ELEKTROTEHNIŠKI VESTNIK 90(4): 206-213, 2023
ORIGINAL SCIENTIFIC PAPER

Voltage stability assessment using different methods

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Abstract. The voltage stability is an important factor needing to be taken into consideration in planning and operation of electric power systems. There are several methods and techniques available to determine the voltage stability and identify the power system weak buses, such as the P-V and Q-V curves, singular value decomposition, modal analysis, V-Q sensitivity and reduced determinant. The paper compares three load flow analysis methods: the modal analysis, V-Q sensitivity analysis and Continuation Power Flow.
The modal analysis method uses the power system Jacobian matrix to determine the eigenvalues necessary to evaluate voltage stability. The V-Q sensitivity method uses the diagonal elements of the inverse of the reduced Jacobian matrix. In the paper, the V-Q sensitivity and modal analysis method are applied to analyze the effect of a weak coupling between the reactive power (Q) and voltage angle (δ).
The results of using the three methods to analyse the western Algerian power system are compared in terms of detecting the weak buses.

Keywords: voltage stability, V-Q analysis, continuation power flow (CPF), modal analysis, Jacobian matrix, sub-matrix J_{qV}.

Ocena napetostne stabilnosti z uporabo različnih metod in tehnik

Napetostna stabilnost je pomemben dejavnik, ki ga moramo upoštevati pri načrtovanju in obratovanju elektroenergetskih sistemov. Na voljo je več metod in tehnik za določanje napetostne stabilnosti in prepoznavanje šibkih vodil elektroenergetskega sistema, kot so krivulje P-V in Q-V, razčlenitev singularne vrednosti, modalna analiza, občutljivost V-Q in zmanjšana determinanta. V prispevku primerjamo tri metode: modalno analizo, analizo občutljivosti V-Q in pretok moči.
Metoda modalne analize uporablja jakobijevo matriko elektroenergetskega sistema za določitev lastnih vrednosti, ki so potrebne za ovrednotenje napetostne stabilnosti. Metoda občutljivosti V-Q uporablja diagonalne elemente inverzne zmanjšane jakobijeve matrike. V prispevku sta metodi V-Q občutljivosti in modalne analize uporabljeni za analizo učinka šibke sklopitve med jalovo močjo (Q) in napetostnim kotom (δ).
Uporabljene metode za smo uporabili pri analizi elektroenergetskega sistema v zahodni Alžirije.

1 INTRODUCTION

The voltage stability is the ability of a power system to maintain an acceptable voltage value at all buses under normal operating conditions and after being subjected to an emergency [1].

Voltage problems have been a subject of great concern in planning and operation of power systems due to the significant number of serious failures believed to have been caused by this phenomenon making the development of the voltage stability analysis an absolute necessity. It is closely related to the notion of a maximum loadability of a power transmission network [2].

Several methods have been used in the static voltage stability analysis such as the P-V and Q-V curves methods, continuation power flow (CPF) method, model analysis method, V-Q sensitivity method, etc [3].

The P-V and Q-V curves methods are the most widely used methods to estimate the voltage stability. They are generated by a series of power-flow solutions and used to determine the load limit of a power system [4]. The P-V curves are generated by increasing the active-and the reactive-power load until the critical voltage value is reached. Unfortunately, the Newton-Raphson load-flow algorithm diverges: the load-flow Jacobian matrix becomes singular at a critical voltage value [5]. To amend a system ill-conditioning situation, the CPF method in 1992 was been proposed by Venkataramana Ajjarapu and Colin Christy [6].

The general CPF principle is simple. It employs a predictor-corrector scheme to find a solution. It adopts a locally-parameterized continuation technique. It includes the load parameter, step length for the load parameter and state variable [7]. In CPF, the complete P-V curve, including the nose point and the lower part of the curve, is drawn [8].

Received 28 August 2023
Accepted 14 October 2023

The CPF technique has been widely used to determine the maximum loading point limit of the system and to identify the weak buses [9].

The modal analysis method, presented in 1992 by Gao, Morisson and Kundur, uses the power-flow Jacobian matrix [10]. Besides providing an accurate estimate of the likely system instability occurrence using the system eigenvalues, the method identifies the elements of the power system most contributing to the system voltage instability (critical load buses, branches and generators) [11].

To predict the voltage instability in complex power system networks, Kundur proposed in 1992 a V-Q sensitivity analysis method using the power-flow Jacobian matrix [12].

