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# PROSIDING




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BRC (Biro Penyelidikan & Perundingan), Universiti Teknologi MARA, 40450 Shah Alam

**Biro Penyelidikan dan Perundingan**
**Universiti Teknologi MARA**
**40450 Shah Alam, Selangor**
**Malaysia**

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Sila majukan sebarang pertanyaan kepada:

**Penolong Naib Canselor(Penyelidikan)**
**Biro Penyelidikan dan Perundingan**
**Universiti Teknologi MARA**
**40450 Shah Alam**
**Selangor, Malaysia**

Tel : 603 5544 2094 / 2093 / 2092
Fax : 603 5544 2096
e-mel : azniz132@salam.uitm.edu.my




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# DEVELOPMENT OF VOLTAGE STABILITY INDEX FOR POWER SYSTEM ANALYSIS

**Ismail Musirin**
**Titik Khawa Abdul Rahman**
Faculty of Electrical Engineering

***Abstract***

*Interruption in power delivery is mainly caused by overloading condition in a system and considerably a serious problem. This issue has been a progressing issue in the power engineering community which subsequently motivated further research in the field in order to maintain a secure power delivery. Conventionally, the study of voltage stability utilizes various indices referred to a line or a bus. This paper presents the development of a novel Fast Voltage Stability Index (FVSI) referred to a line. This index is used for analyzing the voltage stability condition of a power system which then helps to predict the occurrence of voltage collapse in the system. The line which gives index value closest to 1.00 will be considered as the most critical line referred to a bus. FVSI is also able to determine the voltage stability limit of a load bus. It was successfully tested and verified on the IEEE 6-bus and 14-bus systems. Results showed that the formulated index is indicative in predicting the occurrence of system violation hence necessary action can be taken to avoid such incident.*

## INTRODUCTION

**POWER** system network can become stressful with the additional of load in line with a country development. The improper planning of system capacity could cause unpredictable events such as system violation leading to the failure of power delivery. A proper planning and pre-analysis of voltage stability conducted off-line could help in minimizing system interruption that involved monetary losses. A practical power system network can be modeled into a mathematical modeling represented by buses, generators and lines. The interruption in a power system can be caused by the abnormality of voltages and voltage collapse posing a primary threat to power system stability, reliability and security [1]. Various techniques proposed in the literature were found to be less capable in accurately predicting the voltage collapse point and identifying the critical bus [2]. However, this uncertainty has been counter-measured by the use of continuation power flow which accurately capable in determining the voltage collapse point and identifying the critical bus in the system but consumed longer time for large system [4]-[6]. The Prediction of system violation is normally conducted empirically in the analysis stage by looking at the voltage profiles of the system. In addition, the loading capacity of a particular bus can also be determined by identifying the maximum permissible load at a bus. Voltage stability analysis could be conducted by evaluating the voltage stability index of the system [7]-[11]. Several

approaches were employed such as computing the sensitivity of the minimum singular value of the Jacobian matrix as proposed by Tiranuchit *et al.* [11] or setting the discriminant of voltage or power quadratic equations to be greater than zero. These indices are referred to a bus or a line. The derived index referred to a bus is capable in determining the weak bus. This is because the increase in reactive load will directly correspond to the bus index. But this method is found to be time consuming since the tests must be conducted in two phases, i.e., on-load and off-load. The results from these experiments will be applied to the Thevenin's equivalent circuit so that bus index can be computed. On the other hand, the index that is derived referred to a line will be able to determine the line index in a system with respect to the increase of reactive load. These indices identify the unstable line and the corresponding bus which cause the voltage instability and it is possible to be conducted on-line. Voltage stability analysis could be conducted in the static or dynamic modes. Static analysis referred to the steady state analysis and normally assumed that the loads are static in nature. In the dynamic analysis, the systems are modeled covering the excitation systems, under-load-tap-changers, capacitors and power system stabilizers in addition to networks equation.

