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# IDENTIFICATION OF WEAK BUSES IN ELECTRICAL POWER SYSTEM BASED ON MODAL ANALYSIS AND LOAD POWER MARGIN

Ahmad Fateh Mohamad Nor[1] and Marizan Sulaiman[2]
[1]Green and Sustainable Energy (GSEnergy) Focus Group, Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, Parit Raja, Batu Pahat, Johor, Malaysia
[2]Center for Robotics and Industrial Automation, Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka (UTeM), Hang Tuah Jaya, Durian Tunggal, Melaka, Malaysia
E-Mail: afateh@uthm.edu.my

**ABSTRACT**

This paper presents the identification of weak buses in electrical power system with the use of modal analysis technique and load power margin values. A weak bus can be defined as a load bus that has high tendency towards experiencing voltage instability. This type of bus cannot afford high value of load incremental values. The modal analysis technique will show the list of weak buses in the power system. Meanwhile load power margin is very useful for showing how much the load at the bus can be increased before experiencing voltage instability. Both modal analysis technique and load power margin values are applied upon the IEEE 39-bus test power system. From there, five weak buses in the test power system are selected and compared. The results proved that weak buses determined by modal analysis technique have low load power margin values.

**Keywords:** weak buses, load power margin, modal analysis, voltage instability analysis.

## 1. INTRODUCTION

Over the years, power systems blackouts have been one of the major concern in the field of electrical power engineering. Power system blackouts will not only affect the distribution of electrical power to the consumers, but also can lead to economic losses. Most of the blackouts that occurred all over the world were caused by voltage instability phenomena [1-3]. Voltage instability can be defined as the situation when the electrical power system is not able to maintain the buses voltages remain the same after the system is being exposed to a disturbance [3, 4]. The disturbance that may cause voltage instability phenomena is usually related to the increasing of load demand. The increase of load demand especially reactive power (Q) load demand will force the electrical power system to operate near to the voltage instability limit [5]. Hence, more attention need to be given to analysing voltage instability since the load demand is increasing annually. The current fast urbanization especially in developing countries increases the load demand [6]. For example, the load demand in developing countries such as Malaysia is estimated to increase 4% annually [7, 8]. A bus that is close towards experiencing voltage instability is categorized as a weak bus [9]. Weak busses cannot afford huge incremental values of loads. This paper will present the identification of weak buses based onmodal analysis and load power margin (LPM). LPM is very useful to show how much the incremental load can be increased before the system reach the voltage instability limit [10-12]. Meanwhile modal analysis has the ability to directly show the list of weak load buses [13, 14]. The contribution of the research conducted in this paper is to present the list of weak buses in the IEEE 39-bus test power system based on both modal analysis technique and LPM values.

## 2. MODAL ANALYSIS TECHNIQUE

Modal analysis technique was originally presented by Gao, Morisson and Kundur in 1992 [14]. Fundamentally, this technique is about obtaining the values of eigenvalue and eigenvector of the reduced Jacobian matrix (Jr). Jacobian matrix can be found during the load flow analysis. These values are used to calculate the participation factor. Then, the participation factor can tell the list of weak buses in the system. Modal analysis technique can be divided into two categories which are modal analysis for reactive power of load (Q Modal Analysis) and modal analysis for real power of load (P Modal Analysis) [13].

### 2.1 Q modal analysis

#### 2.1.1 Reduced jacobian matrix (Jr)

The first step in modal analysis is determining the reduced Jacobian matrix (Jr). In the Newton Raphson power flow method, there is a Jacobian matrix that represents the injected real power (P) and reactive power (Q) in buses as shown in Eqn. (1) [2, 14-16].

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix}J_{P\delta} & J_{PV}\\ J_{Q\delta} & J_{QV}\end{bmatrix}\begin{bmatrix}\Delta \delta\\ \Delta V\end{bmatrix} \tag{1}$$

where

$\Delta P$ is the incremental change in bus real power
$\Delta Q$ is the incremental change in bus reactive power
$\Delta \delta$ is the incremental change in bus voltage angle
$\Delta V$ is the incremental change in bus voltage magnitude

The Jr values for Q modal analysis can be obtained by letting the value of ΔP in Eqn. (1) equals to 0 as shown in Eqn. (2).

$$\begin{bmatrix} 0 \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{P\delta} & J_{PV} \\ J_{Q\delta} & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} \quad (2)$$