The paper investigates the V-Q sensitivity, the modal analysis and the CPF method to assess the power system voltage stability. The main objective is to study the negative effect of a weak coupling between the reactive power and voltage angle.

The methods are tested on the westen Algerian power system. The results obtained are compared and discussed.

2 VOLTAGE STABILITY ANALYSIS

The voltage stability analysis is based on power flow calculations. The main factor causing the voltage instability is the inability of the power system to meet the reactive power demand. So the voltage stability is highly sensitive to the reactive power variation. The two main methods used to analyze the voltage stability by taking into account the reactive power variation are the V-Q sensitivity and modal analysis method.

The P-V curve method is one of the most used methods to forecast the voltage instability. It is used to determine the load limit of a power system. The curve is produced by running a series of the load-flow cases until the nose of the PV curve is reached [13]. The complete P-V curve is obtained by applying the CPF [14]. The paper proposes a simple method to plot the P-V curve.

2.1 Modal analysis

The modal analysis predicts the voltage collapse in a power system network. It computes the smallest eigenvalues and associated eigenvectors of the reduced Jacobian matrix obtained with the load-flow calculation [15]. The eigenvalues are associated with the mode of the voltage-and reactive-power variation which provides a relative likelihood of the voltage instability occurrence [16]. The weakest bus in the system is detected by using the participation factor values [17].

The linearized steady-state system of the power voltage equations is given by

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{p\delta} & J_{pV} \\ J_{q\delta} & J_{qV} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} \tag{1}$$

where:
ΔP is the incremental change in the bus real power, ΔQ is the incremental change in the bus reactive power, $\Delta\delta$ is the incremental change in the bus voltage angle and ΔV is the incremental change in the bus voltage.

When using the conventional power-flow model to analyze the voltage stability, the Jacobian matrix (1) is the same as the one used to solve the power-flow equations employing the Newton-Raphson technique [18].

The elements of the Jacobian matrix (1) are modified as follows:

The system voltage stability is affected by both P and Q. However, at each operating point P is kept constant and the voltage stability is evaluated by considering the incremental relationship between Q and V [19, 20]. Based on these considerations (1), if $\Delta P = 0$, then

$$\begin{bmatrix} 0 \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{p\delta} & J_{pV} \\ J_{q\delta} & J_{qV} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} \tag{2}$$

$$\Delta Q = (-J_{q\delta}.J_{p\delta}^{-1}.J_{pV} + J_{qV}).\Delta V = J_R.\Delta V \tag{3}$$

$$J_R = J_{qV} - J_{q\delta}.J_{p\delta}^{-1}.J_{pV} \tag{4}$$

J_R is the reduced Jacobian matrix of the system (2). It represents the linearized relationship between ΔV and ΔQ.

If the minimum eigenvalue of J_R is greater than zero, the system is voltage-stable. Using the left and right eigenvectors corresponding to a critical mode, the bus participation factors are calculated. The buses with a large participation factor are the critical buses of a power network [21].

The relative participation of bus k in mode i is given by bus participation factor [22]:

$$P_{ki} = \varepsilon_{ki} * \eta_{ki} \tag{5}$$

where:
P_{ki} is the k^{th} bus participation factor of the i^{th} eigenvalue, ε_{ki} is the right eigenvector (column vector) for the i^{th} eigenvalue, and η_{ki} is left eigenvector (row vector) for the i^{th} eigenvalue.

The algorithm to calculate the minimum eigenvalue and the corresponding left and right eigenvector, for the reduced Jacobian matrix takes the following steps [23]:

Step 1: Obtain the load-flow solution for the base case of the system and set the Jacobian matrix.

Step 2: Compute reduced Jacobian matrix J_R.

Step 3: Compute the eigenvalue of reduced Jacobian matrix (λ). (If $\lambda = 0 \rightarrow$, the system will collapse; if $\lambda > 0 \rightarrow$, the system is voltage stable; if $\lambda < 0 \rightarrow$, the system is voltage unstable). If the system is voltage stable ($\lambda > 0$), find how close the system is to voltage instability:

Step 4: Find the minimum eigenvalue of J_R.

Step 5: Calculate the right and left eigenvectors of the reduced Jacobian matrix (ε_{ki} and η_{ki}).

Step 6: For the minimum eigenvalue of the bus, find the participation factors for the corresponding mode and the bus (P_{ki})

Step 7: Highest P_{ki} indicates the most participating i bus to the k mode in the system, i.e. the bus with the maximum participation factor is considered as the weakest bus of the system.