This paper presents the derivation of a novel voltage stability index termed as Fast Voltage Stability Index (FVSI) formulated from the voltage quadratic equation for a 2-bus system. The mathematical formulation is simple with minimum parameters involved making the index computation comparatively fast. This index is used to determine the voltage stability condition of a line in which the computed index value closed to 1.00 indicates the system instability. The use of this index is further enhanced to identify the maximum loadability and voltage stability limit of the system. The indicator has been successfully tested on the IEEE 6-bus and 14-bus reliability test systems and verified using other techniques in the literature [6]-[7]. The results could be used by the power system operator to take necessary action in maintaining a stable system.

## Derivation of Fast Voltage Stability Index (FVSI)

FVSI is formulated by initially deriving the voltage quadratic equation for a 2-bus power system and the one-line diagram is illustrated in Fig. 1.

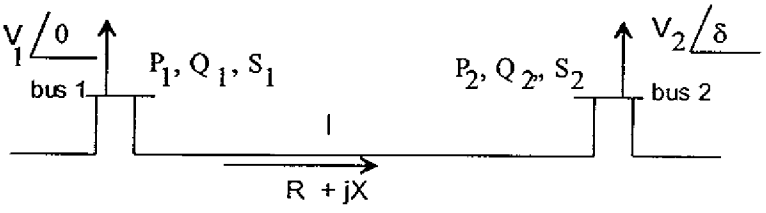



Fig. 1. 2-bus power system model

From the figure,

$V_1, V_2$ = voltage on the sending and receiving buses

$P_1, Q_1$ = active and reactive power on the sending bus

$P_2, Q_2$ = active and reactive power on the receiving bus

$S_1, S_2$ = apparent power on the sending and receiving buses

$\delta$ = $\delta_1 - \delta_2$ = angle difference between sending and receiving buses

The quadratic equation of voltage at bus 2 can be derived as;

$$V_2^2 - \left(\frac{R}{X}\sin\delta + \cos\delta\right)V_1V_2 + \left(X + \frac{R^2}{X}\right)Q_2 = 0 \quad (1)$$

with the roots for $V_2$ given by;

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

To obtain real roots for $V_2$, the discriminant is set greater than or equal to '0'; i.e;

$$\left[\left(\frac{R}{X}\sin\delta + \cos\delta\right)V_1\right]^2 - 4\left(X + \frac{R^2}{X}\right)Q_2 \geq 0 \quad (3)$$

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

Since $\delta$ is normally very small then,

$$\delta \approx 0,\ R\sin\delta \approx 0 \ \ and \ \ X\cos\delta \approx X$$

By taking 'I' as the sending bus and 'j' as the receiving bus, the fast voltage stability index, FVSI can be defined by;

$$FVSI_{ij} = \frac{4Z^2Q_j}{V_i^2X} \quad (4)$$

where: Z = line impedance

X = line reactance

$Q_j$ = reactive power at the receiving end

$V_i$ = sending end voltage

The line that has FVSI closed to 1.00 indicates that the line is closed to its instability point in which beyond this point, voltage collapse will occur in the entire system.

**Line Stability Index**

M Moghavemmi *et al.* [4] derived a line stability index based on a power transmission concept in a single line and the single line diagram is illustrated in Fig. 2.

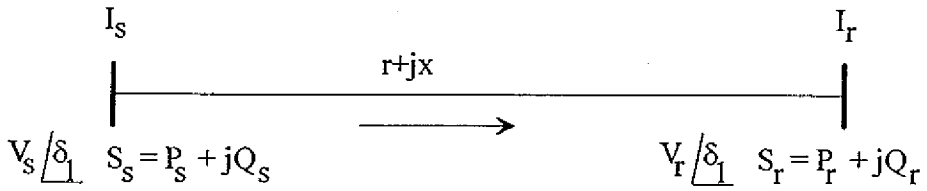



Fig. 2. Typical one-line diagram of transmission line

The line stability index noted as $L_{mn}$ can be reproduced as;

$$L_{mn} = \frac{4Q_r\, x}{\left[|V_s| \sin(\theta - \delta)\right]^2} \tag{5}$$

where:

x = line reactance

$Q_r$ = reactive power at the receiving end

$V_s$ = sending end voltage

$\theta$ = line impedance angle

$\delta$ = the angle difference between the sending voltage and the receiving voltage

**Line Stability Factor**

The formulation proposed by A Mohamed *et al.* [7] begins with the derivation of power equation in a power transmission system. Fig. 3 illustrates a single line diagram of a power transmission concept.

