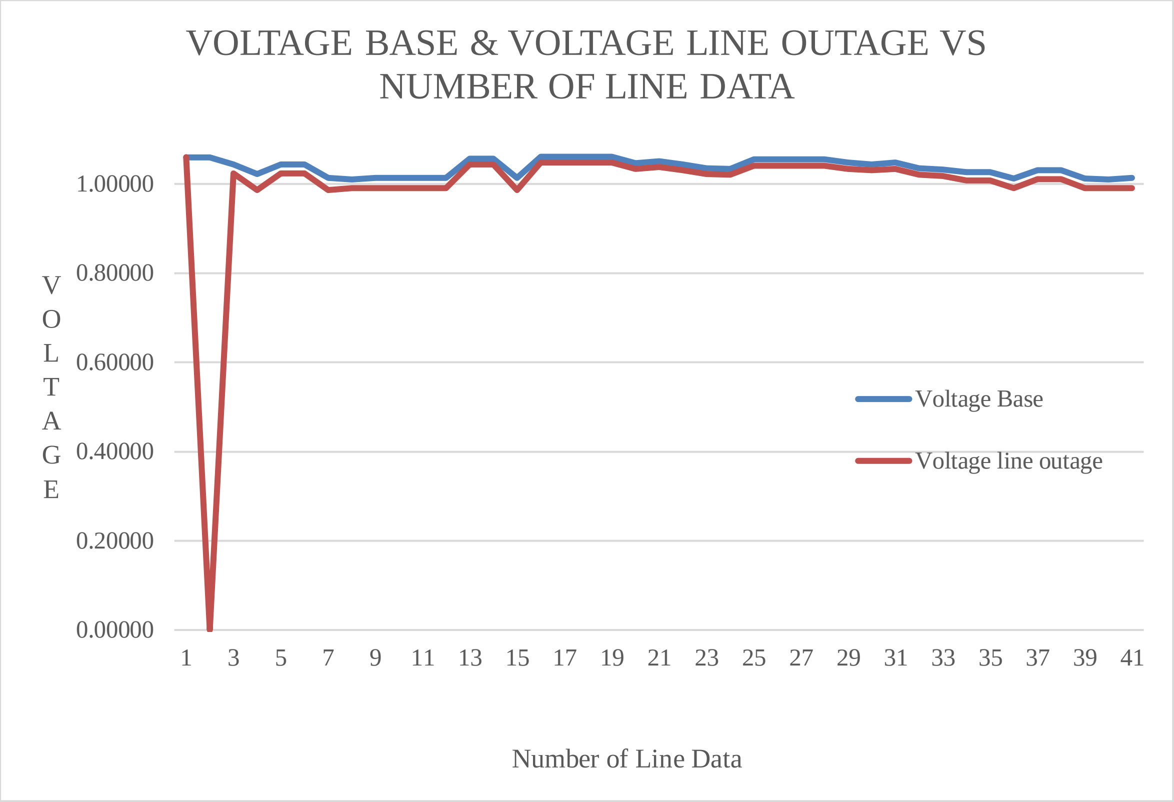

Figure 4.3.3: The graph shows the comparison of voltage value before and after line outage.

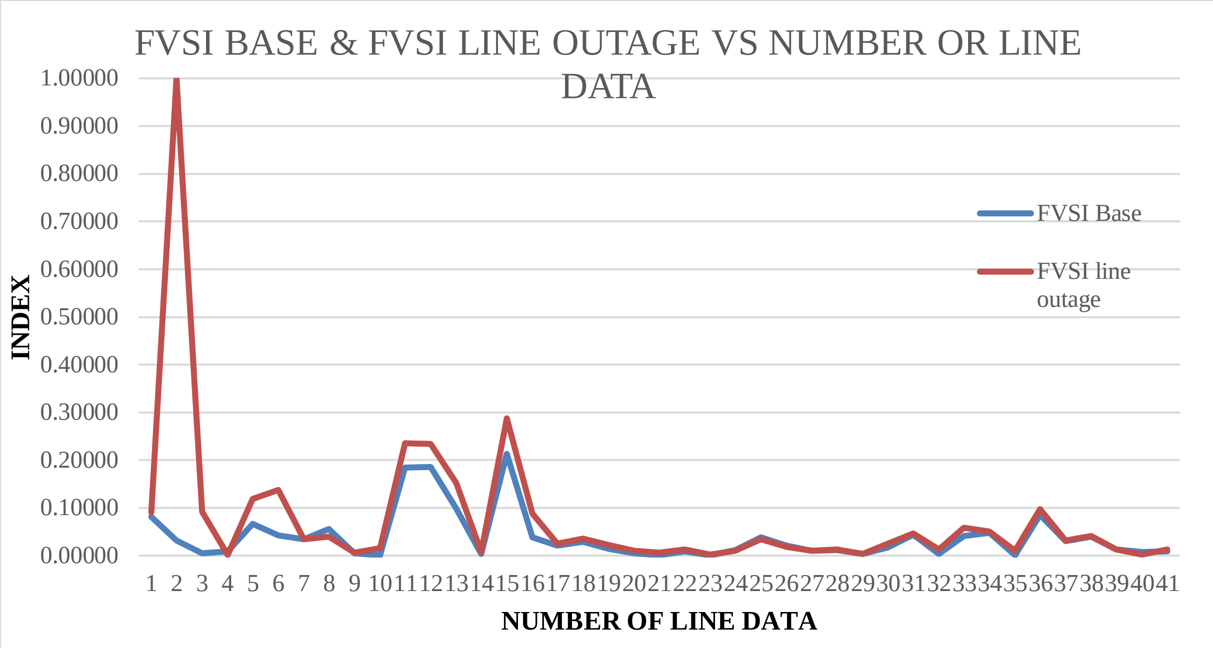

Figure 4.3.4: The graph of comparison for FVSI index before and after line outage.

