ASSESSMENT AND ANALYSIS OF VOLTAGE STABILITY INDICES IN POWER SYSTEM NETWORK

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ABSTRACT

Voltage collapse is one of the major causes of nationwide blackout in recent years. Through the monitoring of power system, issues can be foresee and prevented. Voltage stability indices (VSI) has been proposed to be the monitoring and predicting tool for voltage stability due to its simplicity and fast calculation. These VSI are able to calculate the proximity of the voltage towards voltage collapse or determine a weak bus or line. However, many assumptions have been made in order to derive a simple bus system. As such there will be error subject to tolerance level and different characteristics. In this study, 8 VSI will be examined, consisting both line VSI & bus VSI. These VSI will be evaluated in IEEE-14 bus systems. The IEEE-14 bus will be tested under n-1-line contingency and load variation test conditions. The outcome of this study is to compare performance and suitability of each VSI. Line VSI is suitable to monitor transmission line, whereas bus VSI is suitable to monitor overall bus voltage stability. VSI should be used collectively to ensure reliability of a power system.

Keywords: Voltage Stability Index (VSI), Voltage Collapse, Line VSI, Bus VSI,

ABSTRAK

Keruntuhan voltan adalah salah satu punca utama pemadaman di seluruh negara pada tahun-tahun kebelakangan ini. Melalui pemantauan sistem kuasa, kita boleh meramalkan dan mencegah isu-isu tersebut. Indeks kestabilan voltan (VSI) telah dicadangkan untuk menjadi pemantauan dan meramalkan alat untuk kestabilan voltan disebabkan kesederhanaan dan pengiraan pantas. VSI ini dapat mengira jarak voltan ke arah keruntuhan voltan atau menentukan bas atau garis yang lemah. Walau bagaimanapun, banyak andaian telah dibuat untuk mendapatkan sistem bas mudah. Oleh itu, terdapat ralat yang tertakluk kepada tahap toleransi, dan ciri-ciri yang berbeza. Dalam kajian ini, kita akan melihat ke dalam 8 VSI, yang terdiri daripada VSI & bas VSI. VSI ini akan dinilai dalam sistem bas IEEE-14. Bas IEEE-14 akan diuji di bawah syarat ujian kontingensi n-1-line dan beban variasi beban. Hasil kajian ini adalah untuk membandingkan prestasi dan kesesuaian setiap VSI. Talian VSI sesuai untuk memantau talian penghantaran, bas VSI sesuai untuk memantau kestabilan voltan bas keseluruhan. Menggunakan VSI ini secara kolektif untuk memastikan kebolehpercayaan sistem kuasa.

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VSI- Voltage Stability Indices

L – L Index

$VCPI_{bus}$ – Voltage collapse Prediction Index

NLSI – Novel Line Stability Index

FVSI – Fast Voltage Stability Index

SFVSI – Simplified Fast Voltage Stability Index

LQP – Line Stability Factor

VQI – Voltage Reactive Power Index

NVSI – New Voltage Stability Index

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CHAPTER 1: INTRODUCTION

1.1 Background of Study

In our times, utility companies have economic and environment limitations on building up a power system infrastructure. In addition, with the sharp increase of power demand, power systems are often heavily loaded. Voltage instability is a constant threat. A simple disturbance or sudden increase of load will cause voltage instability, and in the worst case, voltage collapse. Industrialization of the society and economy has evolved to zero tolerance towards any power disruption or black out. Any of such events will cause huge economic losses to all sectors. These are some of the main drivers to ensure voltage stability.

Based on IEEE definition, voltage stability is the ability of a system to maintain voltage so that when load admittance is increased, load power will increase, and so that both power and voltage are controllable (Kunder, 1994). In every power system, there are power margin for the power system to withstand disturbance or to meet an increased load demand. This power margin represents the distance between operating condition and the maximum limit of generation or transmission line (Kunder, 1994). These are the critical points of a power system. Beyond these points, a power system will experience voltage instability or in the worst-case voltage collapse. Knowing the distance of the operation condition against the critical point will shed light on how to manage the power system or apply prevention measure. Voltage Stability Indices (VSI) can fulfil this role.

Voltage stability indices (VSI) are formulas to calculate the proximity of a system towards voltage instability (Benalia Nadia, 2018). VSI formula are derived from simple bus with voltage stability margin. VSI is a scalar magnitude value that ranges from 0 to 1, where 0 is stable, and 1 is near instability (Claudia Reis, 2006). This simplified valueis easy to read and understand. VSI is used as monitoring tool via online to determine the current state of a power system. It can also be used as a calculation tool to determine a weak line or bus of a power system.

By referencing to the VSI value, operator of a power system is able to determine the next course of action to curb voltage collapse. VSI by itself is purely a number, unable to resolve any voltage instability issue. It needs to be interpreted concurrently with a method or mitigation plan. Only then, VSI will be useful to improve the reliability of a power system. Some (H.H. Goh, 2015), (K.R. Vadivelu, 2013) even proposed using VSI with artificial intelligent (AI) to enable AI to react accordingly in ensuring voltage stability.

1.2 Problem statement

Voltage stability index is derived from 2 bus power circuit against the voltage instability points. In order to simplify the voltage stability indices (VSI)'s formula, assumptions have been made. Some common assumptions are power angle (δ) is assumed to be negligible, power factor to be unity, and admittance (Y) or impedance (Z) are ignored. Different assumption made will form different voltage stability index formula. Many VSI formulas have been derived and proposed since there are many variables available. It is expected that deviation will occur when these formulae are applied on real conditioned power system. These deviations or errors will translate into prediction error, thus misinterpretation, and finally result in wrong mitigation action.

Furthermore, different VSI formula have different characteristic. There is no one VSI that is applicable to all power system condition. Some VSI are applicable on power bus, and some on power line. Their functionality is restricted to either monitoring of line or bus only.

The common causes of voltage instability in a power system are sudden loss of generation and transmission line, load increment beyond stability point, and tap changer operation. VSI need to be tested in such voltage instability scenarios to verify its functionality. The performance of the VSI varies according to formula and to system condition.

1.3 Objective

The main goal of this study is to analyze performance of different VSI. The specific objectives of this study are as listed below

1. To model IEEE-14 Bus system for load flow analysis.

2. To analysis different type of voltage stability index for n-1 contingency analysis.

3. To analyse different type of the voltage stability index for load variation analysis.

1.4 Scope of Study

There are over 20 types of VSI proposed over the years. The 8 VSI selected are listed below in Table 1.1. It consists of 2 bus VSI, and 6 line VSI. The selection of these 8 VSI are mainly due to its simple formulas. These VSI are easy to use and are able to be recalculated quickly, becoming one of the most frequently discussed VSI among its peers.

Table 1.1: The 8 Selected VSI

No.	Index	Abbreviation	Type
1	L-index	L	For Bus
2	Voltage Collapse Prediction Index	$VCPI_{bus}$	For Bus
3	Novel Line Stability Index	NLSI	For Line
4	Fast Voltage Stability Index	FVSI	For Line

5	Simplified Fast Voltage stability index	SFVSI	For Line
6	Line Stability Factor	LQP	For Line
7	Voltage Reactive Power Index	VQI	For Line
8	New Voltage Stability Index	NVS	For Line

Steady state analysis will be carried out in this study which is widely accepted compared to dynamic analysis. The power system is assumed to be in a steady state, so that system can be modelled and analyzed easier. In order to analyze the performance of the selected VSI, the test bus system needs to be subjected to voltage instability scenarios. N-1 line contingency and load variation will be used in this study. The modelled power system selected is IEEE-14 bus test system. This model will be simulated on a software MATLAB. MATLAB is able to run load flow analysis to determine the steady state of the power system at each state. Using the steady state variable, we are able to calculate each VSI index value, and analyze them.

1.5 Thesis Outline

There are 5 chapters in this study. Chapter 1: Introduction, brief introduction on VSI, and the objective as well as scope of this paper. Chapter 2: Literature Review, other writings regarding VSI by various authors. This encompasses review on all the selected VSI formulas. Chapter 3: Methodology, detail description on how the simulation is run in order to test VSI. Chapter 4: Result and Discussion, result display from all test and discussion on the performance of selected VSI. Chapter 5: Conclusion, the conclusion of VSI performance.

CHAPTER 2: LITERATURE REVIEW

2.1 Summary

In this chapter will cover the overall types of VSI have been proposed. Listing the difference and comparison of each type of VSI, and discuss the suitability of the selected VSI according to this study. Next, the detailed explanation of how VSI formula been derived, and followed by each formula's derivation & functionality. Lastly, the comparison of each selected VSI's formula and functionally. Understanding these derivation of each selected VSI, will foresee the behavior of the VSI in testing.

2.2 Voltage stability index

There are two concepts of VSI, Jacobian matrix based VSI and system variable based VSI. Jacobian matrix based VSI can calculate voltage collapse point or maximum loadability limit to determine the voltage stability margin. But this concept of VSI requires long computation time. Any topology change will lead to a change in the Jacobian matrix and the whole gigantic table must be recalculated. Thus, this computation technique is not suitable for online system. Alternatively, system variable based VSI which uses system variables to calculate the VSI requires less computation time. Essential system variables for this computation are bus voltages or real and reactive power, impedance and others. This is more suitable for online monitoring and capable of fast assessment on critical line or weak buses [(H.H. Goh, 2015)]. Nevertheless, this concept of VSI is purely an estimation of the actual margin from voltage collapse. Table 2.1 below lists down the differences between these two methods.

Table 2.1: Differences Between Jacobian Matrix and System Variables Based Voltage Stability Indices

Jacobian matrix based VSI	System variables based VSI

Require more amount of computing time	Require less amount of computing time
Suitable for offline monitoring purpose	Suitable for online monitoring purpose
Discover voltage stability margin	Discover weak buses and lines
Proximity towards voltage collapse	Mechanism of voltage instability

VSI have different functionality and are able to monitor different parts of a power system. It is separated into 3 type of VSI, overall VSI, bus VSI and line bus. Overall VSI calculates the overall voltage stability for the whole power system. Bus VSI is able to monitor bus while line VSI monitors transmission line. According to (Javad M., 2016),overall VSI is more accurate but requires more complex formula as compared with bus VSI and line VSI. Conversely, line VSI is more simple in formula but less accurate compared to bus VSI and overall VSI. In this study, we will only cover line and bus VSI for the reasons stated above.

2.3 Derivation of VSI

VSI are derived from the voltage collapse point. Voltage collapse point refers to the critical point where generation unable to meet a load demand. Understanding the characteristics of voltage collapse point will give clarity on VSI derivation. Basically, voltage collapse point can be explain using two bus of a power system shown in figure 2.1 (Javad M., 2016)

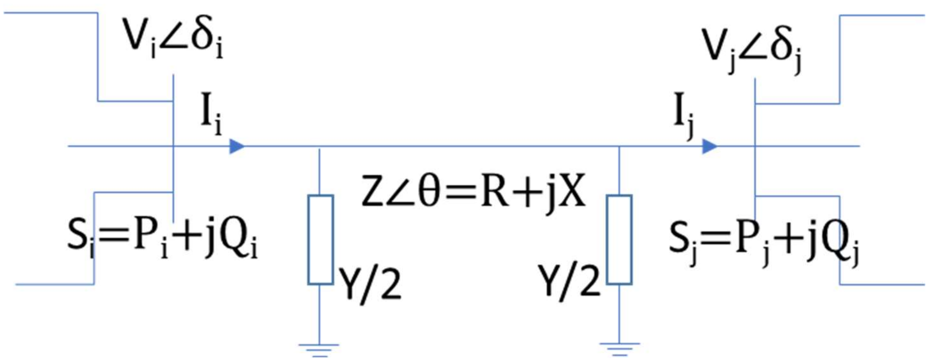


Figure 2.1: 2 Bus Representation of a Power System

V_i, V_j: voltage magnitude at the sending and receiving buses respectively.

P_i, Q_i: active and reactive power at the sending bus

P_j, Q_j: active and reactive power at the receiving bus

S_i, S_j: apparent power at the sending and receiving buses respectively.

δ_i, δ_j: voltage angle at the sending and receiving buses respectively.

Y: Line Shunt Admittance

R, X, Z, θ: line resistance, line reactance, line impedance and angle respectively.

The active (P_j) and reactive (Q_j) power at the receiving bus ca be written as

$$P_j = \frac{V_i V_j cos(\delta_i - \delta_j) - V_j^2 - Q_j X}{R} \quad (2.1)$$

$$Q_j = \frac{P_j X - V_i V_j sin(\delta_i - \delta_j)}{R} \quad (2.2)$$

From (2.1) and (2.2), the following forth degree equation can be derived

$$V_j^4 + (2P_j R + 2Q_j X - V_i^2)V_j^2 + (P_j^2 + Q_j^2)Z^2 = 0 \quad (2.3)$$

In equation (2.3), value zero represents the voltage collapse point. Since it is a fourth-degree equation, solving this equation will have two pair of real identical roots. If the load increase further, then the roots become complex number. In order to ensure stable voltage equation (2.3) must be greater or equal to zero. Solving the equation, the index scalar value will be ranging from 0 to 1. Value 1 represents the equation in an unstable condition.

2.4 Line Voltage Stability Indices

Line VSI are used to calculate the line's voltage condition. All of the VSI are basically derived from simple 2 bus system as illustrated in Figure 2.1. Generally, line VSI equation assumes Y, line shunt admittance is neglected. The system variables needed range from the sending bus and receiving bus, which is inclusive of the transmission line.

