Estimating the Voltage Stability of Electrical Power Systems using Field Programmable Get Array (F.P.G.A) Technique

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ABSTRACT

The voltage stability is the ability of the power system to provide adequate reactive power under all operating conditions and to maintain stable load voltage magnitude within specified operating limits. The modal analysis method is used to investigate the stability of the power system. Q-V curves are used to confirm the obtained results and to predict the stability margin or distance to voltage collapse based on the reactive power load demand. The modal analysis method is applied to the Western System Coordinating Council (WSCC) 3-Machines 9-Bus power system. The weak buses, which contribute to the critical mode, will be identified by using the participation factors. The Field Programmable Get Array (F.P.G.A) technique is used to solve this problem on–line using the Very High Speed Language (V.H.D.L) technique. Two Spartan 3 cit are used to connect directly between the computer and the network; the first will resave the power information from computer and the second will transmit the power information to the network.

KEY WORDS

Voltage Stability, Voltage collapse, Q-V Curves, Modal Analysis, Field Programmable Get Array (F.P.G.A).

1. INTRODUCTION

The voltage collapse problem is one of the major problems facing the electric power utilities in many countries. It is also a main concern in power systems operation and planning. It can be characterized by a continuous decrease of the system voltage. In the initial stage the decrease of the system voltage starts gradually and then decreases rapidly. The following can be considered as the main contributing factors to the problem [1].

1. Stressed power system; i.e. high active power loading in the system.
2. Inadequate reactive power resources.
3. Load characteristics at low voltage magnitudes and their difference from those traditionally used in stability studies.
4. Transformers tap changer responding to decreasing voltage magnitudes at the load buses.
5. Unexpected and or unwanted relay operation may occur during conditions with decreased voltage magnitudes.

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This problem is a dynamic phenomenon and transient stability simulation may be used. However, such simulations do not readily provide sensitivity information or the degree of stability. They are also time consuming in terms of computers and engineering effort required for analysis of results. The problem regularly requires inspection of a wide range of system conditions and a large number of contingencies. For such application, the steady state analysis approach is much more suitable and can provide much insight into the voltage and reactive power loads problem [2] and [3].

So, there is a requirement to have an analytical method, which can predict the voltage collapse problem in a power system. As a result, considerable attention has been given to this problem by many power system researchers. A number of techniques have been proposed in the literature for the analysis of this problem [4, 11].

The problem of reactive power and voltage control is well known and is considered by many researchers. It is known that to maintain an acceptable system voltage profile, a sufficient reactive support at appropriate locations must be found. Maintaining a good voltage profile does not automatically guarantee voltage stability. On the other hand, low voltage although frequently associated with voltage instability is not necessarily its cause [5] and [6].

Fig. (1) shows the Q-V curve which is a general method used by many utilities to assess the voltage stability. It can be used to determine the proximity to voltage collapse since it directly assesses the shortage of reactive power. The curves mainly show the sensitivity and variation of bus voltage with respect to reactive power injection. Using the Q-V curves, the stability margin or distance to voltage collapse at a specific bus can be evaluated. The Q-V curves are generated by series of power flow simulation; they plot the voltage at the critical bus versus the reactive power. The bus is considered to be a PV bus, where the reactive output power is plotted versus scheduled voltage. Most of the time these curves are termed Q-V curves rather than V-Q curves. Scheduling reactive load rather than voltage produces Q-V curves. This approach is a more general method of assessing voltage stability.

The operators may use the curves to check whether the voltage stability of the system can be maintained or not and take suitable control actions. The sensitivity and variation of bus voltages with respect to the reactive power injection can be observed clearly [7, 8].

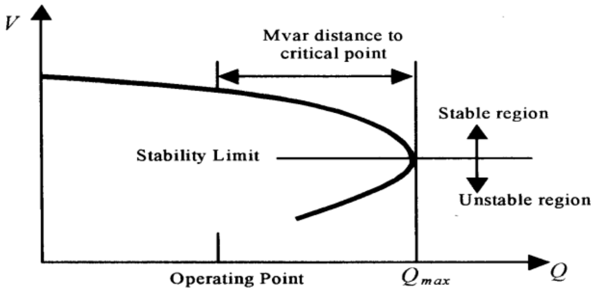

Figure 1 Typical Q-V curve.

The main drawback with Q-V curves is that it is generally not known previously at which buses the curves should be generated.