An important characteristic of any power transmission system operating in a steady-state is the strong interdependence between the real powers and bus voltages angle and between the reactive powers and voltage magnitudes [24]. This interesting property of coupling the Q-V variables has motivated us to analyze the power system eigenvalues without evaluating the reduced Jacobian Matrix J_R.

Since, half of the elements of the Jacobean matrix in any conventional Newton method represents a weak coupling, it is therefore ignored. So, it is reasonable to set sub-matrices J_{pV} and $J_{q\delta}$ of the Jacobian matrix to zero. Therefore, (4) reduces to

$$J_R \approx J_{qV} \tag{6}$$

As the main cause of the voltage instability is the lack of the reactive power, such simplification avoids calculation of matrix J_R and does not entail a great loss of the precision in the results.

While considering J_R, a weak coupling between the reactive power and voltage angle ($-J_{q\delta}.J_{p\delta}^{-1}.J_{pV}.\Delta V$) is taken into account. When J_{qV} is considered, such a coupling is completely ignored.

Fig. 1 shows the steps to calculate the minimum eigenvalue and the corresponding left and right eigenvectors for J_{qV}.

2.2 The V-Q sensitivity analysis

To implement the voltage stability analysis, it is necessary to use$J_R.J_R^{-1}$is the inverse of the reduced Jacobian matrix. Its i^{th}diagonal element is the bus V-Q sensitivity. It represents the slope of the QV curve for a given operating point. The V-Q sensitivity studies evaluate the impact of the reactive power on the voltage values compliably with the following guidelines [25, 26]:

A positive V-Q sensitivity is indicative of a stable operation.

A negative V-Q sensitivity shows an unstable operation.

The smaller the sensitivity, the more stable the system.

A zero sensitivity represents a completely stable system.

If the sensitivity is infinite, then the system operates at the threshold of the stability limit.

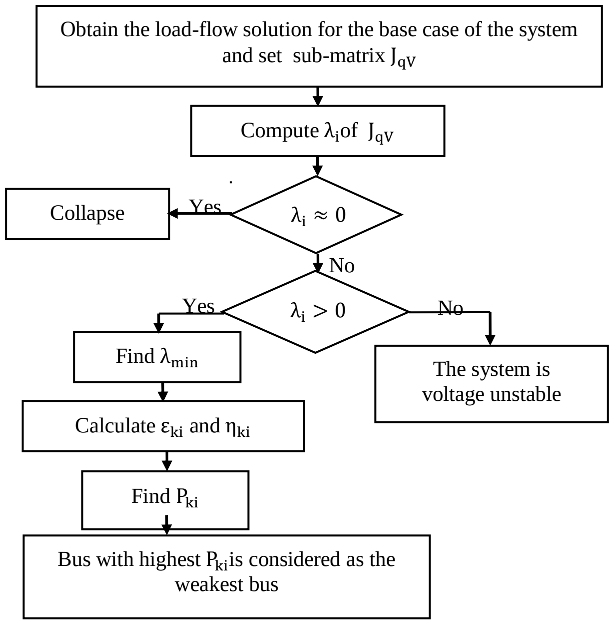

Figure 1. Flow chart for the modal analysis.

2.3 CPF method

Calculating the critical point at a node using the load-flow equations is not a straightforward task as the Jacobian matrix of the system becomes singular when approaching its maximum value [27]. The CPF method is used to solve the problem. The load increment is considered as a new variable in the power-flow equations [6].

The CPF method is an iterative process that employs a predictor–corrector scheme (see Fig.2). The process starts from a known solution corresponding to the bas-case loading (i.e. point A) and uses a tangent predictor to estimate a subsequent solution corresponding to a different value of the load parameter (i.e. point B). Finally, it uses a “corrector” to find an exact solution (i.e. point C) by using the Newton-Raphson technique commonly employed in a conventional power-flow study [28, 29]. After that, a new prediction is made for a particular increase in the load value based upon the new tangent vector. The corrector step is now applied. The process is repeated until the critical point is reached. It is the point where the tangent vector is zero.