2.4.1 Fast Voltage Stability Index (FSVI)

Proposed by Musirin et al., FVSI is based on the concept in which the discriminant of the voltage quadratic equation (2.3), is set to be greater than or equal to zero [x]. Derivation as below: (Musirin I, 2002)

$$I = \frac{V_i\angle\delta_i - V_j\angle\delta_j}{Z\angle\theta} \tag{2.4}$$

$$I = \left(\frac{S_j}{V_j}\right)^* = \frac{P_j - jQ_j}{V_j\angle\delta} \tag{2.5}$$

Taking (2.4) = (2.5), $\delta = \delta_i - \delta_j$ and rearranging the equation will lead to

$$P_j - jQ_j = \frac{-|V_j^2|\angle -\theta + |V_iV_j|\angle(\delta-\theta)}{|Z|} \tag{2.6}$$

From (2.6), the reactive power of the receiving bus forms the quadratic equation for the V_j is evaluated as

$$|V_j|^2 - |V_iV_j|\left[\frac{R}{X}sin\delta + con\delta\right] + \left[\frac{R^2}{X} + X\right]Q_j = 0 \tag{2.7}$$

$$\frac{\left[\frac{R}{X}sin\delta + con\delta\right]|V_i| \pm \sqrt{\left[\left[\frac{R}{X}sin\delta + con\delta\right]|V_i|\right]^2 - 4\left[\frac{R^2}{X} + X\right]Q_j}}{2} \tag{2.8}$$

Where, R is the line resistance and X is the line reactance. In order to obtain the real root, of V_j, the determinant must be set to be greater or equal to 0 to fulfil the stability criterion.

$$\frac{4|Z|^2 Q_j X}{|V_i|^2 (Rsin\delta + Xcon\delta)^2} \leq 1 \tag{2.9}$$

Since the angle difference is normally small and can be neglected, therefore Rsinδ ≈0 and Xcosδ≈X, thus

$$FVSI = \frac{4Z^2 Q_j}{V_i^2 X} \tag{2.10}$$

The FVSI value indicate value near 1 as voltage instable, value near 0 as stable. If the value goes beyond 1, one of the buses that is connected to the line will experience a sudden voltage drop, leading to system collapse.

2.4.2 Simplified Fast Voltage Stability Index (SFVSI)

Proposed by I. Musurin et al, same characterises with FVSI, it is considered unstable if value is greater than 1. FVSI is further simplified, assuming Rsin(δ)≈0, the reactive power at the receiving end can be express as: (Sahari S. Abidin A.F, 2003)

$$Q_r = \frac{X}{Z^2}\left(V_i V_j - V_j^2\right) \tag{2.11}$$

Replace Q_j in FVSI, SFVSI written as

$$SFVSI = \frac{4V_j}{V_i}\left(1 - \frac{V_j}{V_i}\right) \tag{2.12}$$

2.4.3 Line Stability Factor (LQP)

Mohamed et al. developed the line stability factor (LQP) based the same concept as FVSI. For the transmission line to be stable, the value needs to be less than 1. The LQP formula assumed line to be lossless (R/X < 1) and the shunt admittance of line is neglected. (Mohamed A, 1989)

$$P_j = \left[(V_i cos\delta - V_j)\frac{R}{R^2 + X^2} - V_i sin\delta \frac{X}{R^2 + X^2}\right]V_j \tag{2.13}$$

$$Q_j = \left[(V_i cos\delta - V_j)\frac{X}{R^2 + X^2} - V_i sin\delta \frac{R}{R^2 + X^2}\right]V_j \tag{2.14}$$

By considering losses in the system and taking R/X<<1, it can be simplified to

$$P_j = \frac{V_i V_j sin\delta}{X} \tag{2.15}$$

$$Q_j = V_i V_j cos\delta - V_j^2 \tag{2.16}$$

Rearranging (E) and (E) to satisfy $sin^2\delta + cos^2\delta = 1$ yields quadratic equation of V_j

$$V_j^2 + (2Q_jX + V_i^2)V_i^2 + Q_j^2X^2 + P_j^2X^2 = 0 \tag{2.17}$$

Thus, applying stability criterion where the determinant of V_j^2 need to be greater or equal to zero

$$(2Q_jX + V_i^2)^2 - 4(Q_j^2X^2 + P_j^2X^2) \geq 0 \tag{2.18}$$

$$V_i^4 - 4XQ_jV_i^2 - 4(P_j^2X) \geq 0 \tag{2.19}$$

Since the line is considered lossless $P_i = -P_j$, the LQP is below

$$LQP = 4\left(\frac{X}{V_i^2}\right)\left(Q_j + \frac{P_i^2 X}{V_i^2}\right) \tag{2.20}$$

2.4.4 Novel Line Stability Index (NLSI)

Proposed by Yazdanpanah-Goharrizi, NLSI indicate value 1 is close to instability. Substituting equation (2.1) and (2.2), and obtained (Yazdanpanah-Goharrizi A, 2007)

$$V_i V_j sin\delta - RQ_j + XP_2 = 0 \tag{2.21}$$

$$V_j^2 - V_i V_j cos\delta + RP_j + XQ_j = 0 \tag{2.22}$$

The quadratic equation for the receiving bus is given by

$$V_j = \frac{V_i cos\delta \pm \sqrt{V_i^2 cos^2\delta - 4(P_j R + Q_j X)}}{2} \tag{2.23}$$

To obtain real V_j, equation (2.23) must be greater than or equal to zero.

$$\frac{P_j R + Q_j X}{0.25 V_i^2 cos^2\delta} \leq 1 \tag{2.24}$$

Assuming cosδ≈1 and obtain NLSI

$$NLSI = \frac{P_j R + Q_j X}{0.25 V_i^2} \tag{2.25}$$

2.4.5 New Voltage Stability Index (NVSI)

Derived by Kanimozhi et al., NVSI indicate stability when value is less than 1. NVSI assumed figure 2.1, no loss condition. The index is formulated as below (Kanimozhi R, 2013)

$$I = \frac{V_i \angle \delta_i - V_j \angle \delta_j}{-jX} \tag{2.26}$$

$$S_j = V_j I^* \tag{2.27}$$

Incorporating (2.26) into (2.27) and solving it as similar LQP (2.13) to (2.14) and formed

$$\left(2Q_j X + V_i^2\right)^2 - 4\left(Q_j^2 X^2 + P_j^2 X^2\right) \geq 0 \tag{2.28}$$

This equation is similar as (2.18). NVSI direct simplified into

$$NVSI = \frac{2X\sqrt{P_j^2 + Q_j^2}}{2Q_j X - V_i^2} \tag{2.29}$$

2.4.6 Voltage Reactive Power Index (VQI)

Derived by Althowibi et al.. It is considered as unstable if the VQI value is greater than 1. Formula of VQI assumed δ and shunt admittance is neglected. (Althowibi FA, 2010)

$$VQI = \frac{4Q_j}{\left|img\left(\frac{1}{R + jX}\right)\right| V_i^2} \tag{2.29}$$

2.5 Bus Voltage Stability Index

Bus VSI determines the voltage stability of a system buses but unable to provide information on line transmission. Thus Bus VSI is unable to determine the weak transmission line. It can only determine weak buses.

2.5.1 Voltage Collapse Prediction Index (VCPI)

VCPI is derived from the basic power flow equation proposed in (Balamourougan V, 2004). Value near 1 indicates voltage unstable, whereas value near 0 indicates stable. The formula is written as:

$$VCPI = \left| 1 - \frac{\sum_{\substack{m=1 \\ m \neq i}}^{N} V'_m}{V_i} \right| \tag{2.30}$$

Where

$$V'_m = \frac{Y_{im}}{\sum_{\substack{j=1 \\ j \neq i}}^{N} Y_{ij}} \tag{2.31}$$

V_i and V_m are the voltage phasors at bus m and bus i, N is the number of buses, and Y_{im} is the admittance between the buses i and m. This index is based on the concept that the voltage equations must have a solution, the admittance matrix must not be zero.

2.5.2 L-index

Proposed by Kessel et al.,also develop from power flow equation. This index has been derived as follows (Kessel P, 1986)

$$L = max_{j \in \alpha_L}\{L_j\} = max_{j \in \alpha_L} \left|1 - \frac{\sum_{i \in \alpha_G} F_{ji} V_i}{V_j}\right| \tag{2.32}$$

Where α_L is the set of load buses, α_G is the set of generator buses, V_j and V_i are voltage phasors at bus j and bus i. F_{ji} is the element in j-th row and i-th column if matrix F whose elements are generated from the admittance matrix (2.34).

$$F = -Y_{LL}^{-1} Y_{LG} \tag{2.33}$$

And

$$\begin{bmatrix} I_L \\ I_G \end{bmatrix} = \begin{bmatrix} Y_{LL} & Y_{LG} \\ Y_{GL} & Y_{GG} \end{bmatrix} \begin{bmatrix} V_L \\ V_G \end{bmatrix} \tag{2.34}$$

The value of L-index varies between 0 and 1, where 1 is consider voltage collapse. It is shown that the stability limit is L=1 when two conditions are fulfilled (Qitao Liu, 2017). The first condition requires that all generator voltage remain unchanged. The second is related to the nodal currents in which the nodal current at bus j is directly proportional to the current I_i and in indirectly proportional to the voltage V_i. In general, these two conditions are satisfied approximately.

2.6 Theoretical Comparison of VSI and Summary

The selected line VSI are generally derived from a 2 bus system, however with different assumptions, it results into different formula. With different VSI formulas, we will observe different characteristic and reaction with power system. The selected bus VSI's formula consists of Y bus and V. Table 2.2 is the comparison summary of the VSI. (N.A.M. Ismail, 2014)

Table 2.2: Comparison of VSI

Index	Formula	System Variable	Assumption	Critical Value
FSVI	$\frac{4Z^2Q_j}{V_i^2X}$	Q, Z, X, V	δ = 0	1
SFSVI	$\frac{4V_j}{V_i}\left(1-\frac{V_j}{V_i}\right)$	V	δ = 0	1
LQP	$4\left(\frac{X}{V_i^2}\right)\left(Q_j+\frac{P_i^2X}{V_i^2}\right)$	Q, P, X, V	R/X<<1	1
NLSI	$\frac{P_jR+Q_jX}{0.25V_i^2}$	Q, P, R, X	δ = 0	1
NVSI	$\frac{2X\sqrt{P_j^2+Q_j^2}}{2Q_jX-V_i^2}$	Q, P, X, V	R/X<<1	1
VQI	$\frac{4Q_j}{\left\|img\left(\frac{1}{R+jX}\right)\right\|V_i^2}$	Q, R, X, V	δ = 0	1
L-Index	$\left\|1-\frac{\sum_{m=1, m\neq i}^{N} V'_m}{V_i}\right\|$	Y bus, V	All generator voltage remains unchanged	1
$VCPI_{bus}$	$\left\|1-\frac{\sum_{i\in\alpha_G}F_{ji}V_i}{V_j}\right\|$	Y bus, V		1

According to the VSI formulas, FSVI and VQI will react to reactive power load variation since there is only Q in the formula. LQP, NLSI, NVSI consist of system variable P and Q, these VSI will react well to the system when real and reactive power load increases. SFSVI formula is a ratio of receiving bus voltage over sending bus voltage. It will react poorly with the system since other system variables are not included. Both bus VSI, L-Index and $VCPI_{bus}$ using Y bus and voltage (V) should be used to determine the stability condition of a bus.

CHAPTER 3: METHODOLOGY

3.1 Introduction

Voltage Stability Indices (VSI) are able to display scalar value to indicate the proximity of a system toward voltage instability. It is a simple formula derived to be used as a monitoring tool or to determine the weak area of a power system. Since the selected VSI are system variable based VSI, the variable in the modelled bus system will be used to apply on the VSI formula to calculate the VSI value. The VSI value obtained will be used to analyze the performance of the VSI.

Generally, the flow of the simulation is as such: firstly, perform base test to determine the base value VSI by using the initial steady state variables. Next, subject the power system to various test scenarios, and calculate the new VSI value. The two scenarios selected are N-1 line contingency and load variation. After each test, each VSI will be recalculated and recorded for analysis purpose. All modelling and test scenario simulation will be run on MATLAB software.

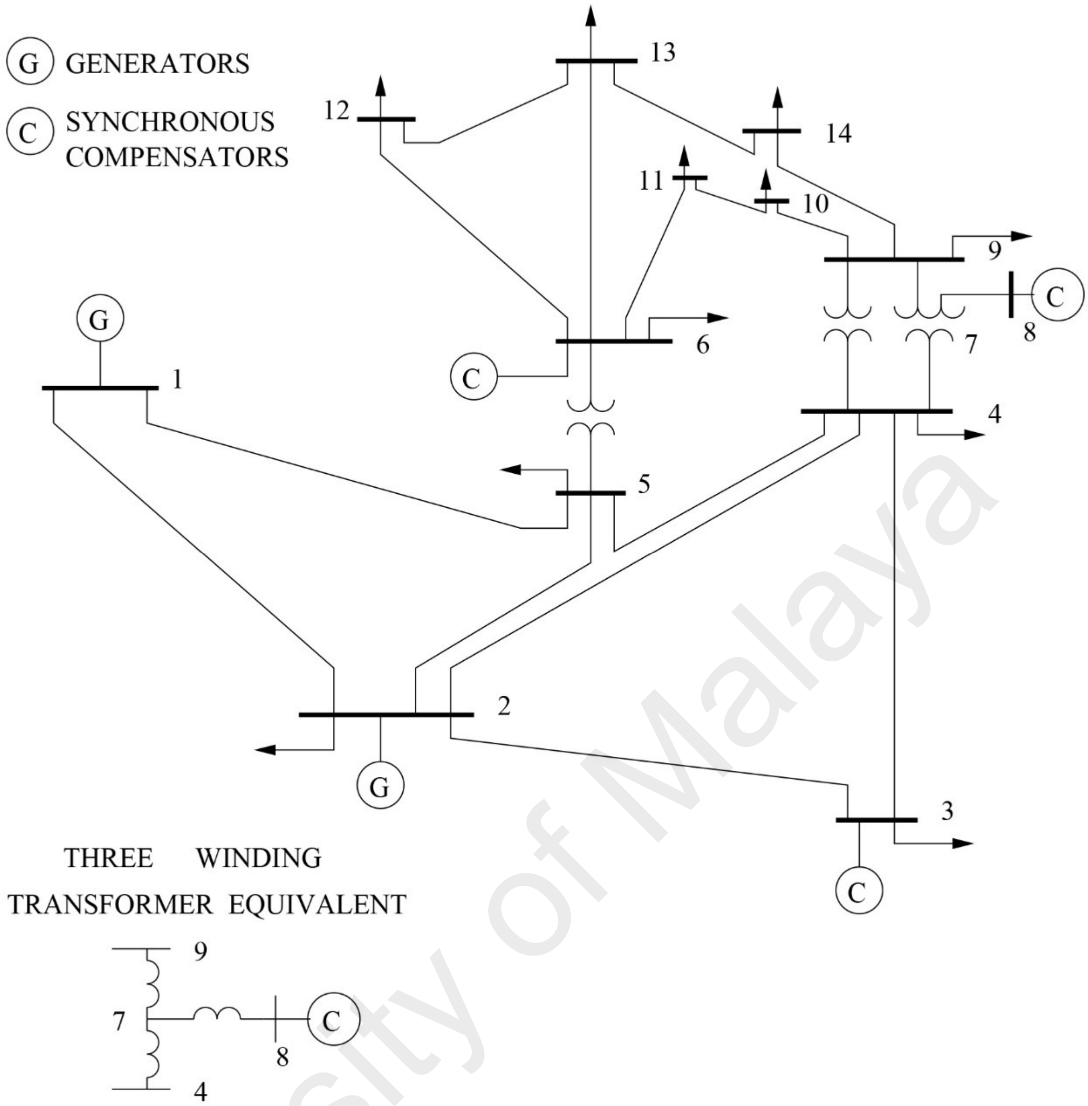


Figure 3.1: IEEE-14 Bus Test System

3.2 Test Model & Simulation

IEEE-14 bus system represents a portion of the American Electric Power System (in the Midwestern US) as of February, 1962 (Illinois Center for a Smarter Electric Grid (ICSEG), n.d.). It consists of 4 generators, one slack bus, 20 transmission and 11 different load buses. Bus 1 is a slack bus, bus 2, 3,6 and 8 are PV buses, and the remaining are PQ bus, refer appendix 2 and 3 as reference. The IEEE-14 bus system tests will be modelled in MATLAB. (Newton Raphson Load Flow for IEEE 14 Bus system, n.d.)