The effects of FACTS devices on voltage stability are presented in [10, 12].
A novel indicator from a parallel algorithm has been derived to predict the voltage instability or the proximity of a collapse [13]. This indicator uses the obtained data of a normal load flow to identify the weak buses in the power system.

The jacobian and the reduced jacobian matrices are obtained from the load flow solution for base case of the case-study power system. The Newton-Raphson method is used and the modal analysis technique is performed using the constant load model. The weak buses will be identified using the participation factors.

The reactive powers and the corresponding values of the capacitors, which will be connected in parallel at these weak buses, to alleviate the voltage instability, will be defined using Fuzzy logic technique. For on-line operation it will be suggested to use (F.P.G.A) to transmit the obtained values of these capacitors in addition to sub-distribution board to carry out the compensation for the power system.

2. Field Programmable Get Array (F.P.G.A)

Field programmable get array (F.P.G.A) is re-programmable digital ICs that were developed in the mid 1980s. (F.P.G.A) contains an internal array of logic elements, surrounded by a ring of programmable input/output blocks, all connected together via programmable interconnects. A personal computer can be used to design a digital circuit which is then compiled into a special programming file that will realize the circuit once it is downloaded to the (F.P.G.A). High density FPGA (offering millions of logic gates) are currently available, with the gate density increasing every year. (F.P.G.A) have been increasingly used as the final product platforms. Their use depends, for a given project, on the relative weights of desired performances, development, and production costs [9].

Field programmable get array (F.P.G.A) using Spartan 3 cit is connected from computer by cable RS232 to resave the information output, the number of weakest bus and size of shunt capacitor used to improve this bus voltage. The data input in the form of binary numbers The second cit will transmit these values to the sub distribution board to choose the size and location of weakest bus.

Field Programmable Get Array (F.P.G.A) using two Spartan 3 cit is connected from computer by cable RS232 , the first resaves the values of size and location of shunt capacitor at series binary number, which can be obtained by using the very high speed language (V.H.D.L). The second cit transmits these values to sub distribution board to put the capacitor at the weakest bus on-line operation. The connections are shown in the Figures from (2) to (4).

Fig. 2 The form of Spartan 3 cit.

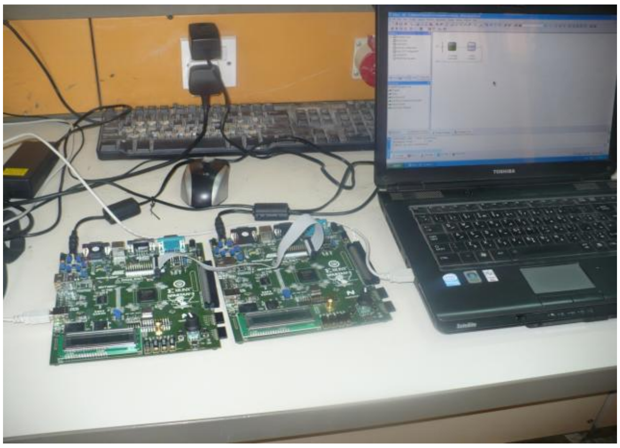

Fig 3 Two spartan 3 cit connected to computer by cable RS232 practically.

Fig 4 Two Spartan 3 cit at the operation.

3. MODAL ANALYSIS

The modal analysis mainly depends on the power-flow Jacobian matrix. An algorithm for the modal method analysis is used in this study is given below,

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix} \begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

By letting $\Delta P = 0$ in Eq. (1):

$$\Delta P = 0 = J_{11}\ \Delta\theta + J_{12}\ \Delta V \quad , \qquad \Delta\theta = -\ J_{11}^{-1}\ J_{12}\ \Delta V \qquad \ldots\ldots\ldots(2)$$

$$\Delta Q = J_{21}\ \Delta\theta\ + J_{22}\ \Delta V \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad (3)$$

Substitute Eq. (2) in Eq. (3):

$$\Delta Q = J_R\ \Delta V \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad (4)$$

$$J_R = [\ J_{22} - J_{21}\ J_{11}^{-1}\ J_{12}\ ]$$

J_R is the reduced Jacobian matrix of the system. Eq. (4) can be written as,

$$\Delta V = J_R^{-1} \Delta Q \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

The matrix J_R represents the linearized relationship between the incremental changes in bus voltage (ΔV) and bus reactive power injection (ΔQ). It is well known that, the system voltage is affected by both real and reactive power variations. Greater attention is focused for the study of the reactive demand and supply problem of the system as well as minimize computational effort by reducing dimensions of the Jacobian matrix J_R . The real power ($\Delta P = 0$) and angle part from the system in Eq. (4) are eliminated.