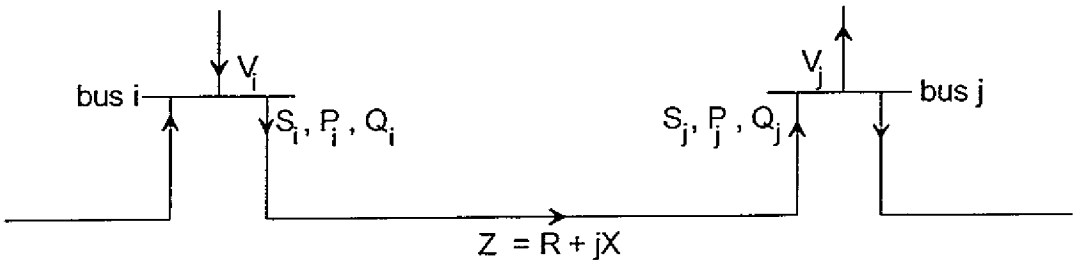



Fig. 3. Single line of power transmission concept

The power equation can be derived as;

$$\frac{X}{V_i^{\,2}} Q_i^{\,2} - Q_i + \left( \frac{X}{V_i^{\,2}} P_i^{\,2} + Q_j \right) = 0 \qquad (6)$$

The line stability factor is obtained by setting the discriminant of the reactive power roots at bus 1 to be greater than or equal to zero thus defining the line stability factor, LQP as,

(7)

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

where:X = line reactance

$Q_j$ = reactive power at the receiving end

$P_i$ = sending end power

$V_i$ = sending end voltage

In order to maintain a stable system, LQP must be kept less than 1.00.

## RESEARCH DEVELOPMENT

The voltage stability analysis in power system was conducted by initially running a load flow program in order to obtain power flow in the system. Results from the po wer flow solution were utilized to compute the voltage stability index (FVSI) on each line for every load variations on the test buses. The whole process is represented in the form of flow chart appeared in Figure 4.