3.3 VSI Base Test

Firstly, load flow analysis will be applied on the IEEE-14 bus system to determine the steady state value. Newton Raphson method is the best calculation method to be applied on 14 bus system. This give 14 bus value which forms our base data, and the result of the load flow analysis will be our control. Below is the load flow analysis result of the IEEE-14 bus system base data. Next, control variables such as voltage, real & reactive power and admittance, are applied to the VSI's formula to obtain the VSI value. Figure 3.1 is the VSI base test flow.

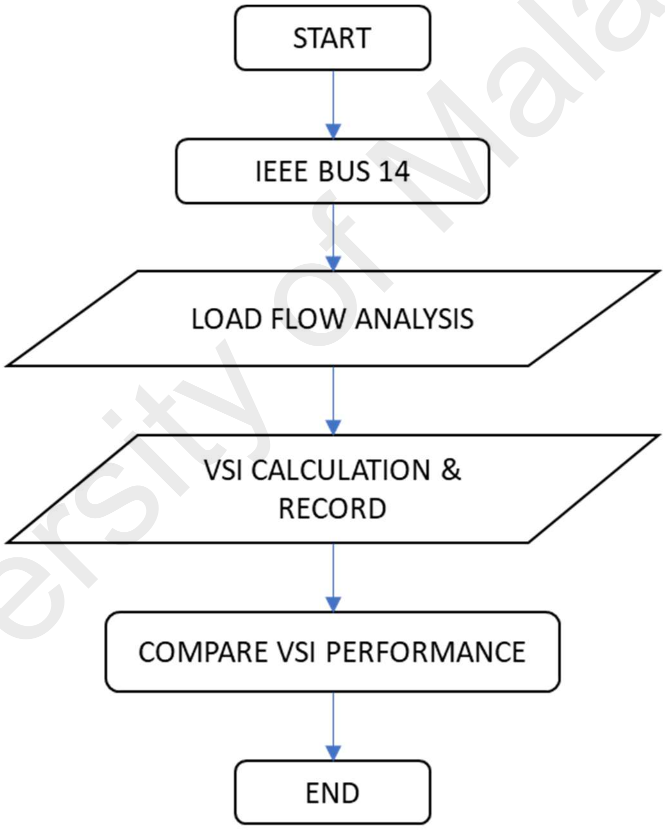


Figure 3.2: VSI Base Test Flow Chart

3.4 Scenario Test 1: Load Variation

The first test to simulate voltage instability scenario is load variation. When the load demand increases more than transmission capability, voltage will start to drop. In this study, all the load will be increased in incremental steps. At each increment, load flow analysis will be executed in order to determine the new steady state. VSI will be calculated and recorded using each new steady state system variables. The load variation test will continue in incremental step until the load flow analysis is unable to reach convergence. In the end, all the VSI will be compared and analyzed.

For this study, the increment of load demand is separated into 3 small tests. First test, the increment of real power (P) for load, refer Figure 3.2. The real power load will increase in 0.5x per step until load flow analysis is diverge. Second test, the increment of the load demand only on reactive power (Q), refer Figure 3.3. The reactive power will increase in 1x per step until load flow analysis is diverge. Third test, the increment of the load demand on the apparent power (S), both real (P) and reactive power (Q), refer figure 3.4. The apparent power will be increased in 0.25x per step until load flow analysis is diverge. By end of each step, VSI can be calculated using system variables, and VSI performance is assessed. This thorough experiment for all 3 tests will shed some light on the voltage behavior and VSI behavior.

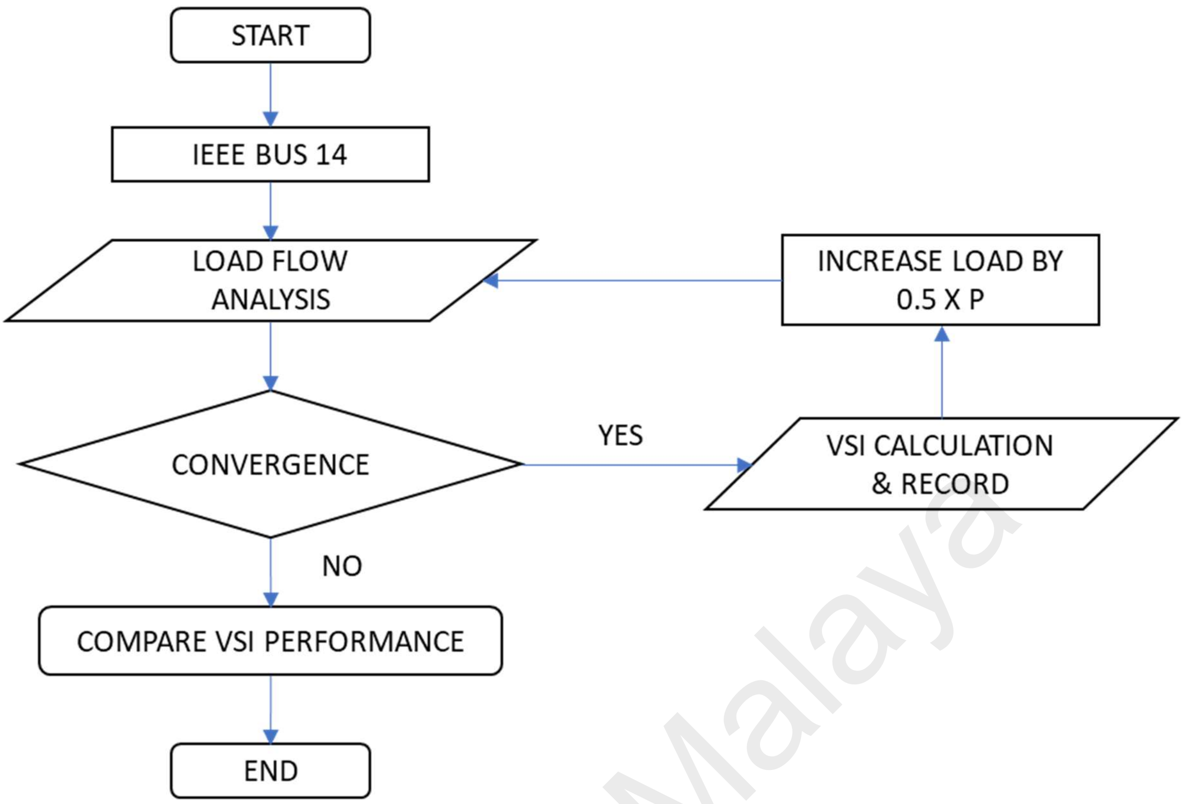


Figure 3.3: Real Power Increment Load Variation Test

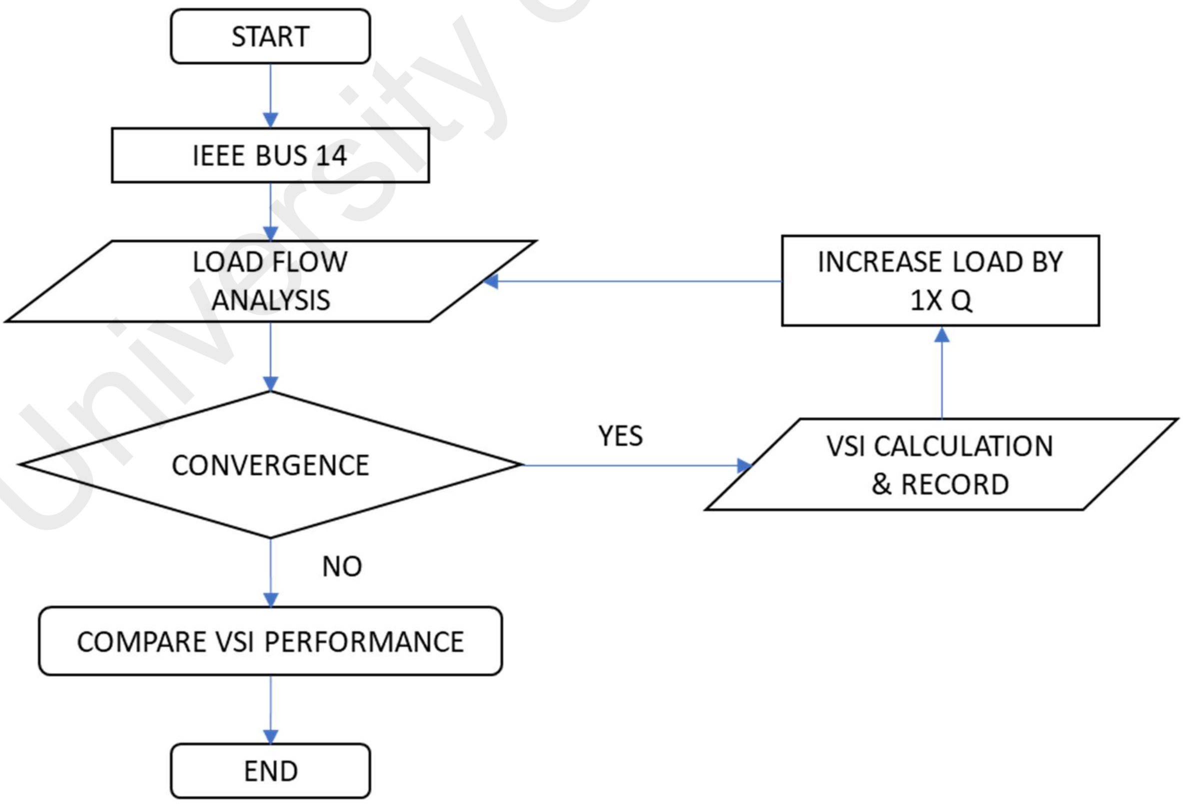


Figure 3.4: Reactive Power Increment Load Variation Test

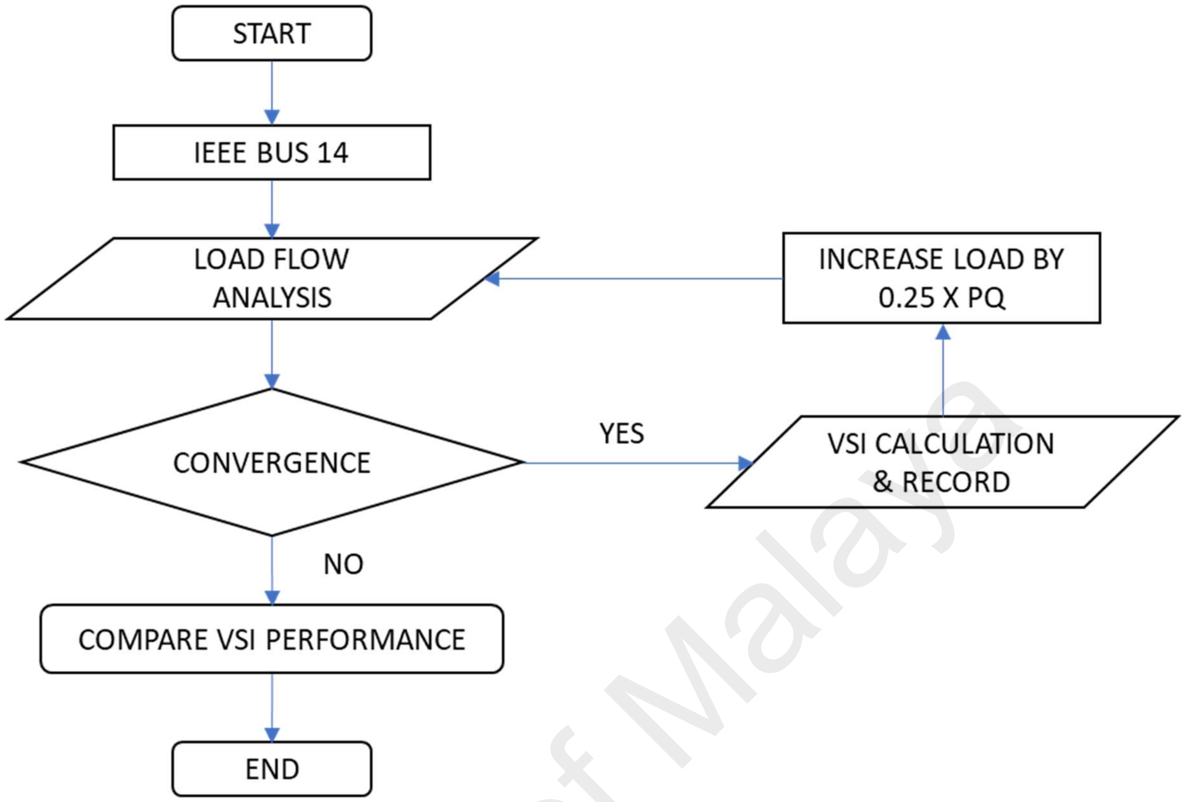


Figure 3.5: Real & Reactive Power Increment Load Variation Test

3.5 Scenario Test 2: N-1 Line Contingency

The second load variable test is to simulate loss of transmission line. This is simulated by removing line impedance coding in the MATLAB. In this study, only 1 line is removed each time for each test. As there is 20 lines in total, hence 20 testing cycle. Similar with load variation test, load flow analysis will be executed to reach the new steady state. And VSI is computed using the new steady state system variables. On each cycle, VSI will be calculated and recorded.