Table 4.3.2 shows the overall value of voltage and Fast Voltage Stability Index before and after line outage at line 2. At figure 4.3.3, the voltage base and voltage line outage at line two shows both have same voltage value at line 1 which is 1.0600 p.u. At line two, the voltage line outage is going to zero due to line outage before bounce back to 1.0200 p.u at line 3. After that, the voltage line outage value shows a gap and have smaller voltage compare to volage base value until line 41. Figure 4.3.4 shows the differences between FVSI base and FVSI line outage value. At the beginning, line one, the FVSI line outage value is 0.09105 and spike to 1 at line 2 due to line outage. The FVSI line outage hit the lowest index at line 4 even lowest compare to FVSI base value at line 4 before stay a little higher than FVSI base value until line 41.

4.4 Case Study 3: The analysis of voltage instability by increase the loading at the selected load bus within IEEE 69 Bus Reliability Test System (RTS).

In this case study, the results are tabulated into table to study the effect of increasing loading at selected bus to the voltage condition and index value. The result will be arranged from raw result to analysis data.

Loading (MVAr)	FVSI	Lmn	Voltage (p.u)
9	0.45134	0.38745	0.92189
10	0.49584	0.41855	0.91606
11	0.54109	0.44902	0.91006
12	0.58711	0.47889	0.90386
13	0.63399	0.50816	0.89747
14	0.68178	0.53686	0.89085
15	0.73055	0.56499	0.88400
16	0.78038	0.59257	0.87690
17	0.83138	0.61961	0.86953

Table 4.4.1: Result when the loading is increase at bus 7 at IEEE 69 Bus RTS.

Table 4.4.1 is the overall result when the loading is test at bus 7 by increase the loading until the voltage collapse. From the data above, the details about the analysis of voltage instability will be conducted which is to determine the weak line that connected to tested bus.

Loading, Qd (MVAr)	Voltage (p.u)	Line 6		Line 7	
		FVSI	Lmn	FVSI	Lmn
10	0.91606	0.49584	0.41855	0.02162	0.02158
11	0.91006	0.54109	0.44902	0.02193	0.02189
12	0.90386	0.58711	0.47889	0.02226	0.02223
13	0.89747	0.63399	0.50816	0.02261	0.02256
14	0.89085	0.68178	0.53686	0.02298	0.02293

Table 4.4.2: The result of weak line at bus 7 at IEEE 69 Bus RTS.

Table 4.4.2 shows the result of voltage instability analysis in order to determine weak line at bus 7 within IEEE 69 Bus RTS. From the result, shows that as the loading (Qd) is increase, the voltage value become decrease. For bus 7, the maximum loadability (Qdmax) or the maximum permissible load that this bus can carry is 12 MVAr. This is because of the voltage value when the loading reached its maximum capacity of loadability is 0.90386, the minimum level of voltage steady state or voltage stable condition for bus 7. Since the test bus is bus 7, the line that connected to bus 7 is line 6 and line 7. Line 6 is a connection from bus 6 to bus 7 while line 7 is a connection from bus 7 to bus 8. Weak line that connected to bus 7 is determined by the value of its index. From both line, line 6 have the highest value for both index Fast Voltage Stability Index (FVSI) and Line Stability Index (Lmn) indicate that line 9 is the weakest line among these two lines.

Loading (MVAr)	**FVSI**	**Lmn**	**Voltage (p.u)**
6	0.32460	0.29752	0.92653
7	0.36802	0.32645	0.91993
8	0.41221	0.35961	0.91309
9	0.45723	0.39223	0.90601
10	0.50316	0.42433	0.89865
11	0.55006	0.45593	0.89100
12	0.59804	0.48706	0.88303
13	0.64719	0.51774	0.87472
14	0.69764	0.54800	0.86603

Table 4.4.3: The Result when Loading is increase at bus 9 at IEEE 69 Bus RTS.

Table 4.4.3 is the overall result when the loading is test at bus 9 by increase the loading until the voltage collapse. From the data above, the analysis of voltage instability will be conducted and explained in details on how to determine the weak line that connected to tested bus.

Loading, Qd (MVAr)	**Voltage (p.u)**	**Line 8**		**Line 9**		**Line 52**	
		FVSI	Lmn	FVSI	Lmn	FVSI	Lmn
7	0.91993	0.05072	0.04987	0.06937	0.06825	0.0271	0.02706
8	0.91309	0.05726	0.05616	0.07042	0.06927	0.02758	0.02751
9	0.90601	0.06401	0.06262	0.07154	0.07035	0.02806	0.02799
10	0.89865	0.07100	0.06927	0.07272	0.07150	0.02858	0.02850
11	0.89100	0.07825	0.07613	0.07400	0.07272	0.02913	0.02905

Table 4.4.4: The result of weak line at bus 9 IEEE 69 Bus RTS.

Table 4.4.4 shows the voltage instability analysis result during determining weak line at bus 9 within IEEE 69 Bus RTS. From the table above, the result shows that as the loading (Qd) is increase, the voltage value is decrease. For bus 9, the maximum loadability (Qdmax) for this bus can afford is 9 MVAr. This is due to the voltage value at 9 MVAr is the minimum level of voltage value which is 0.90601 p.u for the bus 9 can run in a steady state or stable condition. Since the test bus is bus 9, the line that connected to bus 9 is line 8, line 9 and line 52. Line 8 is a connection from bus 8 to bus 9, line 9 is a connection from bus 9 to bus 10, and line 52 is a connection from bus 9 to bus 53. Weak line that connected to bus 9 is determined by the value of its index. Line 8 have the highest value for both index Fast Voltage Stability Index (FVSI) and Line Stability Index (Lmn) indicate that line 8 is the weakest line among these three lines.

4.5 Case Study 4: The analysis of voltage instability by line outage the selected line bus within IEEE 69 Bus Reliability Test System (RTS).