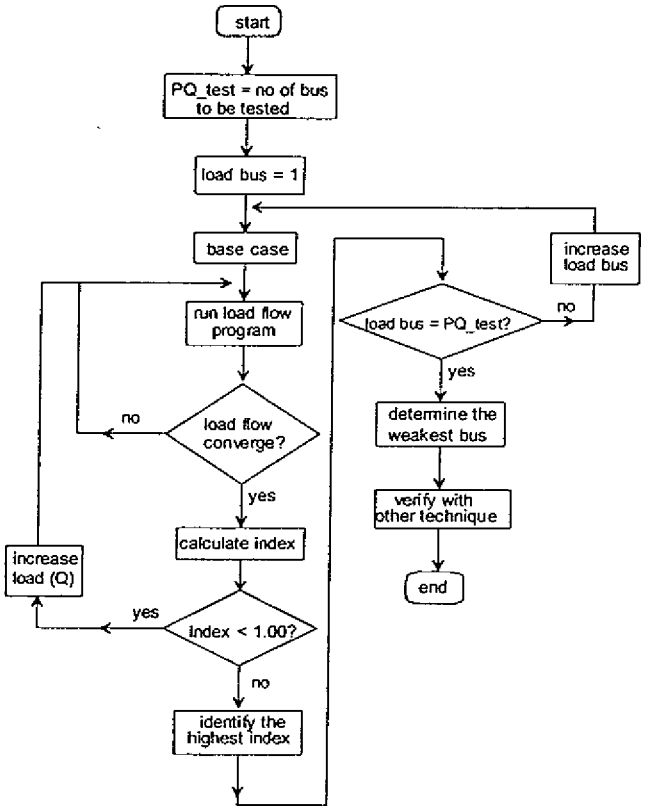



Fig. 4. Flow chart for voltage stability analysis

## TEST SYSTEM

Tests were conducted on the 6-bus and 14-bus IEEE reliability test systems. The 6-bus system has 2 generators, 4 load buses and 7 inter-connected lines while the 14-bus system has 5 generators, 9 load buses and 20 inter-connected lines. A computer program was developed to run the load flow program and the results were utilized to compute the voltage stability indices for each line in the systems for every load variation.

## RESULTS AND DISCUSSION

The FVSI and voltage profiles versus reactive load variation at bus 3 in 6-bus system is illustrated in the graphs of Figure 5.

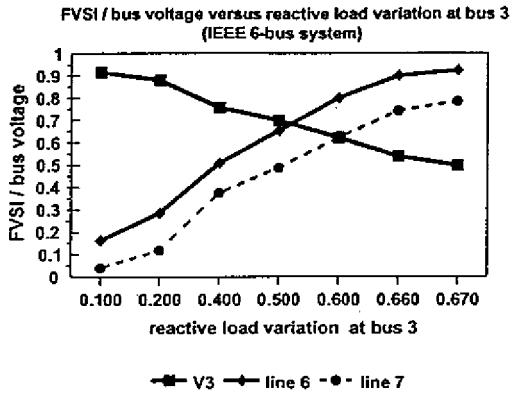



Figure 5. FVSI / bus voltage versus reactive load variation at bus 3 (6-bus system)

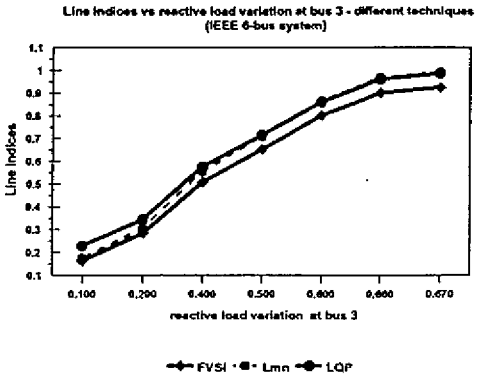



Figure 6. Line 6 was re-evaluated using FVSI, $L_{mn}$ and LQP with reactive load increase.

From the graph, FVSI values for line 6 and 7 tend to increase as the reactive power loading at bus 3 increased since these lines are connected to bus 3. Line 6 has higher response than line 7 as reactive load increased at bus 3. It indicates that FVSI for line 6 is more influenced than line 7. At a reactive load of 0.670 p.u. connected to bus 3, the index for line 6 is closed to 1.00 implying that this line has reached its instability point. A further increase in reactive load at bus 3 could cause FVSI of line 6 exceeding 1.00 leading to entire system collapse. On the same graph, the voltage profile of bus 3 decays accordingly as the reactive power loading increased. The minimum point of the voltage response is determined as the voltage stability limit for bus 3 in which a slight increase in reactive load will force the voltage to drop dramatically to a very low value. Since the maximum load that could be connected to bus 3 prior to system violation is 0.670 p.u. that means the maximum loadability for this bus is 0.670 p.u. Line 6 was re-evaluated using $L_{mn}$ and LQP and the result is shown in Figure 6. Apparently, the response of the indices evaluated using the three techniques are similar and the error is very small making the proposed technique comparable.