The eigenvalues and eigenvectors of the reduced order Jacobian matrix J_R are used for the voltage stability analysis. Voltage instability can be detected by identifying modes of the eigenvalues matrix J_R. The magnitude of the eigenvalues provides a relative measure of proximity to instability. The eigenvectors on the other hand present information related to the mechanism of loss of voltage stability. The eigenvalue analysis of J_R results in the following:

$$J_R = \Phi \Lambda r \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

Where, Φ = right eigenvector matrix of J_R, Λ = left eigenvector matrix of J_R,
r = diagonal eigenvalue matrix of J_R, Eq. (6) will be written as:

$$J_R^{-1} = \Phi \Lambda^{-1} r \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

Where $\Phi \Gamma = I$, Substitute Eq. (7) into Eq. (5), to obtain:

$$\Delta V = J_R^{-1} \Delta Q = \Phi \Lambda^{-1} r \Delta Q \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

Where, λ_i is the i^{th} eigenvalue, Φ_i is the of i^{th} column right eigenvector and
Γ_i is the i^{th} row left eigenvector of matrix J_R.
The eigenvalue λ_i and the corresponding right and left eigenvectors Φ_i and Γ_i define the i^{th} mode of the system.

The i^{th} modal reactive power variation is defined as:

$$\Delta Q_{mi} = K_i \Phi_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (9)$$

Where, K_i is a scale factor to normalize the vector ΔQ_{mi} such that,

$$K_i^2 \sum_j \Phi_{ji}^2 = 1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (10)$$

Eq. (10) can be summarized as follows:

1. If $\lambda_i = 0$, the i^{th} modal voltage will collapse because any change in that modal reactive power will cause infinite modal voltage variation.
2. If $\lambda_i > 0$, the i^{th} modal voltage and i^{th} reactive power variation are along the same direction, indicating that the system is voltage stable.
3. If $\lambda i < 0$, the ith modal voltage and the i^{th} reactive power variation are along the opposite directions, indicating that the system is voltage unstable. In general it can be said that, a system is voltage stable if the eigenvalues of J_R are all positive. This is different from dynamic systems where eigenvalues with negative real parts are stable.

4. CASE STUDY IMPLEMENTATION AND RESULTS

The modal analysis method is applied to the Western System Coordinating Council (WSCC) 3-Machines 9-Bus system, in Fig. (5). The voltage profile of the buses is presented from the load flow simulation as shown in Fig. (6). Then, the minimum eigenvalue of the reduced Jacobian matrix is calculated. After that, the weakest load buses, which are subject to voltage collapse, are identified by computing the participating factors, which are given in Fig. (7).

IF Φ_i and Γ_i represent the right- and the left-hand eigenvectors, respectively, for the eigenvalue λ_i of the matrix J_R, then the participation factor measuring the participation of the k^{th} bus in i^{th} mode is defined as

$$P_{ki} = \Phi_{ki}\ \Gamma_{ik} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad (11)$$

Therefore, the bus participation factor determines the area close to voltage instability provided by the smallest eigenvalue of J_R. A Matlab m-file is developed to compute the participating factor at i_{th} mode.

The voltage profile of all buses of the related power system is obtained from the load flow. It can be seen that all the bus voltages are within the acceptable level (±5%); some standards consider (±10%). The lowest voltage compared to the other buses can be noticed in bus number.