In this case study, the results are tabulated into table to study the effect of line outage to the voltage stability condition at the test IEEE 69 Bus (RTS). The value for Voltage base and Fast Voltage Stability Index is determined first. After that, the line outage is performed and the value for voltage and Fast Voltage Stability Index is compared. The result will be arranged from raw result to analysis data. For this case study, there are two result that will be explain, the first is line outage at line 3 and the second is line outage at line 8.

Line Data	FVSI Base	FVSI Line Outage	Voltage Base (p.u)	Voltage Line Outage (p.u)
1	0.000162	0.000011	1.00000	1.00000
2	0.000162	0.000011	0.99994	1.00000
3	0.000454	1.000000	0.99989	0.00000
4	0.004199	1.000000	0.99973	0.00093
5	0.074044	0.780641	0.99835	0.05128
6	0.078362	1.000000	0.98322	0.02964

7	0.019217	1.000000	0.96748	0.01431
8	0.009901	1.000000	0.96372	0.00929
9	0.063406	1.000000	0.96180	0.01400
10	0.014198	1.000000	0.95357	0.13376
11	0.040351	1.000000	0.95176	0.13687
12	0.036761	0.209916	0.94655	0.06617
13	0.036631	1.000000	0.94171	0.02638
14	0.036506	1.000000	0.93692	0.06032
15	0.006846	1.000000	0.93218	0.06343
16	0.011312	0.274363	0.93130	0.06176
17	0.000114	1.000000	0.92984	0.00131
18	0.006368	1.000000	0.92983	0.00553
19	0.004100	1.000000	0.92906	0.00963
20	0.006622	0.108236	0.92857	0.06455
21	0.000095	1.000000	0.92777	0.00182
22	0.000993	1.000000	0.92776	0.00523
23	0.002161	1.000000	0.92764	0.01305
24	0.002338	1.000000	0.92738	0.01039
25	0.000965	1.000000	0.92710	0.00613
26	0.000271	1.000000	0.92698	0.00182
27	0.000033	0.000033	0.99989	0.99999
28	0.000341	0.000341	0.99988	0.99998
29	0.001497	0.001496	0.99976	0.99987
30	0.000264	0.000264	0.99957	0.99967
31	0.001321	0.001321	0.99953	0.99964
32	0.003120	0.003119	0.99936	0.99947
33	0.004135	0.004135	0.99895	0.99906
34	0.000794	0.000794	0.99841	0.99852
35	0.000065	0.000065	0.99989	0.99999
36	0.000809	0.000808	0.99987	0.99997
37	0.000786	0.000785	0.99959	0.99969
38	0.000227	0.000227	0.99934	0.99944
39	0.000011	0.000011	0.99926	0.99937
40	0.003423	0.003422	0.99926	0.99936
41	0.001434	0.001434	0.99814	0.99824
42	0.000190	0.000190	0.99767	0.99778
43	0.000040	0.000040	0.99761	0.99771
44	0.000473	0.000473	0.99760	0.99770
45	0.000002	0.000002	0.99744	0.99754
46	0.000240	1.000000	0.99973	0.00093
47	0.005957	1.000000	0.99965	0.00057
48	0.018274	1.000000	0.99765	0.00944
49	0.002622	1.000000	0.99146	0.01178
50	0.000306	1.000000	0.96372	0.00929
51	0.000128	1.000000	0.96366	0.02164
52	0.024594	1.000000	0.96180	0.01400
53	0.028761	1.000000	0.95700	0.06834

54	0.039893	1.000000	0.95142	0.10463
55	0.039325	1.000000	0.94372	0.31692
56	0.295412	0.536375	0.93619	0.25239
57	0.156527	1.000000	0.89742	0.07507
58	0.063864	1.000000	0.87836	0.04852
59	0.082702	1.000000	0.87099	0.02862
60	0.075322	1.000000	0.86233	0.09413
61	0.003040	0.502607	0.84960	0.04812
62	0.004073	1.000000	0.84910	0.02482
63	0.019919	1.000000	0.84843	0.05902
64	0.006054	1.000000	0.84515	0.44420
65	0.000831	0.174961	0.95176	0.13687
66	0.000010	0.287360	0.95167	0.00172
67	0.004431	0.510732	0.94655	0.06617
68	0.000014	1.000000	0.94601	0.00259

Table 4.5.1: The result of Voltage and FVSI before and after line outage at line 3 at IEEE 69 Bus RTS.