From Eqn. (2), the following Eqn. (3) and Eqn. (4) can be obtained.

$$\Delta\delta = -J_{P\delta}{}^{-1} J_{PV}\, \Delta V \quad (3)$$

$$\Delta Q = J_{Q\delta}\Delta\delta + J_{QV}\, \Delta V \quad (4)$$

Eqn. (5) is formed by substituting Eqn. (3) into Eqn. (4).

$$\Delta Q \ = \ \Delta V[J_{QV} \ - \ J_{Q\delta}J_{P\delta}{}^{-1}J_{PV}] \ or \ \Delta Q \ = \ J_r\, \Delta V \quad (5)$$

where
$J_r = [J_{QV} - J_{Q\delta}J_{P\delta}{}^{-1}J_{PV}]$
Eqn. (6) is formed by rearranging Eqn. (5).

$$\Delta V \ = \ J_r{}^{-1}\, \Delta Q \quad (6)$$

Eqn. (6) displays the relationship between the incremental changes of voltage ($\Delta V$) and reactive power ($\Delta Q$).

**2.1.2 Determination of the most critical mode**

The second step in modal analysis is to determine the most critical mode. The eigenvalues and eigenvectors of $J_r$ can be used to determine the modes of the power system. The lowest value of eigenvalue of $J_r$ denotes the most critical mode of the power system [14,17]. Eqn. (7) depicts their relationship [2, 14-16].

$$J_r \ = \ \xi\, \Delta\, \eta \quad (7)$$

where
$\xi$ is the right eigenvector of $J_r$
$\Delta$ is the diagonal eigenvalue of $J_r$
$\eta$ is the left eigenvector of $J_r$

**2.1.3 Determination of the bus participation factor**

The bus participation factor is an indicator that shows the tendency of a particular bus towards voltage instability. It should be calculated at the bus that has the most critical mode. The bus participation factor is calculated by using Eqn. (8) [14, 15,17].

$$Pk_i \ = \ \xi_i \eta_i \quad (8)$$

where
$Pk_i$ is the participation factor of bus k to mode $i$
$\xi_i$ is the i$^{th}$ column right eigenvector of $J_r$
$\eta_i$ is the i$^{th}$ row of left eigenvector of $J_r$

Eqn. (8) produces the bus participation factor in matrix form. The row of the matrix designates the number of the bus. While the column of the matrix denotes the mode of the power system. Buses with higher values of participation factor have higher chances of experiencing voltage instability compared to buses with lower values of participation factor.

**2.2 P modal analysis**

**2.2.1 Reduced jacobian matrix (Jr)**

Similar to Q modal analysis technique, the first step in modal analysis is determining Jr. Jr for P modal analysis is obtainable by letting the value of ΔQ in Eqn. (1) equal to 0 as shown in Eqn. (9).

$$\begin{bmatrix} \Delta P \\ 0 \end{bmatrix} = \begin{bmatrix} J_{P\delta} & J_{PV} \\ J_{Q\delta} & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} \quad (9)$$

From Eqn. (9), the following Eqn. (10) and Eqn. (11) can be obtained.

$$\Delta P = J_{P\delta}\, \Delta\delta + J_{PV}\Delta V \quad (10)$$

$$\Delta V = -\, J_{QV}{}^{-1} J_{Q\delta}\Delta\, \delta \quad (11)$$

Eqn. (12) is formed by substituting Eqn. (11) into Eqn. (10).

$$\Delta P \ = \ \Delta\delta[J_{P\delta} \ - \ J_{PV}J_{QV}{}^{-1}J_{Q\delta}] \text{ or } \Delta P \ = \ J_r\, \Delta\delta \quad (12)$$

where

$J_r = J_{P\delta} - J_{PV}J_{QV}{}^{-1}J_{Q\delta}$
Eqn. (13) is formed by rearranging Eqn. (12).

$$\Delta\delta \ = \ J_r{}^{-1}\, \Delta P \quad (13)$$

Eqn. (13) shows the relationship between the incremental changes of voltage angle ($\Delta\delta$) and real power ($\Delta P$).

The next two steps in this P modal analysis technique which are the determination of the most critical mode and bus participation factor are similar to the Q modal analysis technique as explained in Section 2.12 and Section 2.1.3.