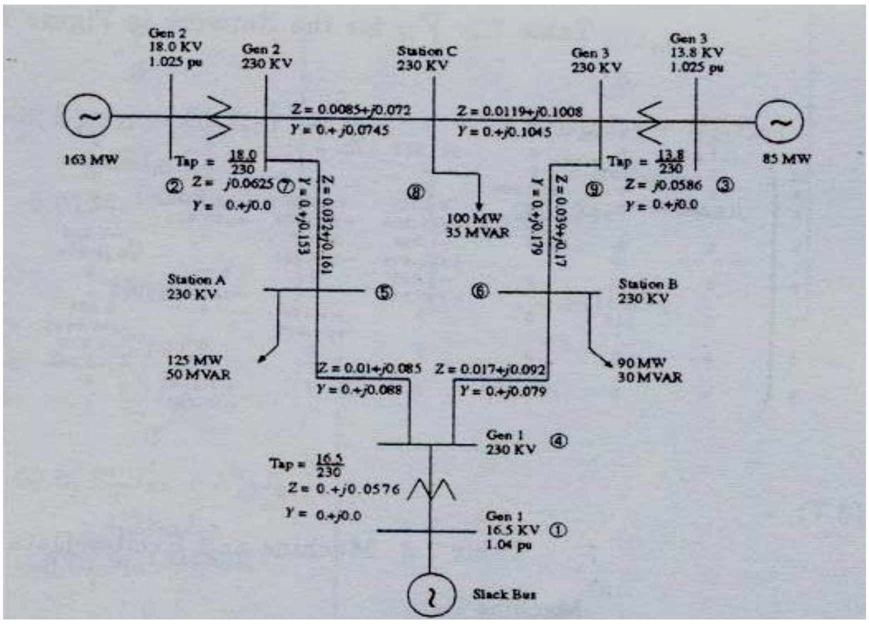

Fig. 5 The Western System Coordinating Council (WSCC) 3-Machines 9-Bus system.

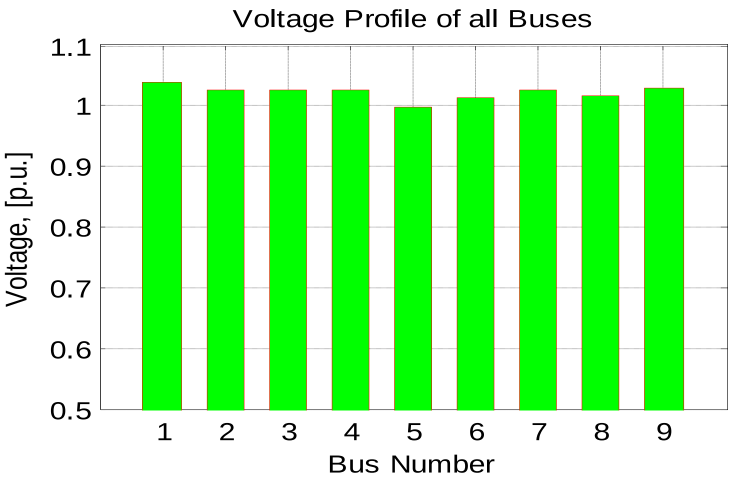

Fig. 6 Voltage profile of all buses of the Western System Coordinating Council(WSCC) 3-Machines 9-Bus System

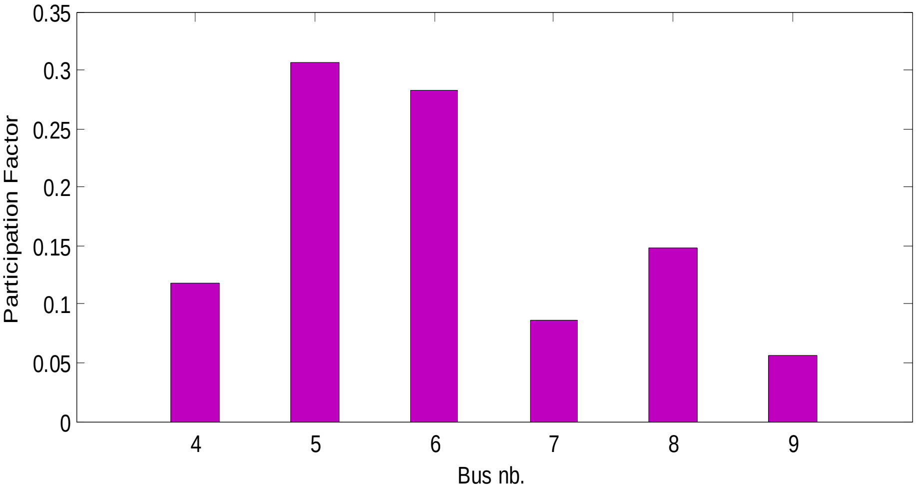

Fig. 7 Participation factor for 9 bus system

Table 1 Eigenvalue of 9-bus system WSCC

Bus No.	4	5	6	7	8	9
Eigenvalue	51.0938	5.9589	46.6306	12.9438	14.9108	36.3053

The Q-V curves are used to determine the Mvar distance to the voltage instability point or the voltage stability margins. The margins were loading points before the voltage collapse. Consequently, these curves can be used to predict the maximum-security margins that can be reached.