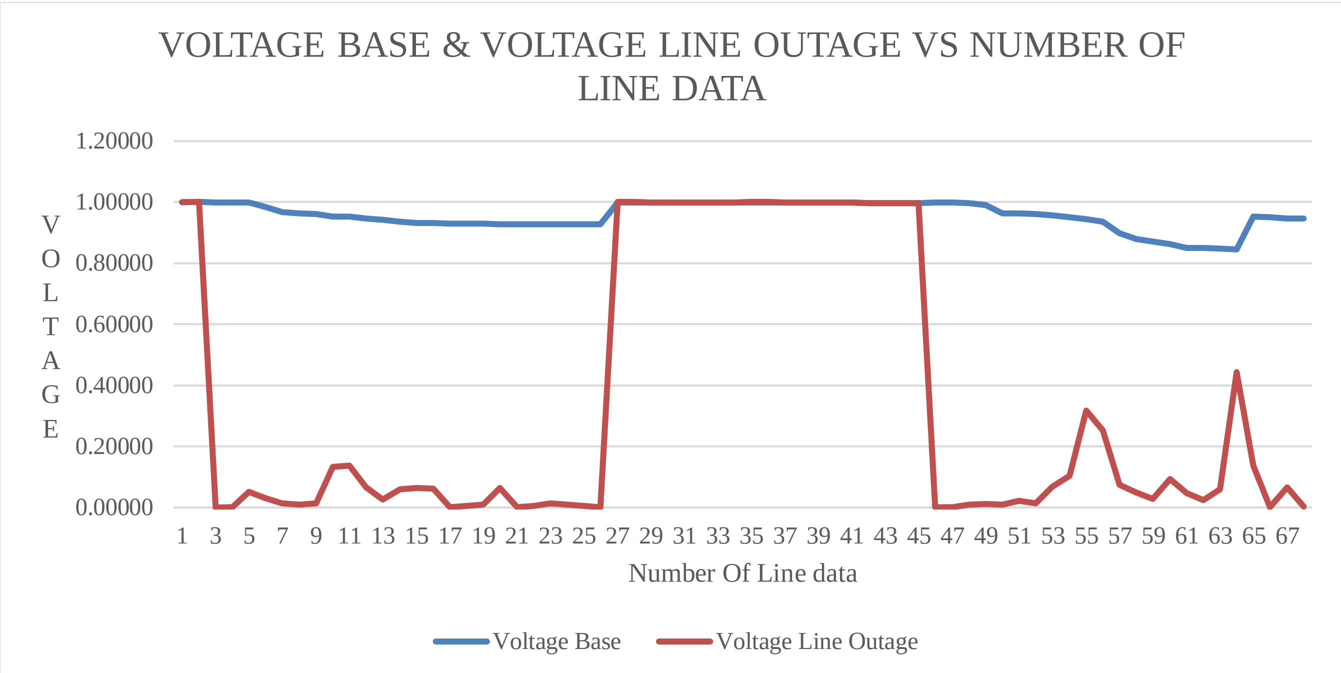

Figure 4.5.1: The graph shows the comparison of voltage value before and after line outage in IEEE 69 Bus RTS.

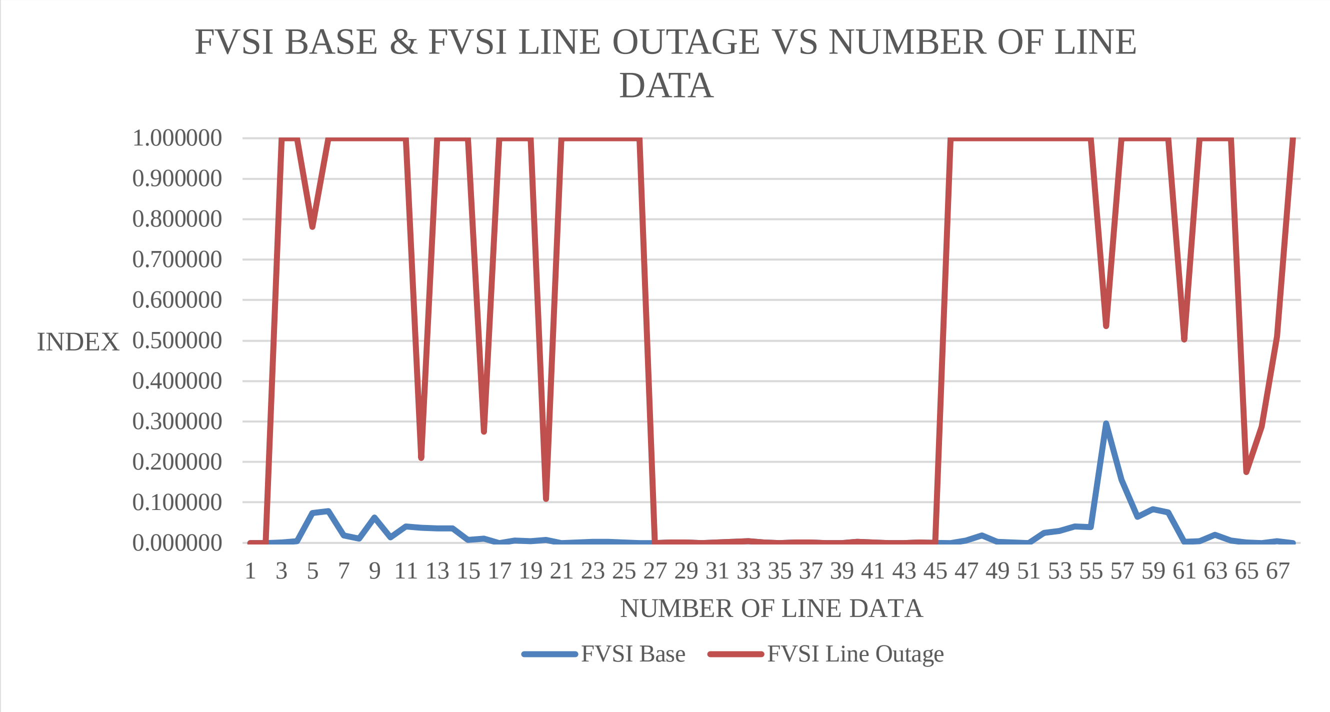

Figure 4.5.2: The graph of the comparison of FVSI index value before and after line outage in IEEE 69 Bus RTS.

Table 4.5.1 shows the value of voltage base, Fast Voltage Stability Index (FVSI) base, voltage value after line outage and FVSI index value after line outage during line outage at line 3. At figure 4.5.1, the voltage base and voltage line outage at line three shows a different pattern for both sides. Voltage base remain in the stable region between 0.9 p.u to 0.9999 p.u from line 1 to line 68. Compared to voltage line outage, a sudden voltage drop at line 3 is the result from line outage at line 3 but the voltage line outage value remain under 0.2 p.u until line 26. At line 27 until line 45, the value of voltage line outage is slightly higher than the voltage base. From line 46 to line 68, the voltage line outage stays below than 0.5 p.u.

Figure 4.5.2 shows the differences between FVSI base value and FVSI line outage value. The FVSI base is constantly at below than 0.3 from line 1 until line 68. But for the FVSI line outage value, the graph is a little bit chaotic starting at line 3, the FVSI index rise to 1.000. After that, the graph is fluctuated until line 26 before going down and have the same index value like FVSI base from line 27 to line 45. After that, the FVSI line outage fluctuated again at index more than 0.500 from line 46 until line 68.