**3. LOAD POWER MARGIN**

Load Power Margin (LPM) shows the allowable range of load incremental before the power system experiencing voltage instability. LPM is obtainable from the power-voltage (PV) and reactive power-voltage (QV) curves. PV and QV curves technique is one of the most well-known technique in analysing voltage instability [18,19]. Both PV and QV curves are generated with a sequence of power flow. For each sequence of power flow, the P of load or Q of load of the power system is increased until the point where the system fails to operate. The variation values of P and Q of loads with the value bus voltages are plotted as the PV and QV curve, respectively [20,21]. In addition, LPM can be divided into two categories. The first one is LPM for P load (LPM_P) and the second category is LPM for Q load (LPM_Q).

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LPM_Pcan be defined as the distance of how far the P of load can be increased from the initial voltage operating point until the voltage critical point. The system will experience voltage instability if the bus voltage drops below the voltage critical point. Figure-1 shows the LPM_P that is available from the PV curve. In addition, LPM_P can be calculated by using Eqn. (14) [10].

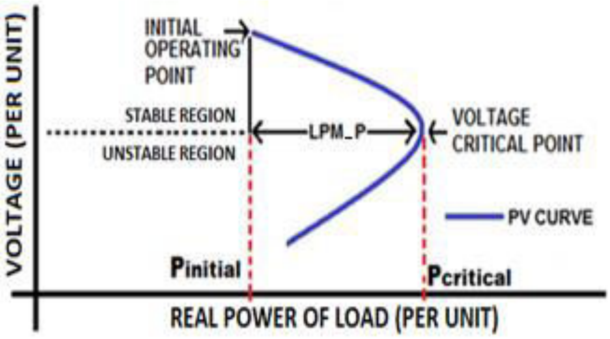


**Figure-1.** LPM_P in PV Curve.

$$LPM\_P = P_{initial} - P_{critical} \quad (14)$$

where
$P_{initial}$ is the value of P of load at initial operating point
$P_{critical}$ is the value of P of load at voltage critical point

LPM_Q on the other hand can be defined as the distance of how far the Q of load can be increased from the initial voltage operating point until the voltage critical point. Figure-2 displays LPM_Q on the QV curve [22]. Eqn. (15) [10] is very useful for calculating LPM_Q.

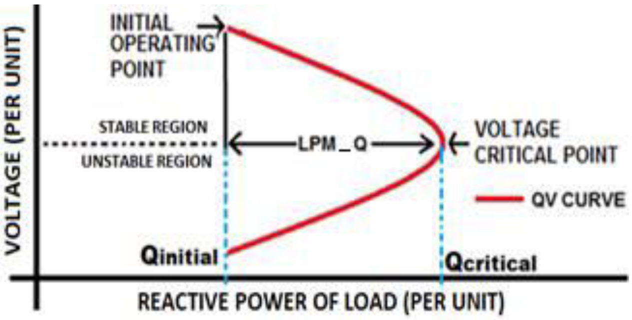


**Figure-2.** LPM_Q in QV Curve.

$$LPM\_Q = Q_{initial} - Q_{critical} \quad (15)$$

where
$Q_{initial}$ is the value of Q load at initial operating point
$Q_{critical}$ is the value of Q load at voltage critical point

## 4. IEEE 39-BUS TEST POWER SYSTEM

The IEEE 39-bus test power system or also known as the 39-bus New England system consists of one slack bus (Bus 31), 9 voltage-controlled buses (Bus 39, Bus 32, Bus 33, Bus 34, Bus 35, Bus 36, Bus 37, Bus 38 and Bus 30) and the rest are 29 load buses. This test system has been chosen because it has been widely used by previous researchers for various purposes [15,23]. Figure-3 [24-27] depicts the diagram of this test power system simulated in Power World Simulator software.