In other words, by using Q-V Curves, it is possible for the operators and the planners to know, what is the maximum reactive power that can be achieved or added to the weakest bus before reaching minimum voltage limit or voltage instability. In addition, the calculated Mvar margins could relate to the size of shunt capacitor or static VAR compensation in the load area.

The Q-V curves were computed for the weakest buses of the critical mode in the related power system as expected by the modal analysis method. The Q-V curve shown in Figure (1) confirms the results obtained previously by the modal analysis method.

Table 2 Voltage and reactive power margins for the related power system from Q-V curves bus – 5

Operating Point		Maximum with standard		Stability Margin		Stability Margin after compensation	
V_{PU}	Q_{PU}	V_{PU}	Q_{PU}	ΔV	ΔQ	ΔV	ΔQ
1	0.45	0.6	0.32	0.4	2.75	0.002	2.3

It can be seen clearly that bus 5 is the most critical bus compared with the other buses, where any more increase in the reactive power demand at that bus will cause a voltage collapse. Table (1) shows the eignvalue of buses (4, 5, 6, 7, 8, 9) to find weakest bus.

Fig (7) shows the participation factor to find the weakest bus; the buses 5 , 6 and 8 are unstable, the system will go to collapse. The Figures from (8) to (13) show the operation of the power system before and after improvement. The voltage and reactive power margins for the related power system from Q-V curve for the bus-5, bus-6 and bus-8 are given in the Tables (2), (3) and (4), respectively.

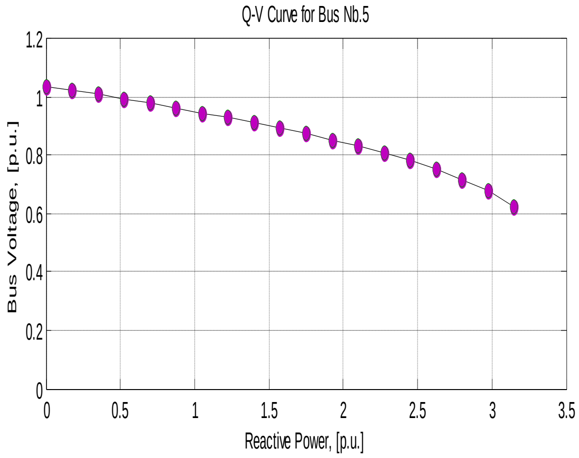

Fig. 8 Q-V curve for bus 5 before compensation

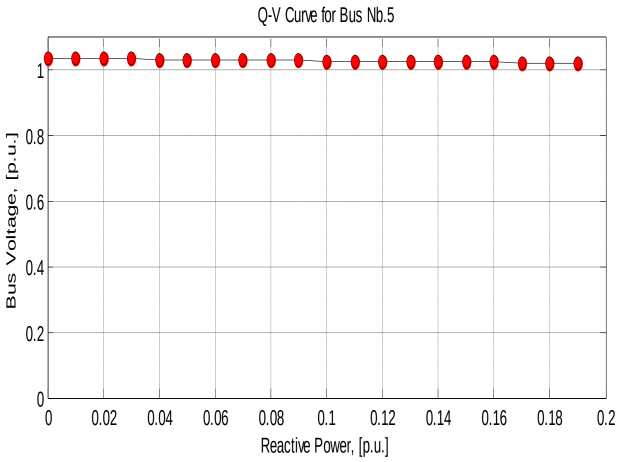

Fig. 9 The Q-V curve for bus 5 after compensation

Table 3 Voltage and reactive power margins for the related power system from Q-V curve bus-6.

Operating Point		Maximum with standard		Stability Margin		Stability Margin after compensation	
V_{PU}	Q_{PU}	V_{PU}	Q_{PU}	ΔV	ΔQ	ΔV	ΔQ
1	0.4	0.625	2.9	0.6	2.5	0.002	2.1

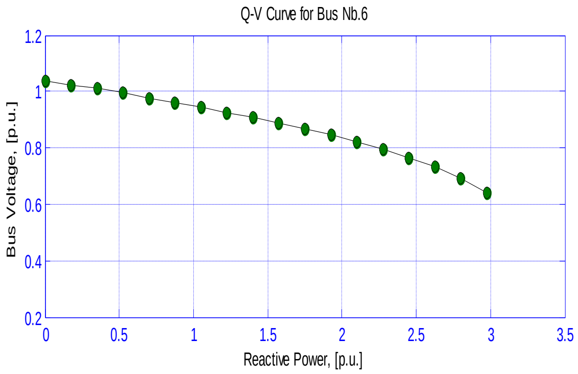

Fig. 10 The Q-V curve for bus 6 before compensation.