Line Data	FVSI Base	FVSI Line outage	Voltage Base (p.u)	Voltage Line Outage (p.u)
1	0.000162	0.000160	1.00000	1.00000
2	0.000162	0.000160	0.99994	0.99995
3	0.000454	0.000454	0.99989	0.99989
4	0.004199	0.004199	0.99973	0.99973
5	0.074044	0.074044	0.99835	0.99835
6	0.078362	0.078362	0.98322	0.98322
7	0.019217	0.019217	0.96748	0.96748
8	0.009901	0.009901	0.96372	0.96372
9	0.063406	0.063405	0.96180	0.96180
10	0.014198	0.014198	0.95357	0.95357
11	0.040351	0.040351	0.95176	0.95176
12	0.036761	0.036761	0.94655	0.94655
13	0.036631	0.036631	0.94171	0.94172
14	0.036506	0.036505	0.93692	0.93692
15	0.006846	0.006846	0.93218	0.93218
16	0.011312	0.011312	0.93130	0.93130
17	0.000114	0.000114	0.92984	0.92985
18	0.006368	0.006368	0.92983	0.92983
19	0.004100	0.004100	0.92906	0.92906
20	0.006622	0.006622	0.92857	0.92857
21	0.000095	0.000095	0.92777	0.92777
22	0.000993	0.000993	0.92776	0.92776
23	0.002161	0.002161	0.92764	0.92764
24	0.002338	0.002338	0.92738	0.92738
25	0.000965	0.000965	0.92710	0.92710
26	0.000271	0.000271	0.92698	0.92699
27	0.000033	0.000009	0.99989	0.99989
28	0.000341	1.000000	0.99988	0.00000
29	0.001497	1.000000	0.99976	0.00532
30	0.000264	1.000000	0.99957	0.00064
31	0.001321	1.000000	0.99953	0.00272
32	0.003120	1.000000	0.99936	0.00306
33	0.004135	1.000000	0.99895	0.00424
34	0.000794	1.000000	0.99841	0.02146
35	0.000065	0.000065	0.99989	0.99989
36	0.000809	0.000809	0.99987	0.99987
37	0.000786	0.000786	0.99959	0.99959
38	0.000227	0.000227	0.99934	0.99934
39	0.000011	0.000011	0.99926	0.99927
40	0.003423	0.003423	0.99926	0.99926
41	0.001434	0.001434	0.99814	0.99814
42	0.000190	0.000190	0.99767	0.99767
43	0.000040	0.000040	0.99761	0.99761

44	0.000473	0.000473	0.99760	0.99760
45	0.000002	0.000002	0.99744	0.99744
46	0.000240	0.000240	0.99973	0.99973
47	0.005957	0.005957	0.99965	0.99965
48	0.018274	0.018274	0.99765	0.99765
49	0.002622	0.002622	0.99146	0.99146
50	0.000306	0.000306	0.96372	0.96372
51	0.000128	0.000128	0.96366	0.96367
52	0.024594	0.024594	0.96180	0.96180
53	0.028761	0.028761	0.95700	0.95700
54	0.039893	0.039893	0.95142	0.95142
55	0.039325	0.039325	0.94372	0.94372
56	0.295412	0.295412	0.93619	0.93619
57	0.156527	0.156527	0.89742	0.89742
58	0.063864	0.063864	0.87836	0.87836
59	0.082702	0.082703	0.87099	0.87099
60	0.075322	0.075322	0.86233	0.86234
61	0.003040	0.003041	0.84960	0.84960
62	0.004073	0.004073	0.84910	0.84910
63	0.019919	0.019919	0.84843	0.84843
64	0.006054	0.006054	0.84515	0.84515
65	0.000831	0.000831	0.95176	0.95176
66	0.000010	0.000010	0.95167	0.95167
67	0.004431	0.004431	0.94655	0.94655
68	0.000014	0.000014	0.94601	0.94601

Table 4.5.2: The result of Voltage and FVSI before and after line outage at line 28 in IEEE 69 Bus RTS.

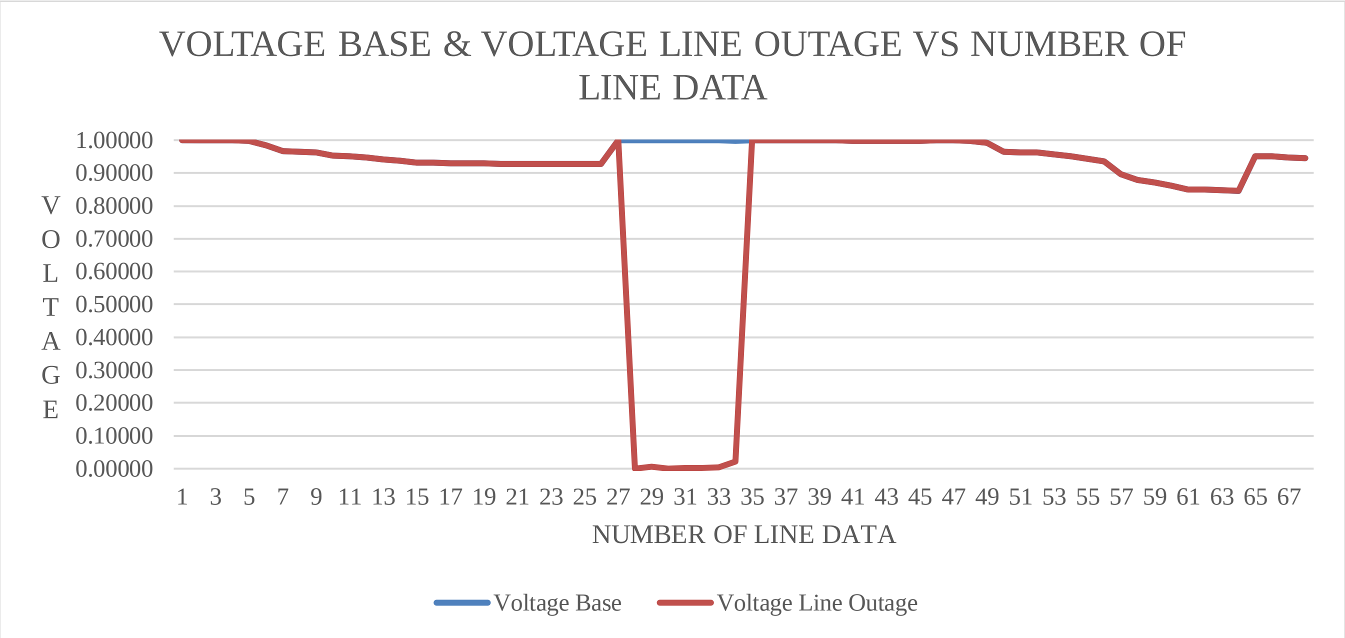

Figure 4.5.3: The graph shows the comparison of voltage value before and after line outage.