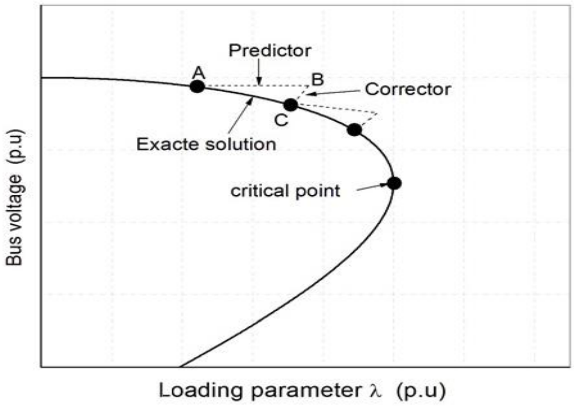

Figure 2. Predictor-corrector steps in the CPF method.

In traditional power-flow equations, the injected active and reactive power for each bus are defined in (7) and (8).

$$P_i = P_{Gi} - P_{Li} = \sum_{j=1}^{n} V_i V_j Y_{ij} \cos(\delta_i - \delta_j + \theta_{ij}) = 0 \quad (7)$$

$$Q_i = Q_{Gi} - Q_{Li} = \sum_{j=1}^{n} V_i V_j Y_{ij} \sin(\delta_i - \delta_j + \theta_{ij}) = 0 \quad (8)$$

where G and L are the generation and load demand, respectively, on the related bus, P, Q are the real and reactive power at bus i, $V_i \angle \delta_i$ is the voltage at bus i and $Y_{ij} \angle \theta_{ij}$ is the $(i,j)^{th}$ element of the system admittance matrix.

To simulate a load change, the loading parameter λ is inserted into the demand powers P_{Li} and Q_{Li}.

$$\Delta P_i = P_{Gi} - \lambda P_{Li0} \quad (9)$$

$$\Delta Q_i = Q_{Gi} - \lambda Q_{Li0} \quad (10)$$

After substituting new demand powers in Equations 9 and 10 to Equations 7 and 8, the new set of equations denoted as F can be expressed as (11).

$$F = \lambda(\delta, V, \lambda) = 0 \quad (11)$$

where δ is the vector of the bus voltage angles and V is the vector of bus voltage values. Then, the continuation and parameterization process are applied [30]. Details of the CPF method are discussed in [6].

3 CASE STUDY

The single-line diagram of the western Algerian power system is shown in Fig. 3. It consists of 14 buses, three generators located at buses 1 (Oran), 4 (Marsat) and 3 (Tiaret) and 17 branches (lines and transformers). The used parameters and data are taken from [31].

The lower voltage value limit at each bus is 0.9 p.u and at the upper it is 1.1 p.u.

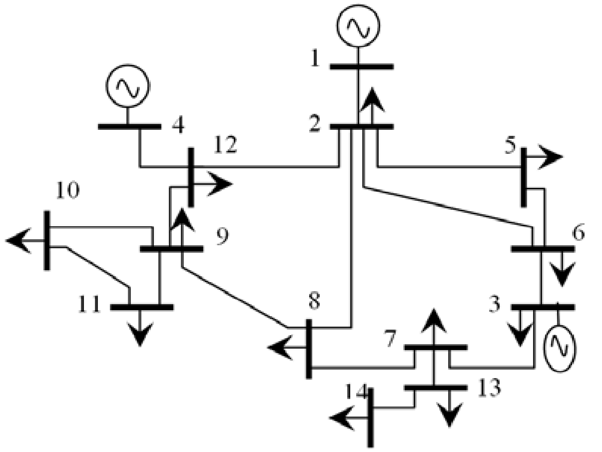

Figure 3. Western Algerian power system.

Initially, a base-case load-flow calculation using the Newton-Raphson method to determine the voltage stability state of the system is performed. The initial voltages denoted by V_i are given in Fig. 4. As seen, all the bus voltages are within the acceptable level (± 10%).

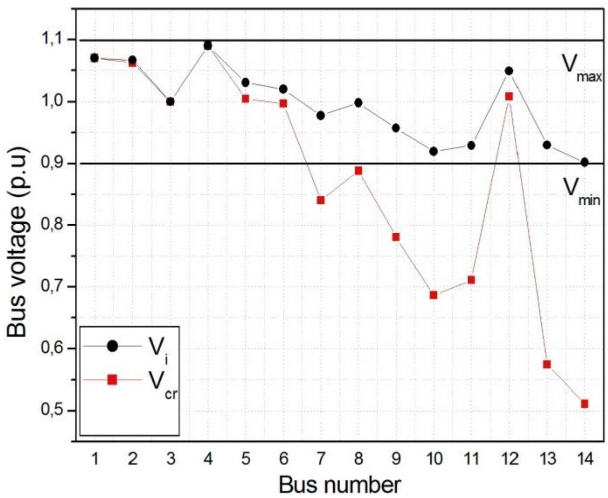

Figure 4. Voltage profiles of each bus .