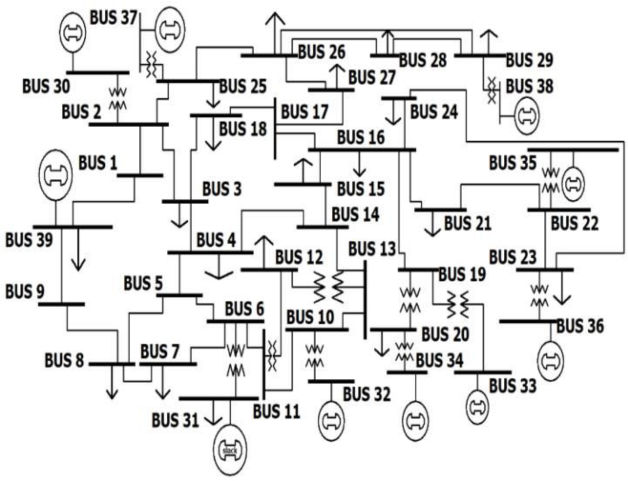


**Figure-3.** IEEE 39-bus test power system.

## 5. RESULTS AND DISCUSSIONS

### 5.1 Q modal analysis

The Q modal analysis technique was applied upon the IEEE 39-bus test power system. Figure-4 shows the bus participation factor obtained from Q modal analysis technique. In order to facilitate the observation process, the participation factor in Figure-4 has been arranged from the highest to the smallest value. The higher the participation factor value of a load bus, the higher the chance of that bus to experiencing voltage instability and vice versa.

From Figure-4, the highest participation factor is observed at Bus 12 which is 0.1082. It is apparent that Bus 12 has the highest value of participation factor. This indicates that Bus 12 has higher chance of experiencing voltage instability. One more significant information that can be obtained from Figure-4 is that Bus 12, Bus 7, Bus 8, Bus 14 and Bus 13 are among the five weakest load buses in IEEE 39-bus test power system. In addition, Figure-4 also displays that Bus 1 and Bus 20 are the two most stable load buses in this power system. This is because the participation factors for Bus 1 and Bus 20 are very low which are 0.0017, respectively.

Moreover, it is shown in Figure-4 that only the load buses that have participation factor. This is for the reason that the Q modal analysis technique emphases on the relationship between the incremental changes of voltage and reactive power as definite in Eqn. (6). Since the voltages of the slack and voltage-controlled buses are the known values prior to the load flow analysis, no participation factor is obtainable on the slack and voltage-controlled buses.

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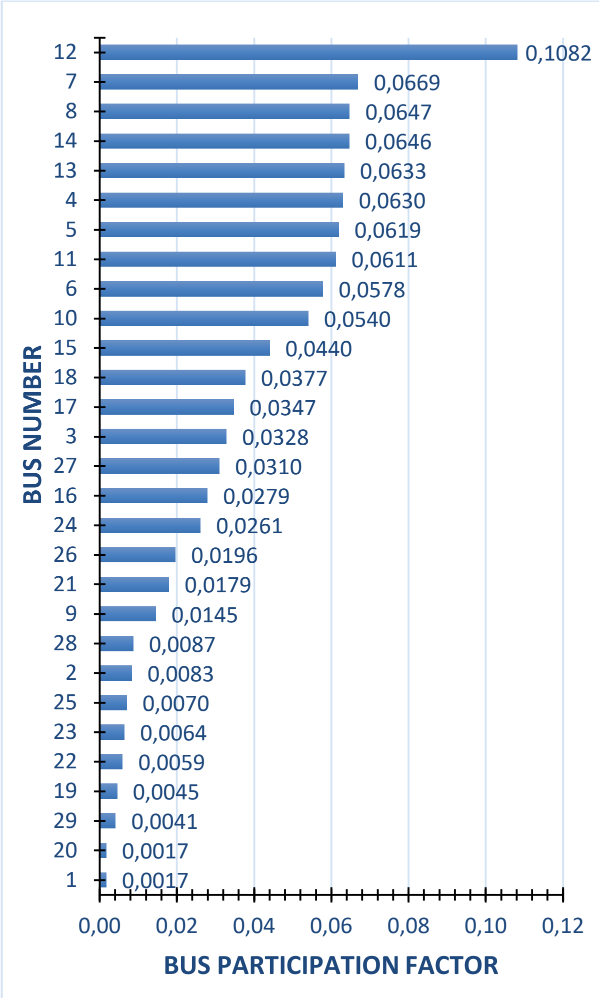


**Figure-4.** Participation Factor for the IEEE 39-Bus Power System (Q Modal Analysis Technique).

### 5.2 P modal analysis

The P modal analysis technique was applied upon the IEEE 39-bus test power system. Figure-5 shows the bus participation factor obtained from P modal analysis technique. In order to smoothen the observation process, the participation factor in Figure-5 has been arranged from the highest to the smallest value.