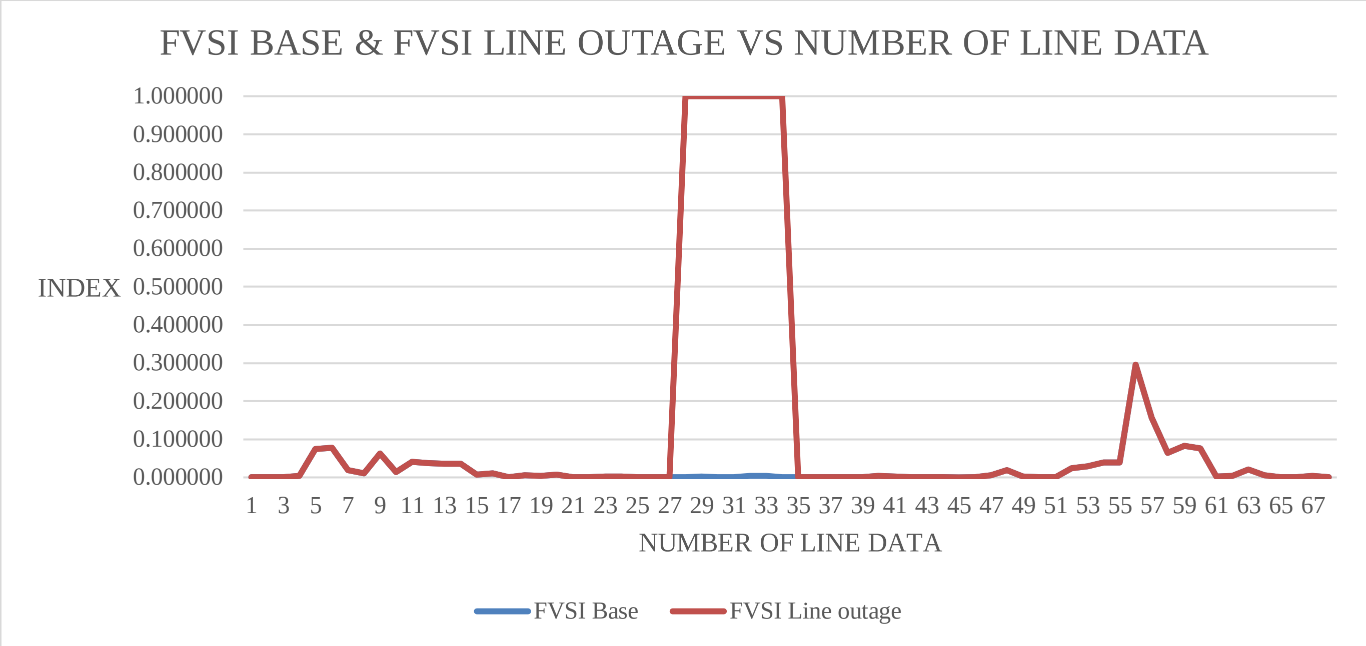

Figure 4.5.4: The graph of the comparison of FVSI index value before and after line outage in IEEE 69 Bus RTS.

Table 4.5.2 shows the value of voltage base, Fast Voltage Stability Index (FVSI) base, voltage value after line outage and FVSI index value after line outage during line outage at line 28. From figure 4.5.3, there are voltage base value and voltage line outage at line 28 value. The voltage line outage for has the same value as voltage base from line 1 until line 27. Starting from line 28, the voltage line outage graph is going down at zero value and the voltage value remain under 0.02200 until line 34. This is due to the line outage. After that, at line 35, the voltage line outage is back to have the same value with voltage base until line 68.

In the figure 4.5.4, the graph of FVSI base index and FVSI line outage index is plotted. At the beginning, line 1 until line 27, the FVSI line outage have same index value as FVSI base. Going to line 28, the FVSI line outage spike up to record 1.0000 index and the result stay the same until line 34. From line 35 to line 68, the FVSI line outage value and FVSI base is identical to each other and stay below than 0.30000 index till the end.

4.6 Critical Discussion

Throughout this project, there are a few matters that can be list here:

- Starting from the main voltage instability analysis of this project, which is to determine the voltage condition of the system when load is increase at the loaded bus. What will happen to the system if the loading increase is exceed the capacity of the load bus? Can the index really detect the voltage instability incident?

- From case study 1 and case study 3, the results at the tabulated data shows as the loading is increased at the selected bus, the voltage value is decrease. The result is relevant to the theory. When the load demand is increase, the system network is forced to work closed to its stability limit. When the load demand is more than the system can supply, it will create instability that can affect either in power generation or transmission line. Know the limit of the bus or the loadabilitiy of buses in the system can help to avoid unwanted incident like voltage collapse from happen. Supposedly in this project, the voltage condition can be determined by the index value of voltage stability index. If the value of FVSI and Lmn is reaching and close to 1.000, the voltage will consider as voltage collapse due to the voltage condition is not stable. But as per request from previous panel, to use the real-time voltage value, the voltage condition is determined by the voltage value itself. The voltage system is entering instability condition when the value is less than 0.9000 p.u. Thus, most of the result of index in the project is far from 1.000 but the system already considered as voltage collapse and the voltage condition is not in stable state.