Test was also performed on the IEEE 14-bus system and similar process was conducted. The results for FVSI evaluated on the lines connected to bus 12 and voltage profile against load increase on bus 12 are plotted in the graph appeared in Figure 7. The FVSI curves for lines 12 and 19 increased accordingly as the reactive power loading increased since these two lines are connected to bus 12. Line 19 has a higher rate of change of FVSI compared to line 12 and performs a higher index profile implying that this line is more sensitive and critical to any change of load at bus 12. From the graph, it can be noticed that the maximum reactive power loading that can be injected to bus 12 in order to give FVSI less than 1.00 is 0.925 p.u. therefore 0.925 p.u. is determined as the maximum permissible load or maximum loadability at bus 12. The computed FVSI on line 19 at this point is 0.9682 indicating that a slight increase in reactive loading at bus 12 would cause FVSI goes beyond 1.00 and forcing the line to be unstable.

The line instability on line 19 leads to voltage at bus 12 drops instantly to a very low value causing entire system violation. On the other hand, the voltage profile noted as V12 decreases slowly with the increase of reactive load. The voltage at reactive loading of 0.925 p.u. is 0.844 p.u. and it will drop instantly if a small reactive load is added. Since the voltage at bus 12 is 0.844 p.u. at the maximum permissible load, then this limit is determined as the voltage stability limit for bus 12. Line 19 is re-evaluated using $L_{mn}$ and LQP and the results are presented in the graphs of Figure 8. The trends of the index response are similar with FVSI positioned in between $L_{mn}$ and LQP. It is observed that the index profile evaluated using $L_{mn}$ is the highest indicating that this indicator is very sensitive while LQP exhibited the lowest one. FVSI evaluated a lower profile than $L_{mn}$ and higher than LQP implying that this indicator is a reliable and indicative one but a bit less sensitive than $L_{mn}$ but it is within acceptable range since the error compared to $L_{mn}$ is very small.

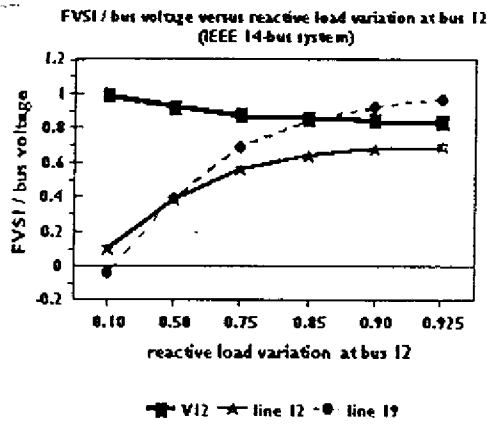



Figure 7. FVSI / bus voltage versus reactive load variation at bus 12 (14-bus system)

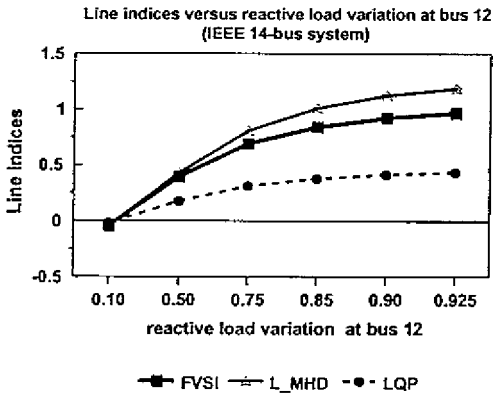



Figure 8. Line 19 was re-evaluated using FVSI, $L_{mn}$ and LQP with reactive load increase.

## CONCLUSION

A study on the system violation caused by reactive power loading in a system is presented. System violation was determined by performing the voltage stability analysis on the IEEE 6-bus and 14-bus reliability systems using the proposed FVSI. Results showed that FVSI is capable in identifying the most critical lines referred to a bus and the information from the FVSI versus reactive load curve determined the maximum loadability. In addition, the voltage stability limit at a particular bus could also be determined by looking at the voltage profiles against reactive load variation. Verification conducted through the comparison with $L_{mn}$ [6] and LQP [7] indicated that the proposed index is indicative and reliable in identifying the most critical lines, voltage stability limit and maximum loadability of a system.

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