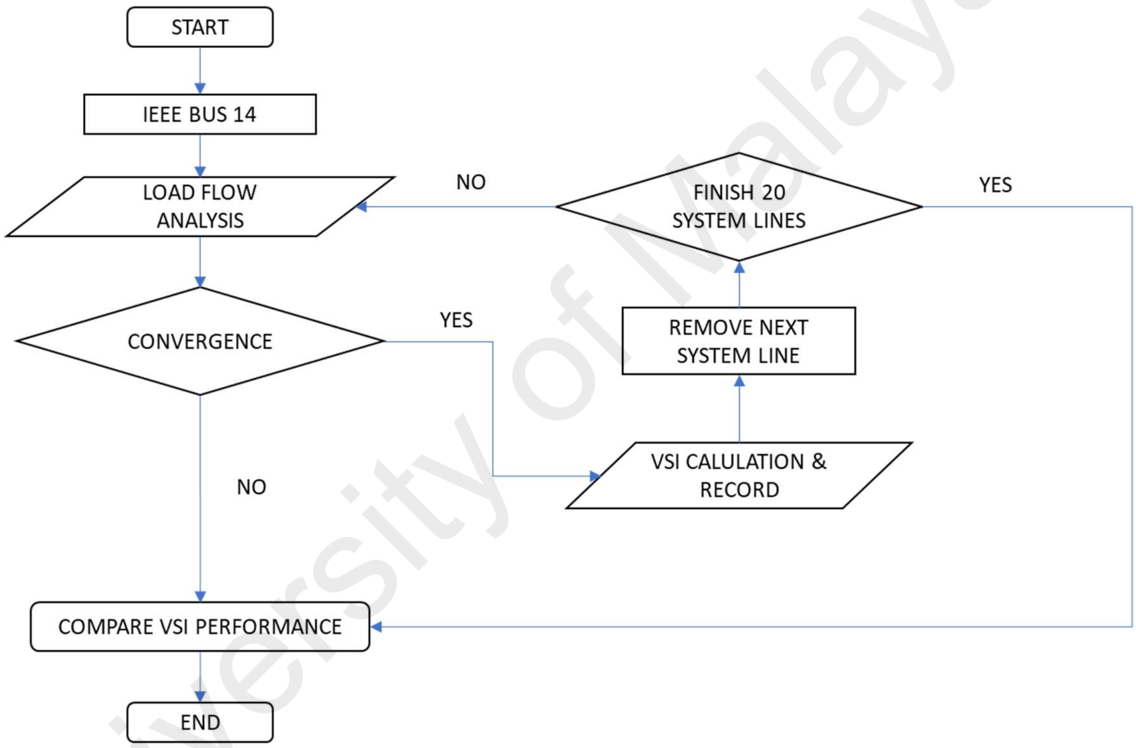


Figure 3.6: N-1 Line Contingency

3.6 Summary

By the end of this simulation, 2 test scenarios will be conducted. In the first test scenario, 3 sets of VSI data for load variation test covering, real power (P) increment, reactive power (Q) increment, and both power increment is obtained. In the second test scenario, only 1 set data of N-1 line contingency test is obtained. In total, there will be 4 sets of data for VSI performance analysis.

CHAPTER 4: RESULTS & DISCUSSION

4.1 Introduction

As mentioned in methodology chapter, there are three test scenarios tested on IEEE-14 bus system; namely, base test, load variation test, and N-1 line contingency test. The load variation test covers 3 type of load variation: real power (P) increment, reactive power (Q) increment, and apparent power (S) increment. The load power is increased in steps, and VSI value on each step is recorded. In N-1 line contingency test, transmission line is removed one by one and VSI at each line loss contingency is recorded. Lastly, we will analyze the VSI behavior and characteristics according to each test carried out.

4.2 Base Test

Base test is the steady state condition of the original IEEE-14 bus system. Load flow analysis will be carried out to determine the steady state value. Appendix 3, base test result is the base test system value at the steady state condition. Using the base test system variables, we are able to calculate the line VSI and bus VSI. Table 4.1 & Table 4.2 are the base result of line VSI and bus VSI.

Table 4.1: Base Line VSI Value

Line	Line VSI					
	FVSI	SFVSI	NLSI	VQI	LQP	NVSI
Line 1-2	0.0822	0.0558	0.0868	0.0845	0.1342	0.0434
Line 1-5	0.0134	0.1557	0.0273	0.0146	0.8654	0.0310
Line 2-3	0.0671	0.1295	0.2256	0.0718	0.0679	0.3543
Line 2-4	0.0279	0.1187	0.0335	0.0297	0.0287	0.0180
Line 2-5	0.0113	0.1043	0.0260	0.0119	0.0136	0.0249
Line 3-4	0.0302	0.0119	0.1518	0.0300	0.1259	0.1629
Line 4-5	0.0029	0.0159	0.0066	0.0029	0.0042	0.0064
Line 4-7	0	0.1346	0	0	0.0380	0
Line 4-9	0.3599	0.0723	0.3599	0.3474	0.6284	0.4474
Line 5-6	0.1513	0.2193	0.1513	0.1367	0.1527	0.1009
Line 6-11	0.0154	0.0877	0.0241	0.0161	0.0140	0.0138
Line 6-12	0.0176	0.0625	0.0405	0.0182	0.0168	0.0284
Line 6-13	0.0332	0.0841	0.0576	0.0347	0.0270	0.0339
Line 7-8	0.1354	0.1342	0.1354	0.1270	0.1354	0.0726
Line 7-9	0.0668	0.0565	0.0668	0.0687	0.0668	0.0704
Line 9-10	0.0211	0.0039	0.0292	0.0211	0.0206	0.0172
Line 9-14	0.0621	0.0460	0.1221	0.0636	0.0734	0.0820
Line 10-11	0.0137	0.0631	0.0224	0.0133	0.0126	0.0140
Line 12-13	0.0929	0.0227	0.1494	0.0940	0.0423	0.0541
Line 13-14	0.0788	0.1041	0.1564	0.0832	0.0708	0.1031

Table 4.2: Base Bus VSI Value

Bus	Bus VSI	
	VCPI	L-index
Bus 1	0.0198	0.0174
Bus 2	0.0077	0.0053
Bus 3	0.0180	0.0208
Bus 4	0.0108	0.0072
Bus 5	0.0127	0.1180
Bus 6	0.0267	0.1193
Bus 7	0.0145	0.0004
Bus 8	0.0315	0.0315
Bus 9	0.0023	0.0046
Bus 10	0.0054	0.0054
Bus 11	0.0033	0.0033
Bus 12	0.0059	0.0175
Bus 13	0.0079	0.0079
Bus 14	0.0186	0.0186

The red color highlighted cell is the top 10% of the VSI value, to indicate the high VSI value in base test. Line 4-9, already have high VSI value at base test. it might indicate line 4-9 is prone to voltage collapse. Line 1-5, 2-3 & 13-14, have some high VSI value. As for bus VSI, bus 5 & 6 have indication that these buses prone to voltage collapse.

Bus 1 will remain 1.06V is because bus 1 is a slack bus. Its voltage and angle are fixed. Power in both real and reactive power are generated and flowed from bus 1 to downstream bus. The bus that are near to bus 1 have strong stable voltage present due to nearer proximity to power generation. It is observed that line 4-9 display 0 value in most of its VSI. This seems to indicate strong and voltage stable line. Unfortunately, it is actually caused by one of the system variables with 0 value. The receiving bus 9 reactive power load Q_j is 0, causing the formula to display 0. This creates a false impression that line 4-9 is constantly showing voltage is stable in all system condition.

4.3 Load Variation Test

4.3.1 Real Power Increment

In this test, the real power is increased 0.5 real power (P) X at each step until the load flow analysis is diverge. The IEEE-14 bus able to run simulation until 3.5 x of real power (P) load. Below Figure 4.1 is the result of the real power (P) increment against voltage.

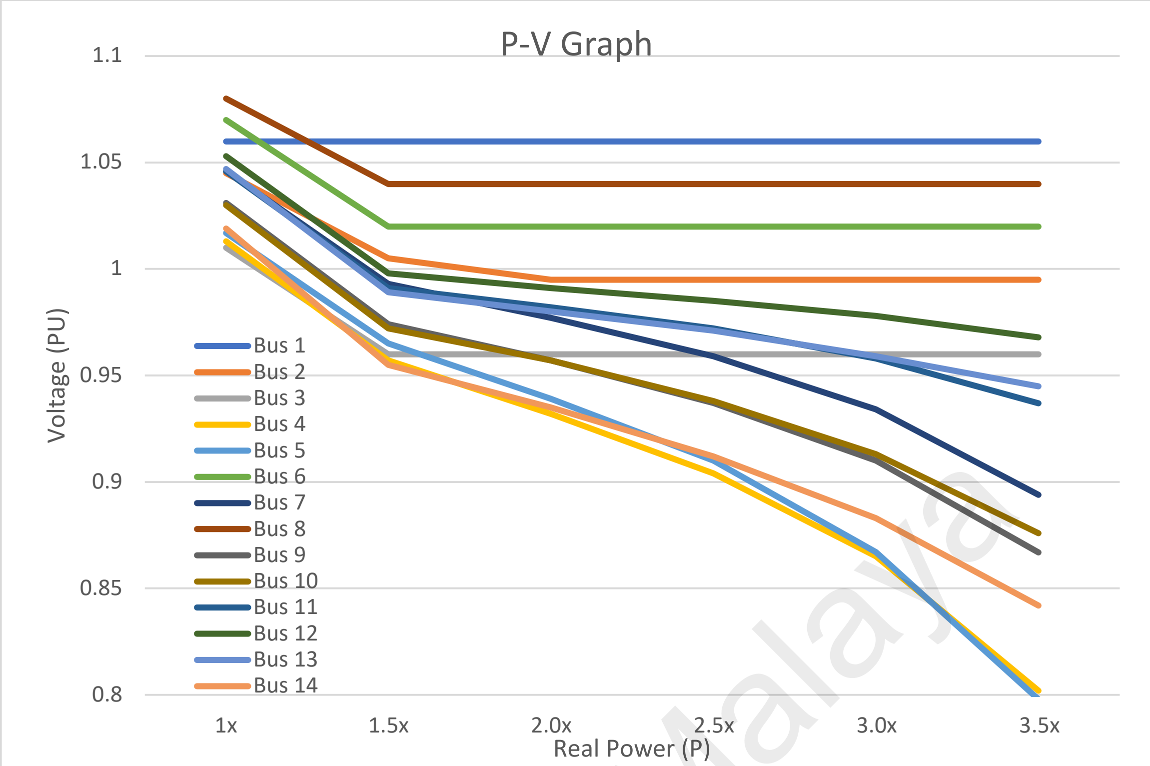


Figure 4.3: P-V graph

Bus 4, 5 & 14 experience voltage drop below 0.85 at 3.5 x real power increment. Bus 1, 6, & 8 experience minimal voltage drop and remain stable. The other bus experience voltage drops below 1, but is not considered as severe.

Table 4.4 is the result of Line VSI by 3.5x real power (P) increment. The red highlighted color cells are the VSI more than 1. By 3.5x real power (P) load, Line 1-2, 2-3 & 5-6, experience high VSI value, indicating lines have reach voltage unstable condition. Other lines are within the VSI limit, even though some bus experience voltage drop. Table 4.5 is bus VSI on 3.5x real power (P) increment. The bus VSI increase slightly according to real power increment, but there is no significant indication on bus experience voltage instability.

Table 4.4: Line VSI on 3.5x Real Power (P) Increment

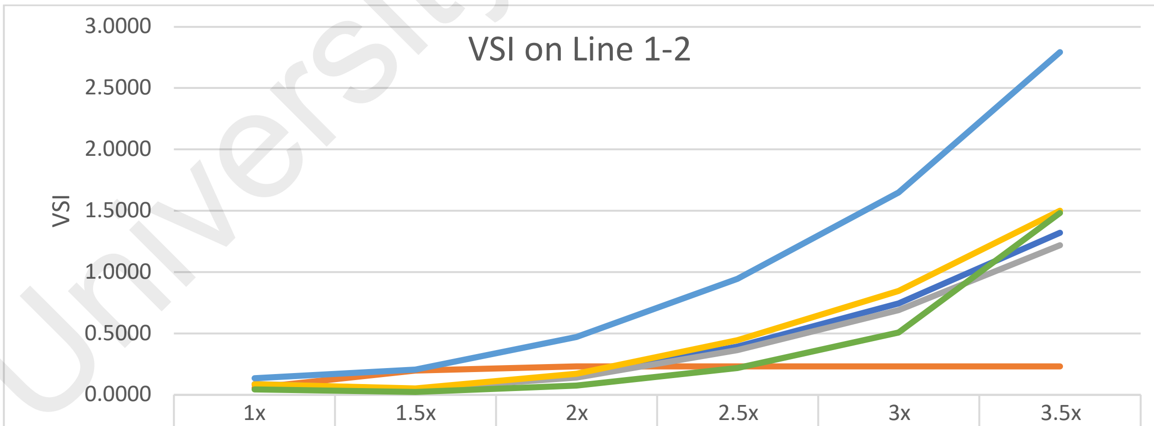
Line	FVSI	SFVSI	NLSI	VQI	LQP	NVSI
	Line VSI					
Line 1-2	1.3220	0.2302	1.2187	1.5003	2.7932	1.4841
Line 1-5	0.0134	0.7443	0.0639	0.0237	22.7375	0.1065
Line 2-3	2.3786	0.1358	2.8777	2.5552	2.2724	13.7737
Line 2-4	0.0308	0.6254	0.0369	0.0474	0.0442	0.0199
Line 2-5	0.0124	0.6352	0.0724	0.0193	0.0272	0.0941
Line 3-4	0.0334	0.5500	0.5155	0.0478	1.5264	0.6302
Line 4-5	0.0046	0.0199	0.0263	0.0047	0.0522	0.0244
Line 4-7	0	0.5115	0	0	1.1834	0
Line 4-9	0.5742	0.3505	0.5742	0.4913	8.9453	2.5368
Line 5-6	2.7123	1.4224	2.7123	1.6602	2.7567	3.9060
Line 6-11	0.0169	0.2990	0.0585	0.0200	0.0362	0.0477
Line 6-12	0.0194	0.1935	0.1166	0.0215	0.0529	0.1061
Line 6-13	0.0365	0.2725	0.1492	0.0426	0.0387	0.1210
Line 7-8	0.7576	0.7599	0.7576	0.5598	0.7576	0.6098
Line 7-9	0.0914	0.1172	0.0914	0.0972	0.0914	0.3017
Line 9-10	0.0298	0.0420	0.0794	0.0292	0.0800	0.0730
Line 9-14	0.0878	0.1120	0.4247	0.0931	0.6237	0.3909
Line 10-11	0.0189	0.2979	0.0684	0.0166	0.0409	0.0623
Line 12-13	0.1099	0.0928	0.4951	0.1154	0.0578	0.2082
Line 13-14	0.0967	0.3885	0.4772	0.1219	0.2136	0.4249