For a steady-state of the western Algerian power system, the modal analysis method is applied:
Table 1 shows eigenvalues λ of reduced Jacobian matrix J_R and sub-matrix J_{qV}.

Table 1. Eigenvalues of J_R matrix and J_{qV} sub-matrix.

Mode	λ of J_R	λ of J_{qV}	Mode	λ of J_R	λ of J_{qV}
1	957.3668	931.3529	7	25.8684	21.1083
2	79.7612	75.5996	8	62.3337	58.2345
3	1.3470	1.2617	9	55.6630	53.6268
4	3.4519	3.4217	10	46.3581	44.5111
5	15.0333	12.4929	11	49.8563	47.9324
6	17.6550	14.4854			

The eigenvalue λ_3= 1.3470 of matrix J_R and the eigenvalue λ_3= 1.2617 of sub-matrix J_{qV} are the smallest ones. Hence, mode 3 is the system most critical mode. The eigenvectors of mode 3 of reduced Jacobian matrix J_R and of the sub-matrix J_{qV} are used to calculate the participation factors that indicate the buses contributing most to the total system voltage stability.

Fig 5 shows the bus participation factors contributing to the system critical mode.

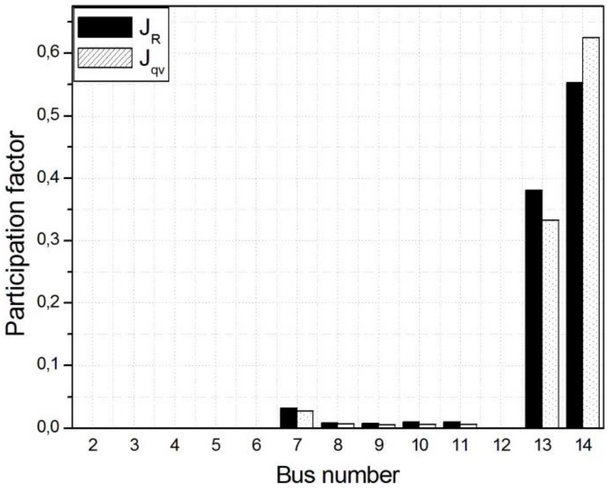

Figure 5. Bus participation factors at a system critical mode

Fig. 5 shows that the highest participation factors are at the buses 14 (Bechar) and 13 (Naama). The factor value for bus 14 is 0.5526 for reduced Jacobian matrix J_R and 0.6252 for sub-matrix J_{qV}. Bus 14 is the weakest bus of the system and is as such contributing maximaly to the system voltage collapse.

As also, Fig. 5 shows only the buses possessing the participation factor. Since the voltages of the slack and PV buses are determined prior to the load flow analysis, no participation factor is considered on these buses.

A sensitivity is mode for the western Algerian power system. Table 2 shows the V-Q sensitivity values calculated for the base case for both the J_R and J_{qV} matrices.

Table 2. The V-Q sensitivity values for the base case

Bus number	V-Q sensitivity		Bus number	V-Q sensitivity	
	J_R	J_{qV}		J_R	J_{qV}
4	0.0011	0.0011	10	0.1234	0.1238
5	0.0489	0.0508	11	0.1184	0.1195
6	0.0376	0.0391	12	0.0199	0.0203
7	0.0660	0.0658	13	0.3099	0.3034
8	0.0435	0.0439	14	0.4387	0.5315
9	0.0758	0.0755			

The sensibility of each bus is positive. The bus with the highest sensitivities, i.e., 0.4387 and 0.5315, for J_R and J_{qV}, respectively is bus 14 (Bechar) the next is bus 13 (Naama) with the sensibilities of 0.3099 and 0.3034. Bus 14 is the weakest.

As the system voltage stability is highly affected by the reactive-power, the total reactive-power load is increased by parameter K from its base value (3.12 p.u) to the critical value (6.792 p.u).

The voltages denoted as V_{cr} and obtained by the load-flow calculation at a critical state, i.e., at a high reactive-power demand, are indicated in Fig. 4. It is show that when the system reaches its maximum loadability point $K = 6.792$, the voltages at bus 14 (Bechar), 13 (Naama) and 10 (Oujda) greatly decrease.