- The effect of line outage or line tripping on the system voltage is crystal clear because of a lot of researchers already done it. For case study 2 and case study 4, the line outage is test at the selected line from the bus data. Since this project are using two test system which is IEEE 30 Bus RTS and IEEE 69 Bus RTS, the result for voltage and FVSI index behaviour is different on both test system. Result on the IEEE 30 Bus test system shows a pattern where the voltage line outage is experience sudden voltage drop before going back to steady state but the voltage value is lesser than the voltage base. This case is happening to FVSI line outage on IEEE 30 Bus test system.

- Compare to the voltage line outage value on IEEE 69 Bus test system, the voltage behaviour is not predictable as voltage line outage value in IEEE 30 Bus test system. The voltage line outage is fluctuated. The line outage not only affecting the tested line but also other lines. Same goes for the FVSI line outage result.

CHAPTER 5

CONCLUSION

5.1 Introduction

As the conclusion, the proposed voltage stability index can be used to determine weak line that connected to the selected bus. The Fast Voltage Stability Index (FVSI) and Line Stability Index (Lmn) can be applied on the real-time system but more practical to used it on off-line model test. If voltage stability index is use to test on pre-develop new power system, it can help to designing a better prepared power system. Fast Voltage Stability Index (FVSI) and Line Stability Index (Lmn) are both reliable to use to test the voltage stability condition on a system. The result for both index is different on different test system thus it is difficult to decide which index is better but one thing for sure, both indexes can determine voltage instability in the power system accurately. As an overall conclusion, the whole study was successful by using voltage stability index to carry out voltage instability analysis.

5.2 Future Recommendation Work.

This study presents the voltage instability analysis by using voltage stability index. The main aim of this study is to determine voltage stability condition when a few contingencies is act upon the system. However, for the further development of this project, the following work are suggested:

- The voltage stability index used in this project were Fast Voltage Stability Index (FVSI) and Line Stability Index (Lmn). Thus, for the future work, try to find why these both indexes give different index value on different test system which might can help to determine which index is better or which index is the most accurate to be used on voltage stability analysis.

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APPENDIX 1: IEEE 30 BUS RTS DATA

BUS SENDING	BUS RECEIVING	R (P.U)	X(P.U)	1/2 B (P.U)	LINE CODE
1	2	0.0192	0.0575	0.0264	1
1	3	0.0452	0.1852	0.0204	1
2	4	0.057	0.1737	0.0184	1
3	4	0.0132	0.0379	0.0042	1
2	5	0.0472	0.1983	0.0209	1
2	6	0.0581	0.1763	0.0187	1
4	6	0.0119	0.0414	0.0045	1
5	7	0.046	0.116	0.0102	1
6	7	0.0267	0.082	0.0085	1
6	8	0.012	0.042	0.0045	1
6	9	0	0.208	0	0.978
6	10	0	0.556	0	0.969
9	11	0	0.208	0	1
9	10	0	0.11	0	1
4	12	0	0.256	0	0.932
12	13	0	0.14	0	1
12	14	0.1231	0.2559	0	1
12	15	0.0662	0.1304	0	1
12	16	0.0945	0.1987	0	1
14	15	0.221	0.1997	0	1
16	17	0.0824	0.1923	0	1
15	18	0.1073	0.2185	0	1
18	19	0.0639	0.1292	0	1
19	20	0.034	0.068	0	1
10	20	0.0936	0.209	0	1
10	17	0.0324	0.0845	0	1
10	21	0.0348	0.0749	0	1
10	22	0.0727	0.1499	0	1
21	22	0.0116	0.0236	0	1
15	23	0.1	0.202	0	1
22	24	0.115	0.179	0	1
23	24	0.132	0.27	0	1
24	25	0.1885	0.3292	0	1
25	26	0.2544	0.38	0	1
25	27	0.1093	0.2087	0	1
28	27	0	0.396	0	0.968
27	29	0.2198	0.4153	0	1
27	30	0.3202	0.6027	0	1
29	30	0.2399	0.4533	0	1
8	28	0.0636	0.2	0.0214	1
6	28	0.0169	0.0599	0.065	1

APPENDIX 2: IEEE 69 BUS RTS DATA

BUS SENDING	BUS RECEIVING	R (P.U)	X(P.U)	1/2 B (P.U)	LINE CODE
1	2	0.0005	0.0012	0	1
2	3	0.0005	0.0012	0	1
3	4	0.0015	0.0036	0	1
4	5	0.0251	0.0294	0	1
5	6	0.366	0.1864	0	1
6	7	0.3811	0.1941	0	1
7	8	0.0922	0.047	0	1
8	9	0.0493	0.0251	0	1
9	10	0.819	0.2707	0	1
10	11	0.1872	0.0619	0	1
11	12	0.7114	0.2351	0	1
12	13	1.03	0.34	0	1
13	14	1.044	0.345	0	1
14	15	1.058	0.3496	0	1
15	16	0.1966	0.065	0	1
16	17	0.3744	0.1238	0	1
17	18	0.0047	0.0016	0	1
18	19	0.3276	0.1083	0	1
19	20	0.2106	0.0696	0	1
20	21	0.3416	0.1129	0	1
21	22	0.014	0.0046	0	1
22	23	0.1591	0.0526	0	1
23	24	0.3463	0.1145	0	1
24	25	0.7488	0.2475	0	1
25	26	0.3089	0.1021	0	1
26	27	0.1732	0.0572	0	1
3	28	0.0044	0.0108	0	1
28	29	0.064	0.1565	0	1
29	30	0.3978	0.1315	0	1
30	31	0.0702	0.0232	0	1
31	32	0.351	0.116	0	1
32	33	0.839	0.2816	0	1
33	34	1.708	0.5646	0	1
34	35	1.474	0.4873	0	1
3	36	0.0044	0.0108	0	1
36	37	0.064	0.1565	0	1
37	38	0.1053	0.123	0	1
38	39	0.0304	0.0355	0	1
39	40	0.0018	0.0021	0	1
40	41	0.7283	0.8509	0	1
41	42	0.31	0.3623	0	1
42	43	0.041	0.0478	0	1