Figure-5 depicts that Bus 29 is the load bus that has the highest participation factor. Bus 29 has participation factor of 0.0354. Even though the participation factor for Bus 34 and Bus 38 are higher than Bus 29, both Bus 34 and Bus 38 are not load buses (they are generator buses). This value explains that according to the P modal analysis technique, the probability of Bus 29 to experience voltage instability is the highest compared to other load buses in the IEEE 39-bus test power. Furthermore, Figure-5 also tells that Bus 29, Bus 28, Bus 20, Bus 19 and Bus 23 are among the five weak buses in this power system.

Apart from that, the result shown in Figure-5 also conveys that for P modal analysis technique, all buses in the IEEE 39-bus test power system has participation factor except for the slack bus (Bus 31). This situation is compatible with Eqn. (13). It can be seen from Eqn. (13) that the P modal analysis technique is about the relationship between the incremental changes of voltage angle ($\Delta\delta$) and real power ($\Delta P$). Since the voltage angle of the slack bus are fixed prior to the load flow analysis, no participation factor is considered on slack buses for P modal analysis technique.

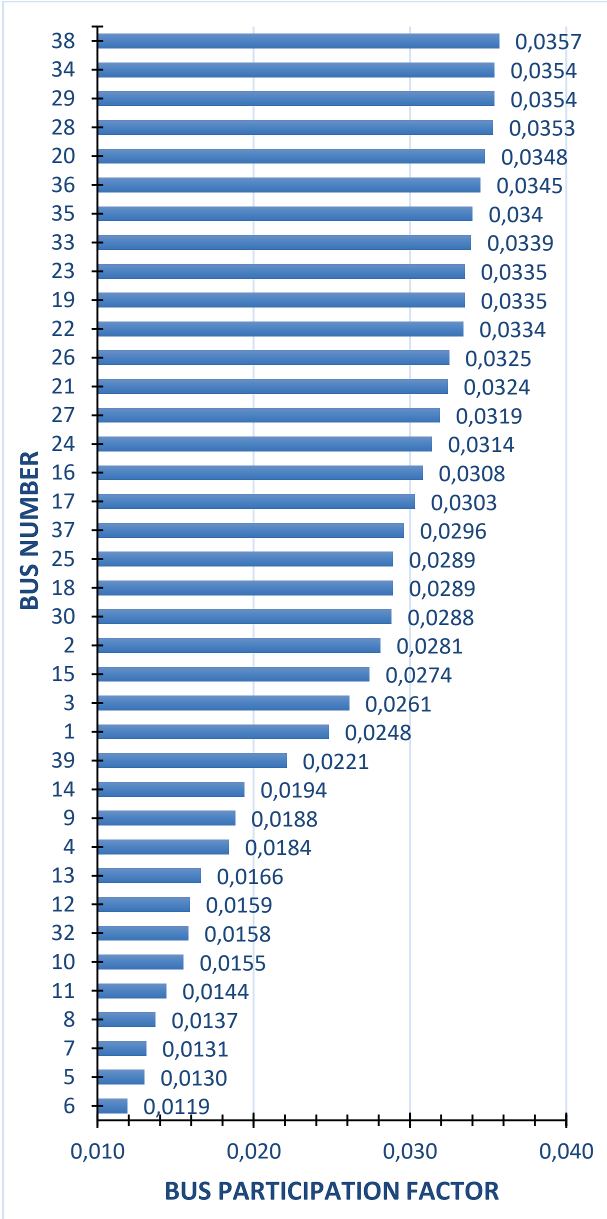


**Figure-5.** Participation Factor for the IEEE 39-Bus Power System (P Modal Analysis Technique).

### 5.3 LPM_P

The values of LPM_P was calculated for all load buses in the IEEE 39-bus test power system by using Eqn. (14). The LPM_P values are displayed in Figure-6. In order to make the observation process easier, the LPM_P values in Figure-6 has been arranged from the highest to the smallest value. The smaller the LPM_P value of a load bus, the higher the chance of that bus to experiencing

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voltage instability and vice versa. It is obvious from Figure-6 that the LPM_P value for Bus 12 is the lowest among the load buses in the IEEE 39-bus test power system. The LPM_P value for Bus 12 is 13.4847 per unit. That is to say, according to the LPM_P values, Bus 12 has higher tendency towards voltage instability compared to other load buses in this power system. It is also observable from this figure that the second, third, fourth and fifth lowest LPM_P calculation values belong to Bus 9, Bus 28, Bus 29 and Bus 1, respectively. As far as the most stable buses are concerned, Bus 6 has the highest LPM_P calculation value, followed by Bus 11, Bus 5 and Bus 10.