Table 4.5: Bus VSI on 3.5x Real Power (P) Increment

Bus	1x	3.5x	1x	3.5x
	Bus VSI			
	VPCI		L-index	
Bus 1	0.019783	0.100957	0.017439	0.09879
Bus 2	0.007709	0.039294	0.005257	0.036918
Bus 3	0.018033	0.069582	0.020754	0.067252
Bus 4	0.010786	0.073508	0.007187	0.069738
Bus 5	0.012682	0.110656	0.117988	0.054671
Bus 6	0.026716	0.102416	0.119322	0.175495
Bus 7	0.014479	0.039565	0.000383	0.013145
Bus 8	0.031481	0.140385	0.031481	0.140385
Bus 9	0.002337	0.006591	0.004582	0.00892
Bus 10	0.005367	0.013857	0.005367	0.013857
Bus 11	0.003333	0.009803	0.003333	0.009803
Bus 12	0.005901	0.017671	0.017514	0.043696
Bus 13	0.007902	0.02696	0.007902	0.02696
Bus 14	0.01861	0.070008	0.01861	0.070008

Bus 14 experience huge voltage drop until 0.85, however, line VSI indicate both line 13-14 and 9-14 voltage are stable. The bus 14 voltage drop may cause by low reactive power reaching to bus 14, even though the line 13-14 – 9-14 are in stable condition. Line VSI only able to monitor transmission line but unable to monitor bus. Furthermore, there are at least 2 to 3 lines that interconnecting to each bus, ensuring bus have sufficient power flow to maintain the voltage level.

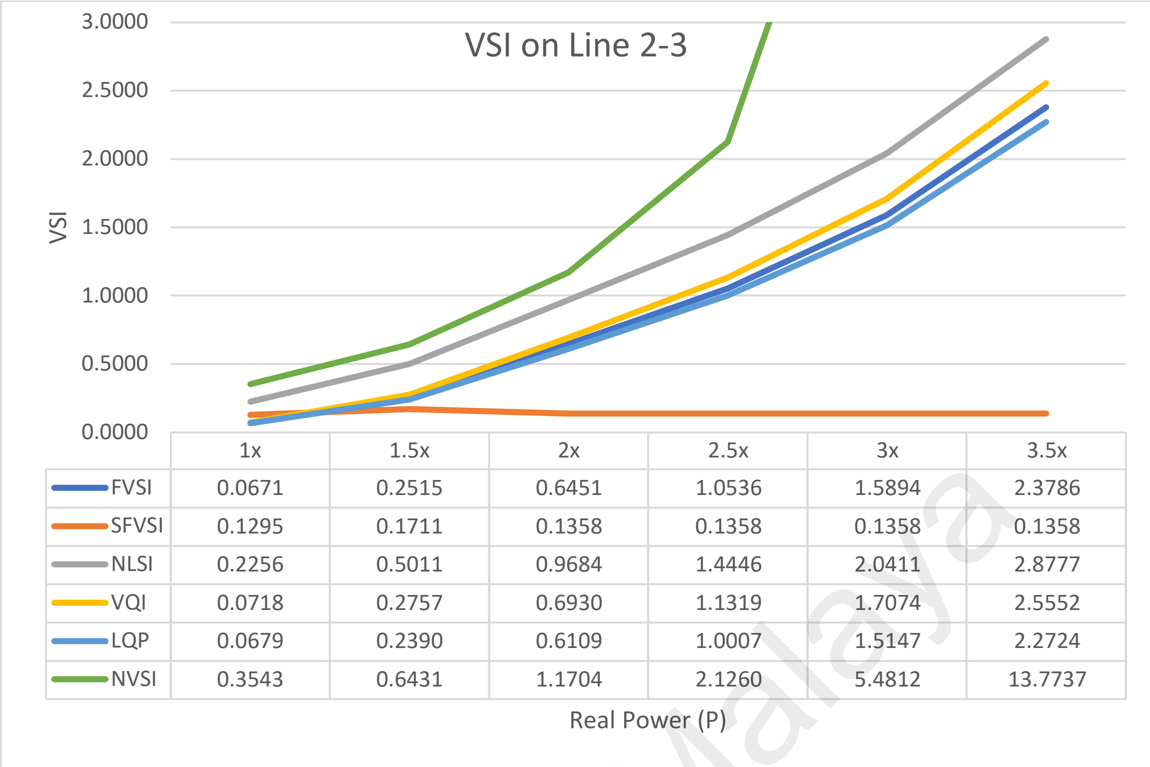
Figure 4.6, 4.7 and 4.8 are the worst line VSI in real power increment test. Generally, The figures show that these line VSI starting to reach critical value by 2.5x of real power increment. However, each line VSI reach critical value in different step of power increments, unable to determine clearly the actual value is the voltage instability occur. We observed that SFVSI remains low in line 1-2 & 2-3, and NVSI obtain huge value at line 5-6, huge error distance displayed. This shows that line VSI have accuracy issue. LQP and NVSI have system variable real power (P) in its formula, it will have greater influence in this real power increment test.



	1x	1.5x	2x	2.5x	3x	3.5x
FVSI	0.0822	0.0454	0.1507	0.3923	0.7440	1.3220
SFVSI	0.0558	0.1968	0.2302	0.2302	0.2302	0.2302
NLSI	0.0868	0.0461	0.1384	0.3641	0.6893	1.2187
VQI	0.0845	0.0505	0.1710	0.4452	0.8444	1.5003
LQP	0.1342	0.2047	0.4696	0.9449	1.6478	2.7932
NVSI	0.0434	0.0224	0.0731	0.2160	0.5075	1.4841

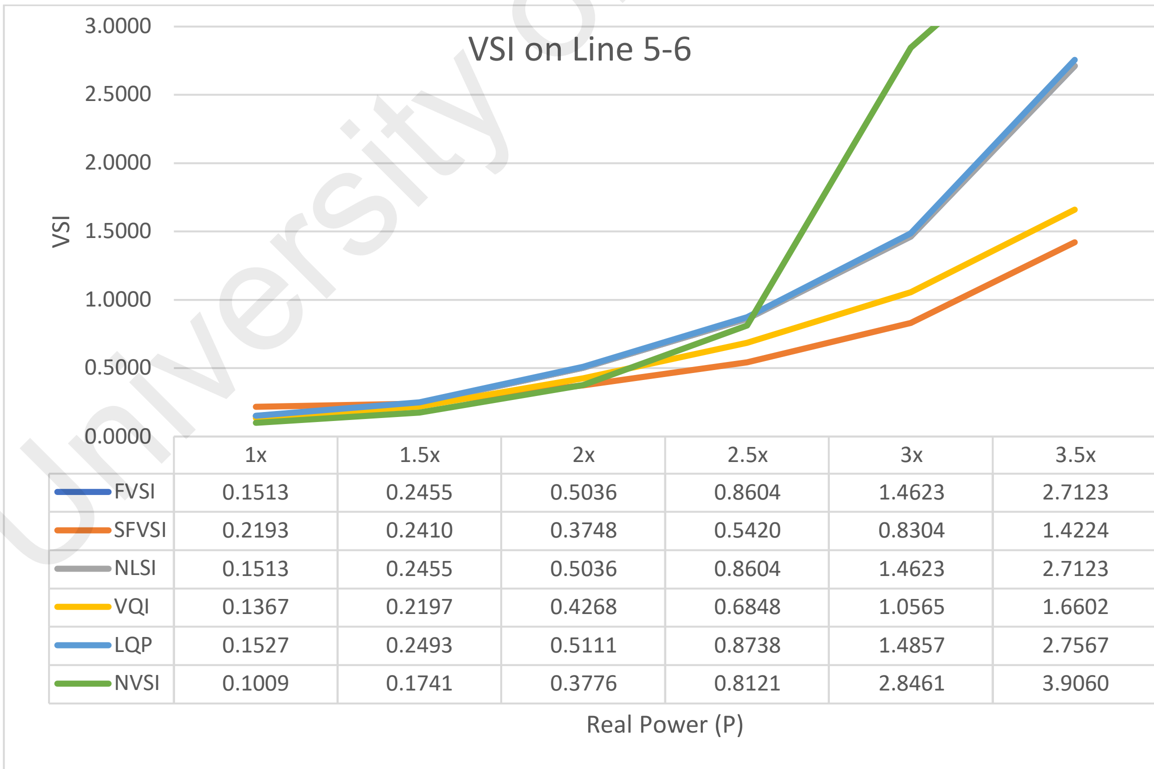
Real Power (P)

Figure 4.6: VSI on Line 1-2 on Real Power (P) Increment



	1x	1.5x	2x	2.5x	3x	3.5x
FVSI	0.0671	0.2515	0.6451	1.0536	1.5894	2.3786
SFVSI	0.1295	0.1711	0.1358	0.1358	0.1358	0.1358
NLSI	0.2256	0.5011	0.9684	1.4446	2.0411	2.8777
VQI	0.0718	0.2757	0.6930	1.1319	1.7074	2.5552
LQP	0.0679	0.2390	0.6109	1.0007	1.5147	2.2724
NVSI	0.3543	0.6431	1.1704	2.1260	5.4812	13.7737

Figure 4.7: VSI on Line 2-3 on Real Power (P) Increment



	1x	1.5x	2x	2.5x	3x	3.5x
FVSI	0.1513	0.2455	0.5036	0.8604	1.4623	2.7123
SFVSI	0.2193	0.2410	0.3748	0.5420	0.8304	1.4224
NLSI	0.1513	0.2455	0.5036	0.8604	1.4623	2.7123
VQI	0.1367	0.2197	0.4268	0.6848	1.0565	1.6602
LQP	0.1527	0.2493	0.5111	0.8738	1.4857	2.7567
NVSI	0.1009	0.1741	0.3776	0.8121	2.8461	3.9060

Figure 4.8: VSI on Line 5-6 on Real Power (P) Increment

Since the slack bus, bus 1 is supplying all the load, line that is near the bus 1 will transmit all of the power to downstream bus. High current will flow from bus 1 to downstream. In this case, line 1-2 and 2-3 have pass VSI critical value indicating these lines have reach the power transfer limit, unable to transmit more power. It will cause more power loss than transmitting power, more power need to be generated especially reactive power to compensate the power lost. Line 5-6 also have reach power transfer limit, due to high demand from bus 6. Bus 6 have 3 downstream connecting bus, requiring more power demand from bus 6. Since putting line 5-6 to stress to transmit more power in order to meet the power demand on bus 6.

4.3.2 Reactive Power (Q) Increment

In this test, the real power increase 1x reactive power (Q) at each step until the load flow analysis diverge. The IEEE-14 busable to run simulation until 9 x of reactive power (Q) load. Figure 4.9 is the result of the reactive power (Q) increment against voltage.

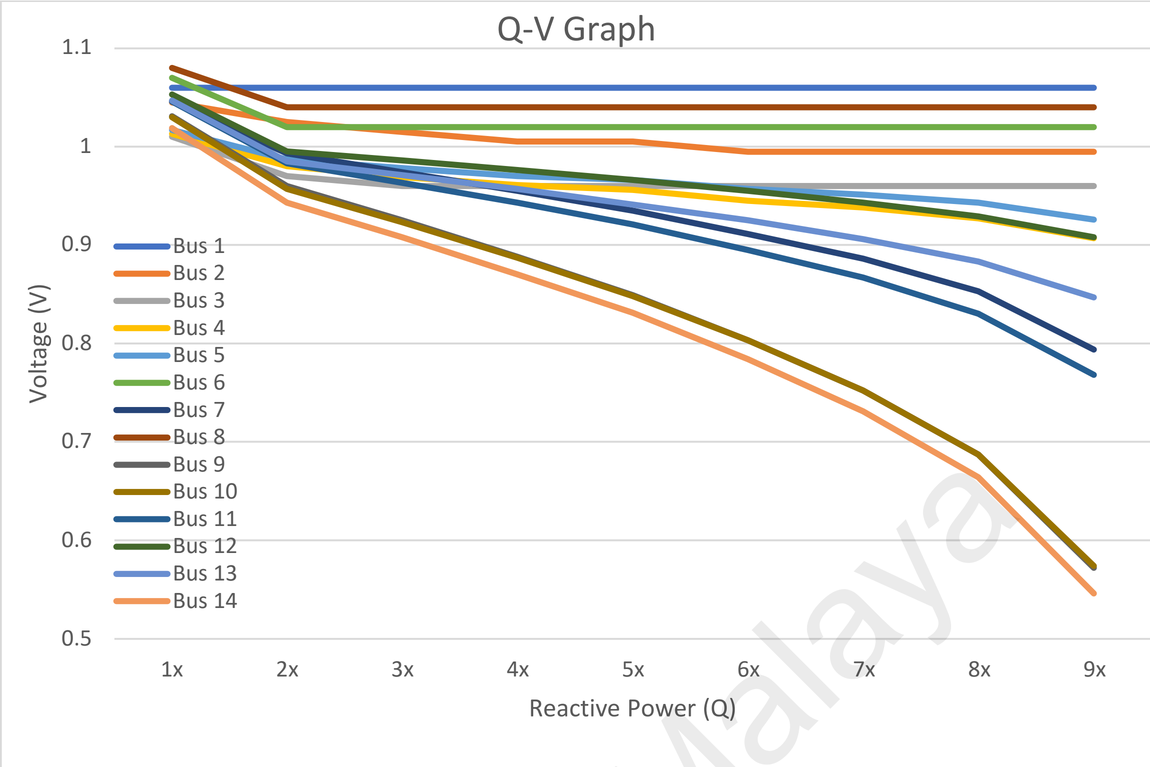


Figure 4.9: Q-V Graph

Bus 9, 10 & 14 experience the most voltage drop nearly to 0.5. Bus 7, 11 & 13 too experience voltage drops below 0.85. Most of the upstream bus (high voltage section), have quite stable voltage.