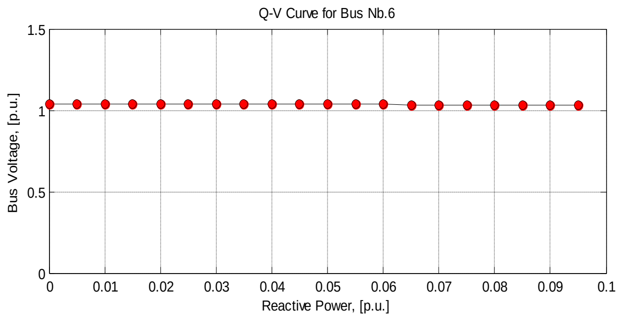

Fig. 11 Q-V curve for bus 6 after compensation

Table 4 Voltage and reactive power margins for related power system from Q-V curves bus-8

Operating Point		Maximum with standard		Stability Margin		Stability Margin after compensation	
V_{PU}	Q_{PU}	V_{PU}	Q_{PU}	ΔV	ΔQ	ΔV	ΔQ
1	0.5	0.72	3.25	0.28	2.75	0.002	2.28

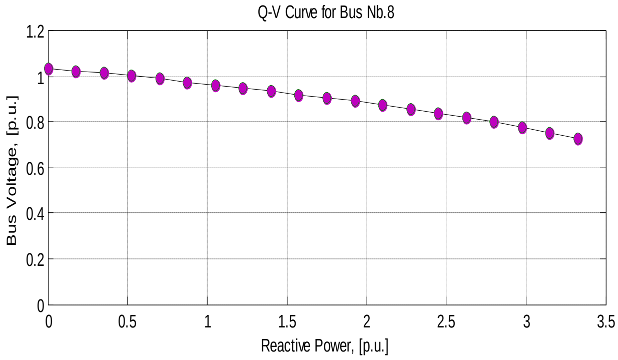

Fig. 12 The Q-V curve for bus 8 before compensation

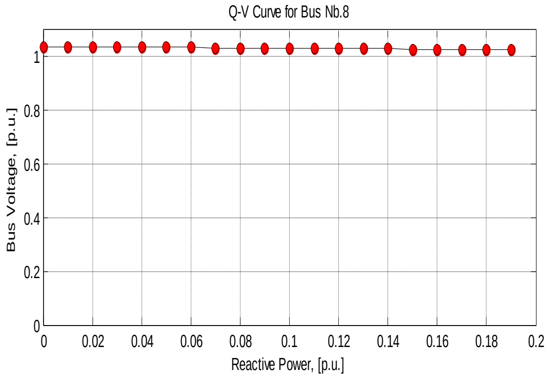

Fig. 13 The Q-V curve for bus 8 after compensation

The obtained reactive powers for compensation are:

At Bus 5 = 137.5 MVAR, At Bus 6 = 75 MVAR, At Bus 8 = 96.25 MVAR

5. CONCLUSIONS

The Modal analysis technique is applied to investigate the stability of the power systems. The method computes the smallest eigenvalue and the associated eigenvectors of the reduced Jacobian matrix using the steady state system model. The magnitude of the smallest eigenvalue gives a measure of how close the system is to the voltage collapse.

Then, the participating factor can be used to identify the weakest node or bus in the system associated to the minimum eigenvalue. The Q-V curves are used successfully to confirm the result obtained by Model analysis technique, where the same buses are found to be the weakest and contributing to voltage collapse. Using the Q-V curves, the stability margin or the distance to voltage collapse is identified based on voltage and reactive power variation. Furthermore, the result can be used to evaluate the reactive power compensation. The using of the obtained reactive powers and the corresponding shunt capacitors at the weak buses 5, 6 and 8 will improve the voltage stability and the system stability margin as shown in Figs. 9, 11 and 13.

The results obtained by the constant load model and the voltage dependent load models are in agreement about the weakest buses that contribute to voltage instability or voltage collapse. However, using voltage dependent load models changes the stability margin and the distance to voltage collapse is improved. In addition, using the voltage dependent load models maintains much better voltage level.

Field Programmable Get Array (F.P.G.A.) is used as an on-line solution for the voltage collapse problem using two Spartan 3 cit is connected between the computer and the network, the first resaves the values of size and location of shunt capacitor at series binary number and the second transmits these values to sub distribution board to put online the capacitor at the weakest bus.

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