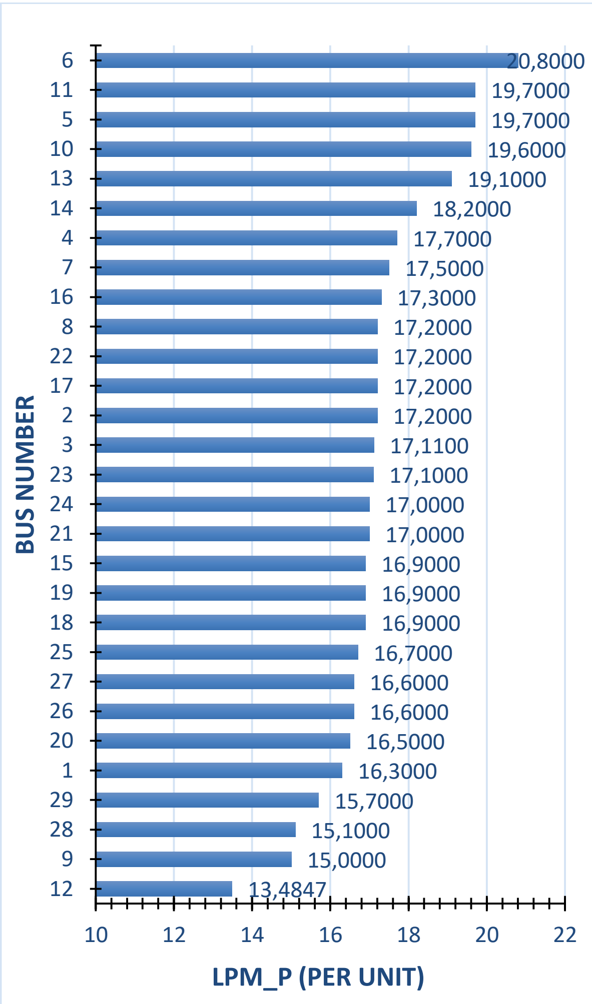


**Figure-6.** LPM_P values for the load buses in IEEE 39-bus test power system.

### 5.4 LPM_Q

The values of LPM_Q was calculated for all load buses in the IEEE 39-bus test power system by using Eqn. (14). The LPM_Q values are displayed in Figure-7. In order to make the observation process simpler, the LPM_Q values in Figure-7 has been arranged in a descending order. The smaller the LPM_Q value of a load bus, the higher the chance of that bus to experiencing voltage instability and vice versa.

In view of the LPM_Q calculation values presented in Figure-7, it is noticeable that Bus 12 has the lowest LPM_Q calculation value. The LPM_Q calculation value for Bus 12 is 7.2887 per unit. The previous Figure-6 has shown that the LPM_P calculation value for Bus 12 is 13.4847 per unit which is higher than LPM_Q for Bus 12. This clarifies that the allowable range for P load to increase is higher than Q load. This proves that Q load gives more contribution towards voltage instability compared to P load.