Table 4.10 are the results of line VSI & bus VSI on 9x reactive power increment. The red color highlighted cells are the VSI value more that 1, indicate that voltage instability occur. Most of the high VSI value located below downstream bus (low voltage section). Line 4-9, 5-6, 7-8-7-9, 9-14 & 13-14 are indicated experience voltage instability. Referring Figure 3.1, system circuit, bus 4 is connected to downstream bus 9 then to bus 14, these interconnected buses have high VSI value, indicating that region of the system experience with voltage instability, not just line alone. This region voltage instability also reflects in voltage drop at that region, bus 9, 10 & 14.

Table 4.10: Line VSI on 9x Reactive Power (Q) increment

	Line VSI					
Line	**FVSI**	**SFVSI**	**NLSI**	**VQI**	**LQP**	**NVSI**
Line 1-2	0.0235	0.2784	0.0339	0.0267	0.1111	0.0222
Line 1-5	0.1210	0.6626	0.1290	0.1586	1.1628	0.0611
Line 2-3	0.3589	0.1512	0.1609	0.3856	0.3451	0.4978
Line 2-4	0.2772	0.4257	0.3325	0.3336	0.2543	0.2021
Line 2-5	0.1120	0.3203	0.1187	0.1293	0.0970	0.0544
Line 3-4	0.3006	0.2474	0.1215	0.3367	0.3828	0.2531
Line 4-5	0.0324	0.0804	0.0344	0.0311	0.0271	0.0147
Line 4-7	0	0.6503	0	0	0.0591	0
Line 4-9	4.0403	3.7147	4.0403	10.1586	3.6225	0.6818
Line 5-6	3.4118	0.3347	3.4118	2.8120	3.4138	2.4184
Line 6-11	0.1521	1.7432	0.1367	0.2683	0.1220	0.0597
Line 6-12	0.1743	0.5543	0.1705	0.2200	0.1386	0.0718
Line 6-13	0.3289	0.9839	0.2958	0.4769	0.2607	0.1194
Line 7-8	1.6235	0.7224	1.6235	0.9463	1.6235	4.3125
Line 7-9	1.0428	2.1550	1.0428	2.0093	1.0428	0.3493
Line 9-10	0.6157	0.0139	0.5743	0.6114	0.5160	0.2155
Line 9-14	1.8162	0.1995	1.7190	1.9933	1.2498	0.4493
Line 10-11	0.3971	0.7552	0.3706	0.2218	0.3248	0.1479
Line 12-13	1.1246	0.3088	0.6509	1.2924	0.5053	0.2086
Line 13-14	1.0838	3.4208	1.0152	2.6082	0.8560	0.3201

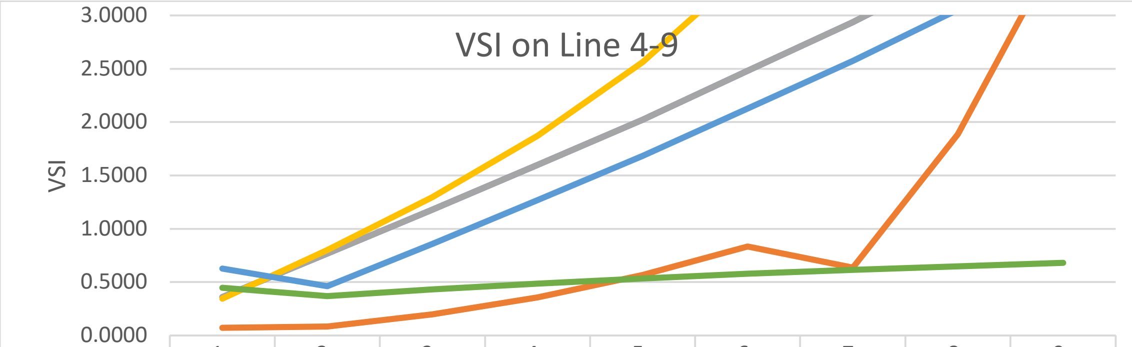
These bus also far away from the slack bus, bus 1 that providing power. Even though there are reactive power generator at bus 2, 3, 6 & 8, it seems that the reactive power generated unable to supply to the downstream bus, causing voltage drop. Transmission lines are considered reactive power load, consuming reactive power, further reducing reactive power at the receiving bus.

Table 4.11 is the bus VSI on 9x reactive power (Q) increment. Similar with table 4.5, bus VSI indicate the overall bus condition, but unable to indicate line condition. Bus 9, 10 & 14 voltage drop nearly to 0.5, yet the bus VSI still indicate bus 9, 10 & 14 voltage are still stable.

Table 4.11: Bus VSI on 9x Reactive Power (Q) increment

	Bus VSI			
	VPCI		L-index	
Bus	**1x**	**9x**	**1x**	**9x**
Bus 1	0.019783	0.075198	0.017439	0.07298
Bus 2	0.007709	0.000799	0.005257	0.003175
Bus 3	0.018033	0.012161	0.020754	0.009999
Bus 4	0.010786	0.010669	0.007187	0.011635
Bus 5	0.012682	0.027324	0.117988	0.115659
Bus 6	0.026716	0.160782	0.119322	0.244382
Bus 7	0.014479	0.093897	0.000383	0.001061
Bus 8	0.031481	0.236538	0.031481	0.236538
Bus 9	0.002337	0.18115	0.004582	0.183873
Bus 10	0.005367	0.099598	0.005367	0.099598
Bus 11	0.003333	0.03055	0.003333	0.03055
Bus 12	0.005901	0.035751	0.017514	0.112633
Bus 13	0.007902	0.056623	0.007902	0.056623
Bus 14	0.01861	0.266822	0.01861	0.266822

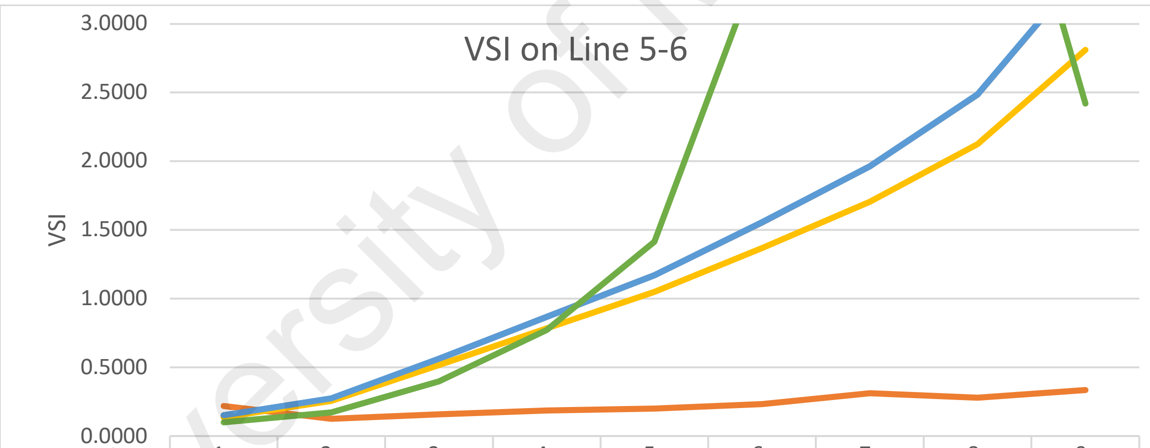
Figure 4.12, and 4.13 are the worst line VSI in the reactive power increment test. The line 4-9, & 5-6 seem to be the bottleneck of this system, unable to cope with reactive power demand. These lines reach critical value early, by 3 – 5 x of reactive power increment. The VSI also show the same accuracy weakness in this test. SFVSI and NVSI obtain low value in line 4-9 and 5-6 respectively, showing inconsistency and huge error distance with other VSI.



Reactive Power (Q)	1x	2x	3x	4x	5x	6x	7x	8x	9x
FVSI	0.3599	0.7691	1.1799	1.5995	2.0204	2.4813	2.9382	3.4381	4.0403
SFVSI	0.0723	0.0851	0.1993	0.3559	0.5677	0.8324	0.6359	1.8855	3.7147
NLSI	0.3599	0.7691	1.1799	1.5995	2.0204	2.4813	2.9382	3.4381	4.0403
VQI	0.3474	0.8014	1.2949	1.8733	2.5618	3.4364	4.5714	6.2598	10.1586
LQP	0.6284	0.4626	0.8593	1.2681	1.6819	2.1268	2.5730	3.0552	3.6225
NVSI	0.4474	0.3715	0.4313	0.4863	0.5333	0.5775	0.6139	0.6476	0.6818

Reactive Power (Q)

Figure 4.12: VSI on Line 4-9 on Reactive Power (Q) Increment



Reactive Power (Q)	1x	2x	3x	4x	5x	6x	7x	8x	9x
FVSI	0.1513	0.2718	0.5611	0.8667	1.1691	1.5550	1.9625	2.4844	3.4118
SFVSI	0.2193	0.1252	0.1579	0.1865	0.2006	0.2318	0.3113	0.2792	0.3347
NLSI	0.1513	0.2718	0.5611	0.8667	1.1691	1.5550	1.9625	2.4844	3.4118
VQI	0.1367	0.2545	0.5158	0.7838	1.0486	1.3688	1.7059	2.1235	2.8120
LQP	0.1527	0.2734	0.5627	0.8683	1.1708	1.5567	1.9642	2.4863	3.4138
NVSI	0.1009	0.1710	0.3984	0.7720	1.4146	3.5052	52.3743	5.1351	2.4184

Reactive Power (Q)

Figure 4.13: VSI on Line 5-6 on Reactive Power Increment

4.3.3 Apparent Power (S) Increment

In apparent power (S) increment test, the increment step is 0.25x of apparent power. The maximum increment before the system diverge is 2.5x of apparent power. Figure 4.14, is the S-V graph. Bus 4, 5 & 14 experience voltage drop until 0.85. Rest of the bus voltage is still within 0.85.

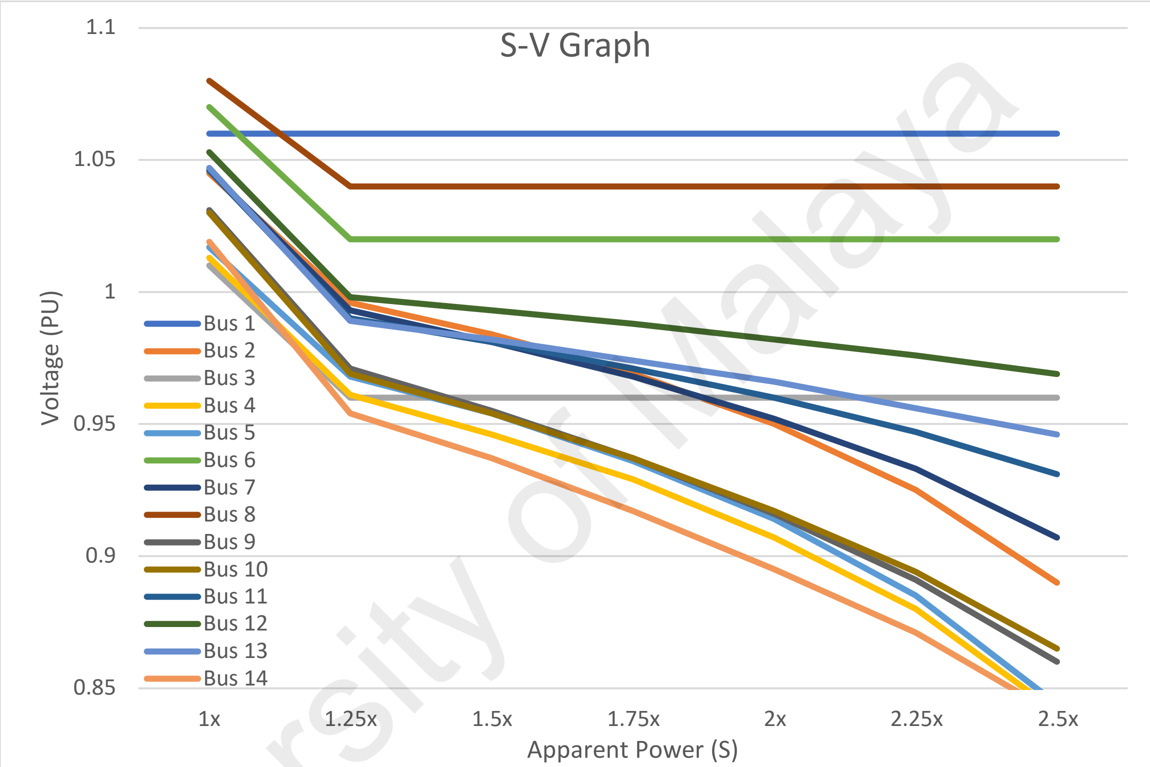


Figure 4.14: S-V Graph

Table 4.15 is the result of Line VSI on 2.5x apparent power. The red color highlighted cells are higher than 1. These cells indicate these lines experience voltage instability. Line 2-3, 4-9, & 5-6 have the higher VSI value, this indicate that the lines are at the limit of the power transfer or heavily load line. These lines unable to transfer power anymore, it will cause high power losses in order to transmit power. Comparing to the previous 2 tests, these lines consider bottleneck in the system. When the load is increase, these lines will have high VSI value.