43	44	0.0092	0.0116	0	1
44	45	0.1089	0.1373	0	1
45	46	0.0009	0.0012	0	1
4	47	0.0034	0.0084	0	1
47	48	0.0851	0.2083	0	1
48	49	0.2898	0.7091	0	1
49	50	0.0822	0.2011	0	1
8	51	0.0928	0.0473	0	1
51	52	0.3319	0.1114	0	1
9	53	0.174	0.0886	0	1
53	54	0.203	0.1034	0	1
54	55	0.2842	0.1447	0	1
55	56	0.2813	0.1433	0	1
56	57	1.59	0.5337	0	1
57	58	0.7837	0.263	0	1
58	59	0.3042	0.1006	0	1
59	60	0.3861	0.1172	0	1
60	61	0.5075	0.2585	0	1
61	62	0.0974	0.0496	0	1
62	63	0.145	0.0738	0	1
63	64	0.7105	0.3619	0	1
64	65	1.041	0.5302	0	1
11	66	0.2012	0.0611	0	1
66	67	0.0047	0.0014	0	1
12	68	0.7394	0.2444	0	1
68	69	0.0047	0.0016	0	1

APPENDIX 3
MATLAB FVSI AND LMN CODING

```
nl = linedata(:,1);
nr = linedata(:,2);
R  = linedata(:,3);
X  = linedata(:,4);

for n=1:nbr;
    V_1(n)=Vm(nl(n))*cos(delta(nl(n)))+j*Vm(nl(n))*sin(delta(nl(n)));   % V sending in complex
    V_2(n)=Vm(nr(n))*cos(delta(nr(n)))+j*Vm(nr(n))*sin(delta(nr(n)));   % V receiving in complex
    Z_line(n)=R(n)+j*X(n);                                    % Line impedance in complex
    Z_mag(n)=abs(Z_line(n));                                  % Line impedance magnitude
    I(n)=(V_1(n)-V_2(n))/Z_line(n);                           % Line current complex
    I_mag(n)=abs(I(n));                                       % Line current magnitude
    I_ang(n)=angle(I(n));                                     % Line current angle
    Q2(n)=Vm(nr(n))*I_mag(n)*sin(delta(nr(n))-I_ang(n));      % Reactive power at receiving bus
    FVSI(n)=4*Z_mag(n)^2*abs(Q2(n))/(Vm(nl(n))^2*X(n));       % FVSI

    if FVSI(n) > 1.0000 ;
        FVSI(n) = 1.0000;

    end

    output(n,:)= [n FVSI(n)];
%     pause(0.2)
end

max_FVSI=max(output(:,2))
```

```
for n=1:nbr
    V_1(n)=Vm(nl(n))*cos(delta(nl(n)))+1i*Vm(nl(n))*sin(delta(nl(n)));   % V sending in complex

    V_1_mag(n)=abs(V_1(n));
    V_1_angle(n)=angle(V_1(n));

    V_2(n)=Vm(nr(n))*cos(delta(nr(n)))+1i*Vm(nr(n))*sin(delta(nr(n)));   % V receiving in complex

    V_2_mag(n)=abs(V_2(n));
    V_2_angle(n)=angle(V_2(n));

    Z_line(n)=R(n)+1i*X(n);                              % Line impedance in complex
    Z_mag(n)=abs(Z_line(n));                            % Line impedance magnitude

    Z_angle(n)=angle(Z_line(n));          %--line impedance angle

    I(n)=(V_1(n)-V_2(n))/Z_line(n);                     % Line current complex
    I_mag(n)=abs(I(n));                                 % Line current magnitude
    I_ang(n)=angle(I(n));                               % Line current angle
    Q2(n)=Vm(nr(n))*I_mag(n)*sin(delta(nr(n))-I_ang(n));

    Theta= Z_angle(n);
    Delta= V_1_angle(n)-V_2_angle(n);
    Lmn(n)=(4*X(n)*abs(Q2(n))/(Vm(nl(n))*sin(Theta-Delta))^2);

   % Sol(n,:)=[n V_1 V_2 Z_line Z_mag I I_mag I_ang Q2 Lmn];
     if Lmn(n) > 1.0000
        Lmn(n) = 1.0000;

    end

    output(n,:)= [n Lmn(n)];
   %     pause(0.2)
end

    max_Lmn=max(output(:,2))
```

APPENDIX 4: MAIN CODING

```
clc
clear

fprintf('\n')
fprintf(   'Estimation of max loadability point and FVSI & Lmn at a particular loading condition   \n\n')

load_bus= 9
loading =6
step=1

count=1

%while loading<=15
while loading<=10
 IEEE69_DATA
%bus_data6
busdata(load_bus,6) = loading;

lfybus_opt                              % form the bus admittance matrix
LFNEWTON_opt                            % Load flow solution by Newton Raphson method
BUSOUT_opt                              % Prints the power flow solution on the screen
Lineflow_opt_1                            % Computes and displays the line flow and losses
FVSI_opt
FVSI_set=max_FVSI;
Lmn_set=max_Lmn
Ploss;
Vm_load_cond=Vm(:,load_bus)

fprintf('  loading     FVSI_set    Lmn_set    Ploss     Qloss      Vm_load_cond\n')
Pre_opt(count,:)=[loading FVSI_set Lmn_set Ploss Qloss Vm_load_cond]
% pause

loading = loading + step;
count=count+1;
end
```

APPENDIX 5: LINE OUTAGE CODING

```

clc
clear

Abus_data
AIFYBUS_opt                                % form the bus admittance matrix
Alfnewton_opt                              % Load flow solution by Newton Raphson method
ABUSOUT_opt                                % Prints the power flow solution on the screen
ALINEFLOW_opt_1                              % Computes and displays the line flow and losses
Afvsi_opt

FVSI_set=max_FVSI;
%Lmn_set=max_Lmn;
```