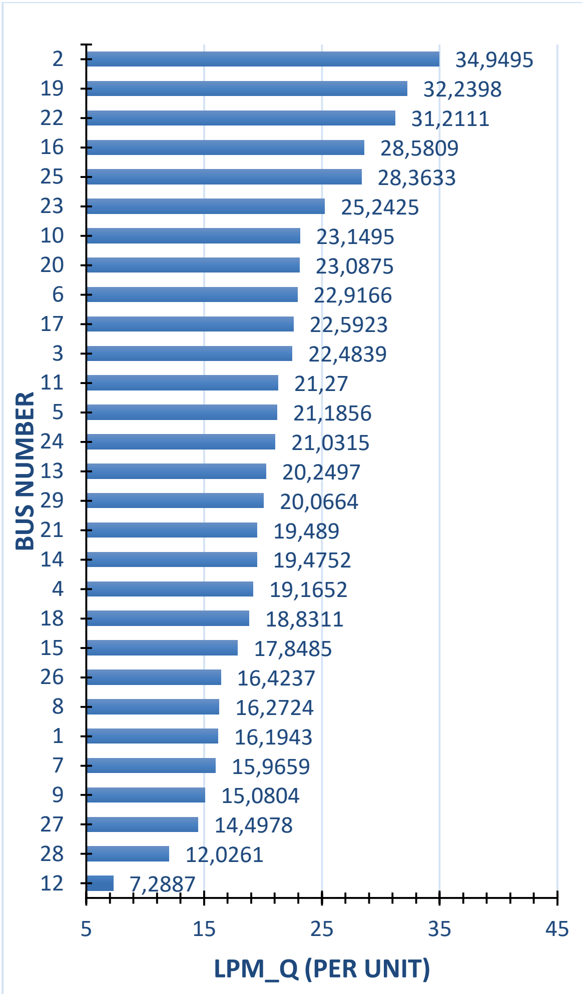


**Figure-7.** LPM_Q values for the load buses in IEEE 39-bus test power system.

### 5.5 Determination of the weakest load buses

Five weak buses in the test power system are identified and analysed. Table-1 summarized the list of these weak buses. The 1st weakest bus is the bus that is most prone towards voltage instability. While the 5th weakest bus is the bus that is least prone towards voltage instability among of these five weak buses.

**Table-1.** Summary of Weakest Bus for IEEE 39-Bus Test Power System.

| | Q Modal Analysis | PModal Analysis | LPM_P | LPM_Q |
|---|---|---|---|---|
| 1st Weakest Bus | Bus 12 | Bus 29 | Bus 12 | Bus 12 |
| 2st Weakest Bus | Bus 7 | Bus 28 | Bus 9 | Bus 28 |
| 3st Weakest Bus | Bus 8 | Bus 20 | Bus 28 | Bus 27 |
| 4st Weakest Bus | Bus 14 | Bus 19 | Bus 29 | Bus 9 |
| 5st Weakest Bus | Bus 13 | Bus 23 | Bus 1 | Bus 1 |

As can be seen in Table-1, Bus 12 has been marked as the 1st weakest bus by all of the voltage instability parameters except for the P modal analysis technique. The P modal analysis technique has approved Bus 29 as the 1st weakest bus. Not only that, the LPM_P value for Bus 29 quite low which is 15.7 per unit. This shows the importance of using both Q and P modal analysis because the P modal analysis manage to identify Bus 29 as one of the load buses that need to be given more attention.

Bus 28 has been marked as the 2nd weakest bus by the values of LPM_Q and the P modal analysis technique. The values of LPM_P have shown that Bus 9 is the 2nd weakest bus. Only Bus 7 has been marked as the 2nd weakest bus by Q modal analysis technique. The values of LPM_P have marked Bus 28 as the 3rd weakest bus. The values of LPM_Q have decided that Bus 27 as the 3rd weakest bus. The Q modal analysis technique and P modal analysis technique have set Bus 8 and Bus 20 respectively, as the 3rd weakest bus.

Bus 29 has been marked as the 4th weakest bus by the values of LPM_P. The values of LPM_Q have shown that Bus 9 is the 4th weakest bus. The Q modal analysis technique and P modal analysis technique have set Bus 14 and Bus 19 respectively, as the 4th weakest bus.

Finally, the values of LPM_P have marked Bus 1 as the 5th weakest bus. The values of LPM_Q have decided that Bus 7 as the 5th weakest bus. The Q modal analysis technique and P modal analysis technique have set Bus 13 and Bus 23 respectively, as the 5th weakest bus.

Hence, it can be concluded from this table that the five weak buses in the IEEE 39-bus test power system are Bus 12, Bus 28, Bus 27, Bus 29 and Bus 7.

## 6. CONCLUSIONS

Identifying weak load buses in electrical power system is of paramount importance to prevent voltage instability from happening. Both modal analysis technique and LPM values are very useful in determining the weak load buses. It can be seen from the results that more than one load bus are prone towards experiencing voltage instability. The results also have shown that the modal analysis technique if used with LPM values will prove that the allowable range of load incremental values are very little. As soon as the weakest load bus has been determined, preventive action can be engaged in order to avoid voltage instability from going on. Voltage instability must be prevented from happening at any cause because the consequences of voltage instability are fatal. The power systems blackouts caused by voltage instability might spread to one local area or even severe, to the entire country. This will cause problem in distributing electrical power to the consumers that is one of the major factors to economic losses.

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