Table 4.15: Line VSI on 2.5x Apparent Power (S)

	Line VSI					
Line	**FVSI**	**SFVSI**	**NLSI**	**VQI**	**LQP**	**NVSI**
Line 1-2	0.0741	0.5386	0.1043	0.1050	0.8023	0.0685
Line 1-5	0.0336	0.6490	0.0683	0.0530	10.4819	0.0783
Line 2-3	2.4178	0.3394	2.8476	2.0780	2.3623	11.3690
Line 2-4	0.0962	0.2081	0.1154	0.1078	0.1451	0.0642
Line 2-5	0.0389	0.1961	0.0898	0.0432	0.0919	0.0868
Line 3-4	0.0835	0.4344	0.4199	0.1088	0.8364	0.4617
Line 4-5	0.0105	0.0143	0.0239	0.0104	0.0298	0.0178
Line 4-7	0	0.3385	0	0	0.4993	0
Line 4-9	1.3054	0.0924	1.3054	1.2483	4.8375	3.8320
Line 5-6	2.0544	1.0081	2.0544	1.4066	2.0725	38.4738
Line 6-11	0.0423	0.3186	0.0664	0.0507	0.0459	0.0383
Line 6-12	0.0484	0.1900	0.1114	0.0537	0.0583	0.0791
Line 6-13	0.0913	0.2691	0.1572	0.1062	0.0775	0.0943
Line 7-8	0.6721	0.6726	0.6721	0.5112	0.6721	0.5062
Line 7-9	0.2220	0.1965	0.2220	0.2469	0.2220	0.2546
Line 9-10	0.0757	0.0234	0.1050	0.0748	0.0947	0.0633
Line 9-14	0.2232	0.0909	0.4389	0.2339	0.4736	0.3162
Line 10-11	0.0486	0.3285	0.0795	0.0419	0.0544	0.0504
Line 12-13	0.2743	0.0927	0.4364	0.2878	0.1277	0.1646
Line 13-14	0.2413	0.3980	0.4790	0.3061	0.2613	0.3385

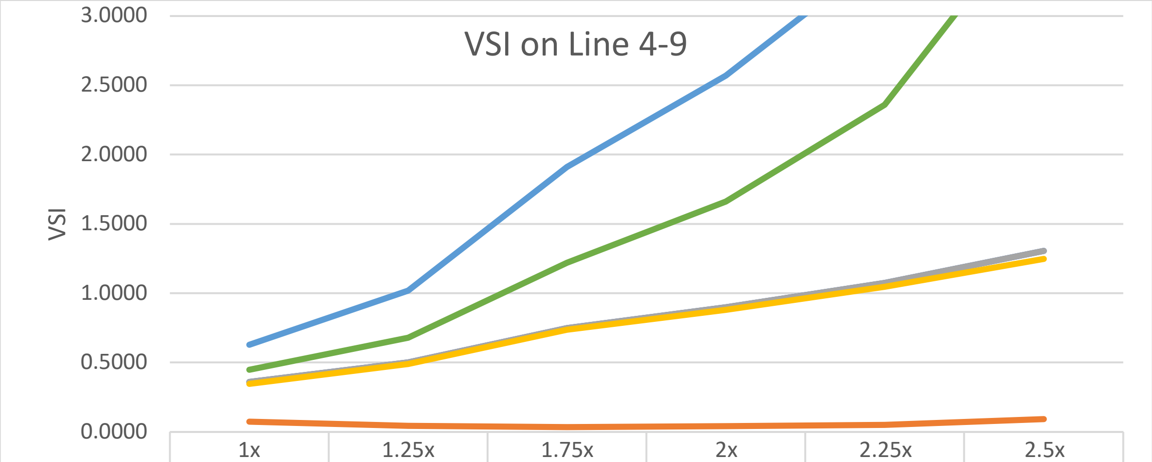
This apparent power increment test is more realistic compare the previous 2 tests. In real condition, load increase mainly with real power and small portion of reactive power. Power factor plays a role in the determining the amount of reactive power. With slack bus's generator, and other reactive power generator providing the real and reactive power, the lines near slack bus experienced high-power transfer to transmit to downstream, similar with real power (P) increment test. Bus 14 experience voltage drop below 0.85, but line VSI value still within voltage stability.

Table 4.16 is the bus VSI on 2.5x apparent power (S) increment. Similar with table 4.5, bus VSI indicate the overall bus condition, but unable to indicate line condition. Bus 9, 10 & 14 voltage drop nearly to 0.5, yet the bus VSI still indicate bus 9, 10 & 14 voltage are still stable.

Table 4.16: Bus VSI on 2.5X Apparent Power (S) Increment

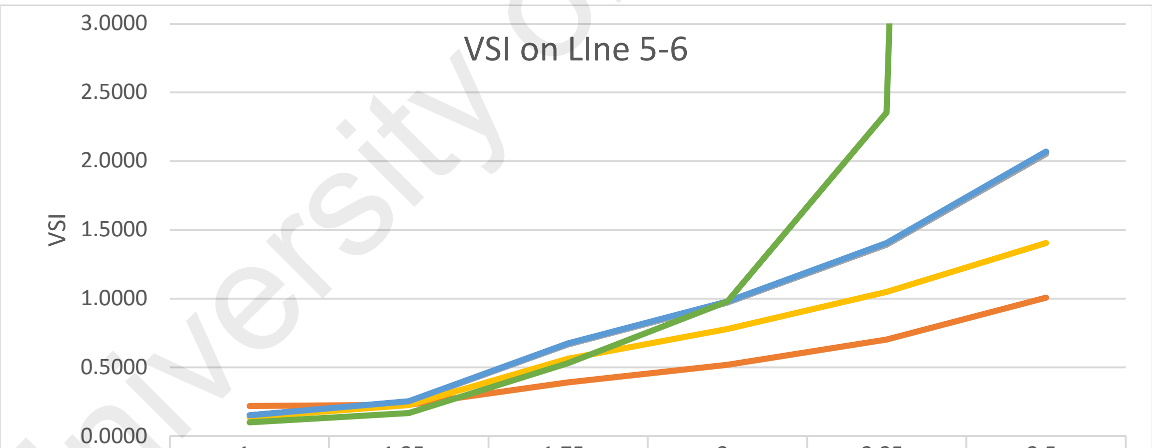
	Bus VSI			
	VPCI		**L-index**	
Bus	**1x**	**2.5x**	**1x**	**2.5X**
Bus 1	0.019783	0.169626	0.017439	0.167638
Bus 2	0.007709	0.090346	0.005257	0.093056
Bus 3	0.018033	0.099764	0.020754	0.097427
Bus 4	0.010786	0.039348	0.007187	0.035701
Bus 5	0.012682	0.060291	0.117988	0.096236
Bus 6	0.026716	0.093414	0.119322	0.171117
Bus 7	0.014479	0.042064	0.000383	0.00579
Bus 8	0.031481	0.127885	0.031481	0.127885
Bus 9	0.002337	0.017889	0.004582	0.020243
Bus 10	0.005367	0.019002	0.005367	0.019002
Bus 11	0.003333	0.010259	0.003333	0.010259
Bus 12	0.005901	0.017132	0.017514	0.04262
Bus 13	0.007902	0.025716	0.007902	0.025716
Bus 14	0.01861	0.068367	0.01861	0.068367

Figure 4.17 & 4.18 are the worst VSI in this test. Line 4-9 reach critical value starting from 1.75x of apparent power, while line 5-6 reach critical value 2x of apparent power. Since the load increment involve real (P) and reactive (Q) power, LQP and NVSI that have system variable P and Q will result to have greater VSI value. Line 4-9 and 5-6 seem to be the bottleneck of the system according to this test.



	1x	1.25x	1.75x	2x	2.25x	2.5x
FVSI	0.3599	0.4999	0.7488	0.8978	1.0730	1.3054
SFVSI	0.0723	0.0421	0.0347	0.0401	0.0506	0.0924
NLSI	0.3599	0.4999	0.7488	0.8978	1.0730	1.3054
VQI	0.3474	0.4896	0.7361	0.8803	1.0467	1.2483
LQP	0.6284	1.0178	1.9113	2.5688	3.4596	4.8375
NVSI	0.4474	0.6795	1.2205	1.6611	2.3603	3.8320

Figure 4.17: VSI on Line 4-9 on Apparent Power Increment



	1x	1.25x	1.75x	2x	2.25x	2.5x
FVSI	0.1513	0.2508	0.6684	0.9713	1.3928	2.0544
SFVSI	0.2193	0.2264	0.3912	0.5177	0.7032	1.0081
NLSI	0.1513	0.2508	0.6684	0.9713	1.3928	2.0544
VQI	0.1367	0.2259	0.5629	0.7799	1.0485	1.4066
LQP	0.1527	0.2534	0.6743	0.9797	1.4049	2.0725
NVSI	0.1009	0.1672	0.5298	0.9800	2.3550	38.4738

Figure 4.18: VSI on Line 5-6 on Apparent Power Increment

4.3.4 N-1 Line Contingency

Line loss is one of the most frequent happen, and it can cause voltage instability in a region. N-1 line contingency test is to simulate with one line loss on IEEE-14 bus system. We will remote one line at each test, total 20 lines, will have 20 tests. During the test, there will be no load variation included.

In load variation test, it is observed that line 2-3, line 4-9, and line 5-6, have the highest value of line VSI, we will display these VSI against N-1 line contingency. These sensitive lines will react more when one of the line loss happen. Figure4.19, 4.20 and 4.21 are the results of 3 lines' VSI.

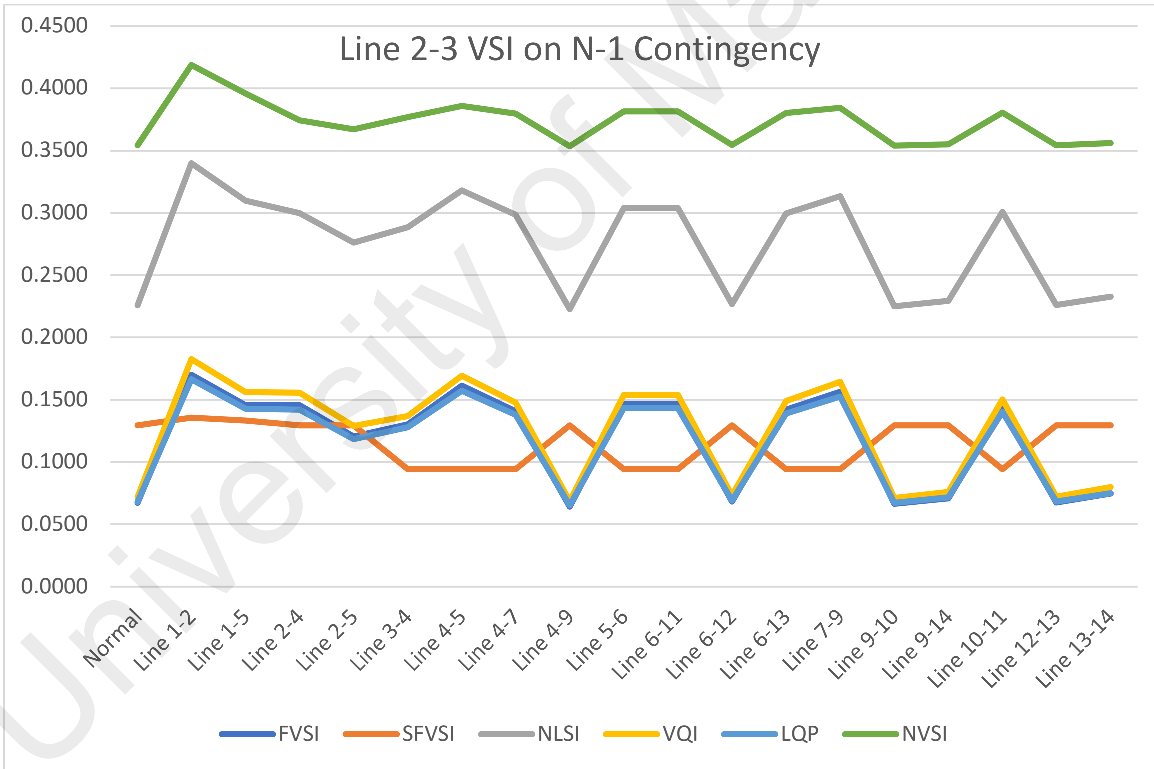


Figure 4.19: VSI on Line 2-3 on N-1 Contingency

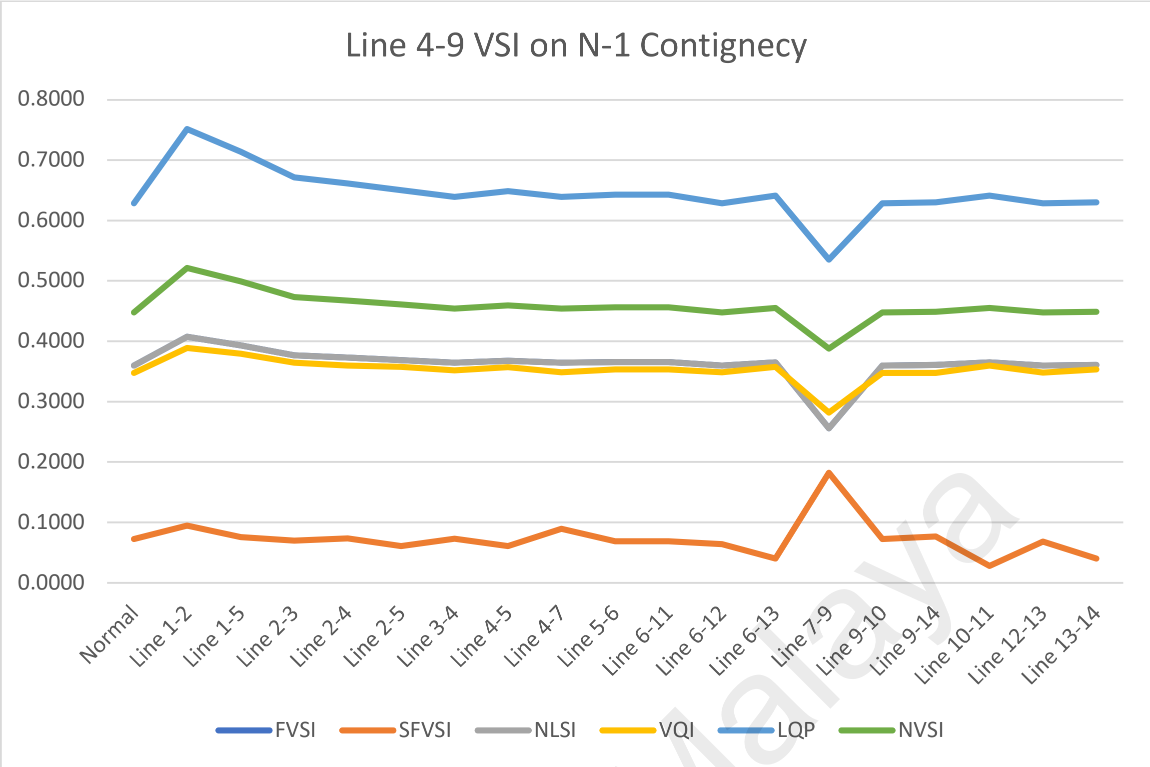


Figure 4.20: Line 4-9 VSI on N-1 Contingency

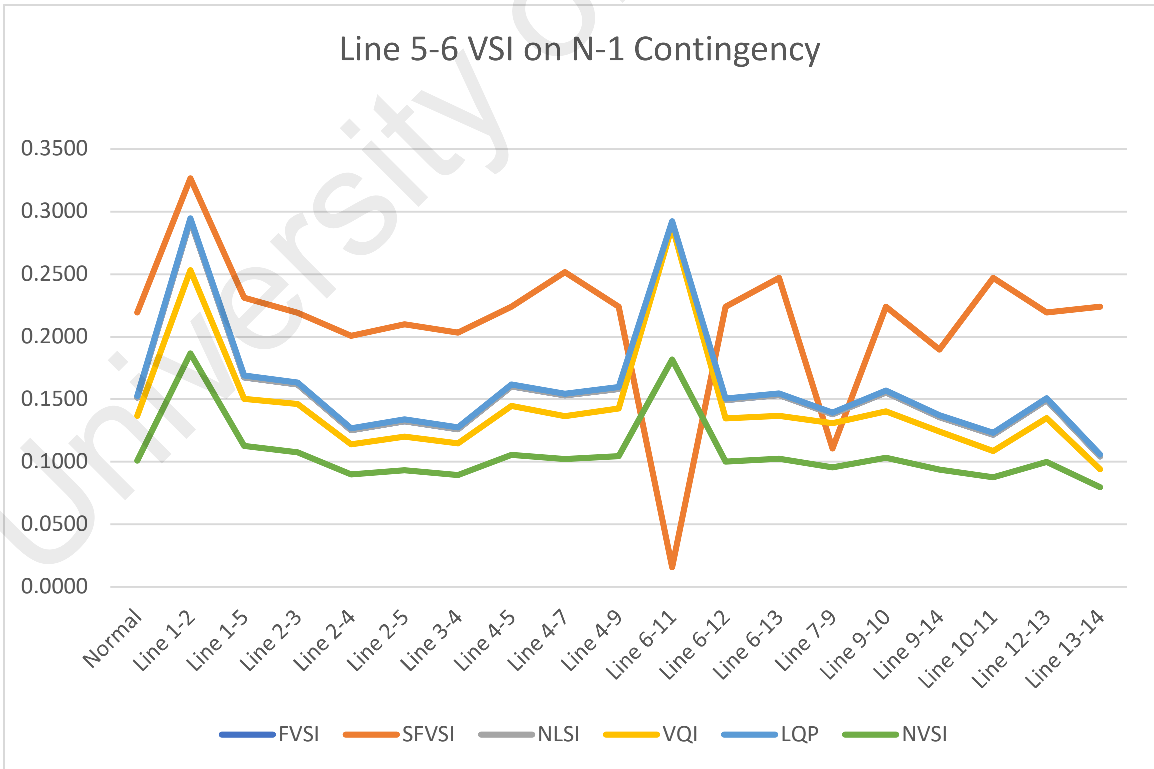


Figure 4.21: Line 5-6 VSI on N-1 Contingency

Comparing these 3 sensitive lines, there have similar trend that react to line lost. These 3 lines' VSI will raise up when their upstream line loss, especially case for line 1-2. Line 1-2 have such apparent effect because most the power generated from bus 1. Loss of line 1-2 will put stress on downstream but not critical enough to cause voltage instability. These 3 lines' VSI react to down stream line loss differently. It all depending where the power flow during the downstream line loss. For example: line 5-6's VSI increase when line 6-11 loss, causing more stress on line 5-6 because the power transfer to downstream bus required to go through longer route, through bus 12 & 13.

Another example where VSI drop when downstream line loss is line 4-9, when line 7-9 loss. This is because reactive power generator at bus 8 generated power need to flow through bus 4 in order to flow to bus 9 and onwards, reducing the reactive power requirement for power transfer, indirectly improve the VSI value on the line.

Figures,4.22 and 4.23 are rate of change of 2 bus VSI. Most of the bus VSI value are small, even after experience line loss, the bus VSI value are still small. We will use the formula 4.1 to calculate the rate of change of VSI. The rate of change of VSI will show how much change or effect by a line loss.

$$Rate\ of\ change\ of\ VSI = \left|\frac{VSI_{line\ loss} - VSI_{normal}}{VSI_{normal}}\right| \tag{4.1}$$

Generally, there are no bus experience voltage instability in all line loss test. Every bus reacts hugely with the line loss nearest to its bus. For example: L-index's Bus 7 in Figure 4.23, react highly at the line loss around its bus. Voltage

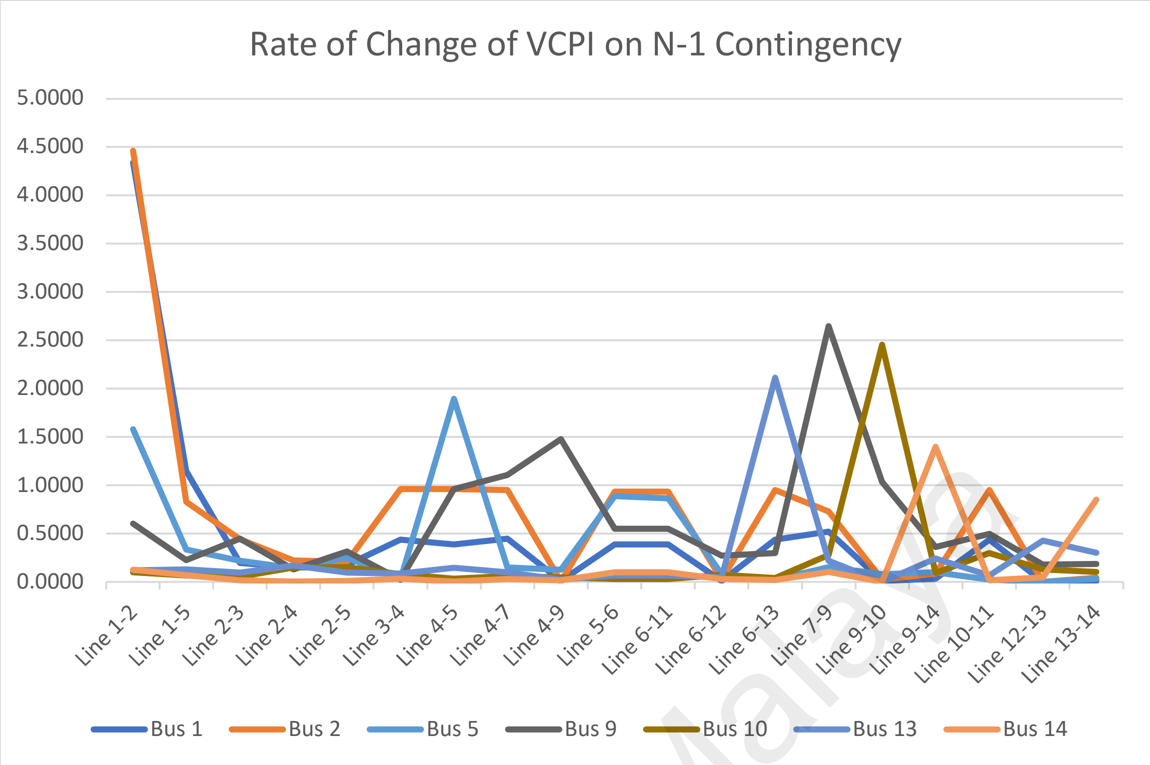


Figure 4.22: Rate of Change of VCPI on N-1 Contingency

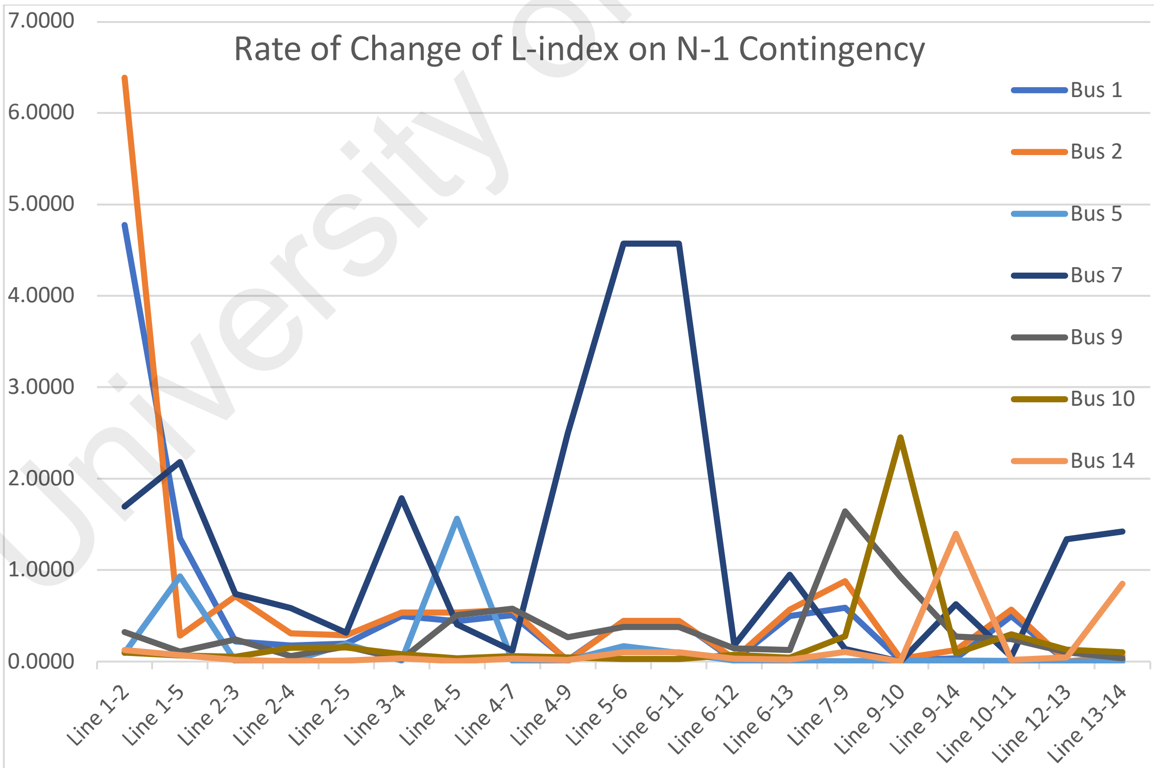


Figure 4.23: Rate of change of L-index on N-1 Contingency

4.4 Overall performance of Voltage Stability Indices

a) FVSI vs SFVSI

SFVSI is simplified formula for FVSI, its formula only consists of sending bus voltage V_i and receiving bus voltage V_j. However, SFVSI apparently have poor accuracy compared to FVSI. It does not align with its formal counterpart. In most cases, FVSI reach voltage instability, SFVSI still indicate stable.

b) False Positive Zero

There are few VSI showing constant zero throughout the tests. According to VSI formulas, it indicates line is still in voltage stability condition. After examine the formula and the receiving bus variables, there are a common factor that causes zero value. For line 4-7, there are no receiving bus reactive power Q_j, direct affect VSI value to become zero.

c) Comparing Line VSI

In the case of load variation test, we observed that each VSI have its voltage instability point. When the load increases, VSI increase in different rate, some VSI reach value 1 fast, but some VSI reach value in later load increment step. All VSI indicate coherently that a line is going to experience voltage instability, but unable to show when the voltage instability occurs.

d) Line VSI vs Bus VSI

We observed that Line VSI perform well in monitoring voltage stability on transmission line only. It able to determine weak line that is experiencing voltage instability. We able to deduce the weak bus if multiple weak lines connected to the bus. However, it unable to show the voltage stability condition on a bus. Bus VSI able to show the overall "health" of the bus, but it unable to indicate line condition. The selected bus VSI are more suitable to monitor line loss compare to line VSI. When a line loss happens, the system impedance will change, affecting the bus VSI value.

CHAPTER 5: CONCLUSION

5.1 Conclusion

Through this study, 6 Line VSI and 2 Bus VSI are able to be tested on IEEE-14 bus system. Each VSI are able to be observed to react differently in a power system, rendering it hard to determine the voltage stability condition accurately on transmission line or bus. It is even harder to single out a VSI that is functional in all situation and condition. Since these VSI are simplified formula for fast calculation, accuracy on where is the voltage instability point is questionable.

Each VSI has different functionality. Line VSI is able to monitor the voltage stability on transmission line, and determine a weak line or weak bus. This is apparent in the load variation test where line VSI are able to detect weak power transfer limit. On the other hand, Bus VSI is able to monitor the overall bus voltage stability condition. System variable based VSI is suitable for voltage stability monitoring both online and offline due to its simple formula.

It is recommended to use VSI collectively for better interpretation and decision making. If more VSI data pointing at the same outcome, it would be more certain about the voltage stability condition. Using line and bus VSI together, it can monitor both transmission line and bus together. It is proven in test, when transmission line is affected, both line VSI and bus VSI will capture and display in index value.

5.2 Future Works

Knowing the proximity of a system condition toward voltage instability is already a half-won battle against voltage collapse. The next step is to come up with mitigation plan to curb voltage collapse from happening. Through this study, it is apparent that line 2-3, 4-9 and 5-6 pose as a bottleneck to the power system, it poses a challenge on power to transfer downstream. Enhancing and strengthening the transmission line and bus by adding static VAR compensator or capacitor bank to ensure reactive power transfer that downstream bus lack. Therefore, it can reduce the possibility of voltage collapse from happening to ensure reliable and secure power source for customer.

Line VSI is able to monitor line's voltage stability, however, it is unable to determine when does the voltage instability occurs. A research can be conducted to determine the VSI accuracy error against power margin before the voltage collapse. Determining the accuracy error of VSI will enable us to accurately determine the proximity of the system toward voltage collapse.

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