Table 3 shows the eigenvalues of the J_R matrix and J_{qV} sub-matrix for loading parameter K.

Table 3 shows that when the load increases, the eigenvalues positively decrease and λ_3 reaches zero.

Table 3. Eigenvalues of the J_R matrix and J_{qv} sub- matrix for different load values

k	Matrix	λ_1	λ_2	λ_3	λ_4	λ_5	λ_6
0.000	J_R	960.11	86.75	**1.81**	4.32	15.60	19.47
	J_{qV}	934.04	82.19	**1.68**	4.21	14.28	15.03
1.000	J_R	957.36	79.76	**1.34**	3.45	15.03	17.65
	J_{qV}	931.35	75.59	**1.26**	3.42	12.49	14.48
1.500	J_R	955.74	75.37	**1.01**	2.87	14.73	16.26
	J_{qV}	929.77	71.47	**0.97**	2.91	11.23	14.20
2.177	J_R	952.97	66.94	**0.26**	1.57	6.86	14.33
	J_{qV}	927.08	63.58	**0.20**	1.87	7.70	13.80

k	Matrix	λ_7	λ_8	λ_9	λ_{10}	λ_{11}
0.000	J_R	29.77	70.45	57.72	49.49	51.08
	J_{qV}	23.09	65.84	55.60	47.52	49.11
1.000	J_R	25.86	62.33	55.66	46.35	49.85
	J_{qV}	21.10	58.23	53.62	44.51	47.93
1.500	J_R	23.33	57.15	54.31	44.28	49.21
	J_{qV}	19.83	53.42	52.29	42.51	47.31
2.177	J_R	18.03	51.68	48.33	39.66	46.49
	J_{qV}	17.00	49.74	46.46	38.08	43.45

Fig. 6 shows a variation in the smallest eigenvalues of the J_R matrix and J_{qV} sub-matrix at a critical mode with respect to loading parameter K.

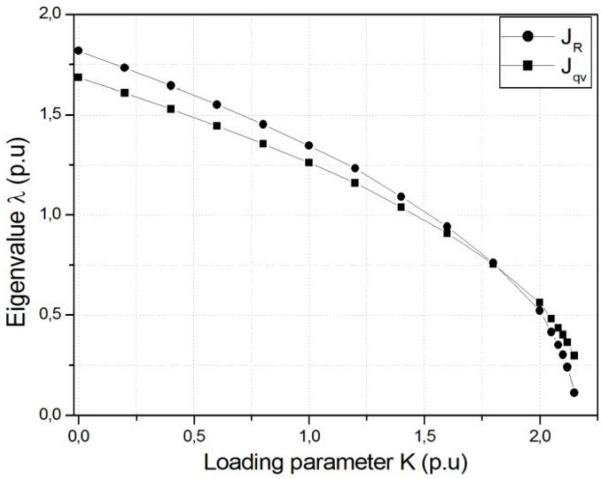

Figure 6. Variation in the smallest eigenvalues of J_R and J_{qV}

The minimum eigenvalues correspond to the loading parameter K=2.177. They indicate that the system operating point is close to the voltage instability.
Table 4 shows the V-Q sensitivities of the J_R and J_{qV} at the critical state.

Table 4.V-Q sensitivities at a critical state

Bus Number	V-Q sensitivity		Bus Number	V-Q sensitivity	
	J_R	J_{qV}		J_R	J_{qV}
4	0.0011	0.0011	**10**	0.1792	0.2475
5	0.0511	0.0532	**11**	0.1606	0.2239
6	0.0393	0.0408	**12**	0.0204	0.0223
7	-0.0870	0.1292	**13**	-1.7551	1.4953
8	0.0119	0.0649	**14**	-1.5127	3.3006
9	0.0842	0.1310			

Table 4 shows that the V-Q sensitivity coefficient value is infinite at the stability limit point for the J_R matrix and is negative for sub-matrix J_{qV}. This indicates that system is unstable.

The system voltage stability is assessed by examining the system PV curves obtained by increasing the load level up to the maximum load limit at which the system voltage collapses [12]. The curves are calculated by using the CPF method. Fig. 7 shows the P-V curves of each bus of the western Algerian power system. The curves show the bus voltage level while increasing loading factor K. The loading factor which is 0 is gradually increased in all the bus bars until reaching the maximum loading point.

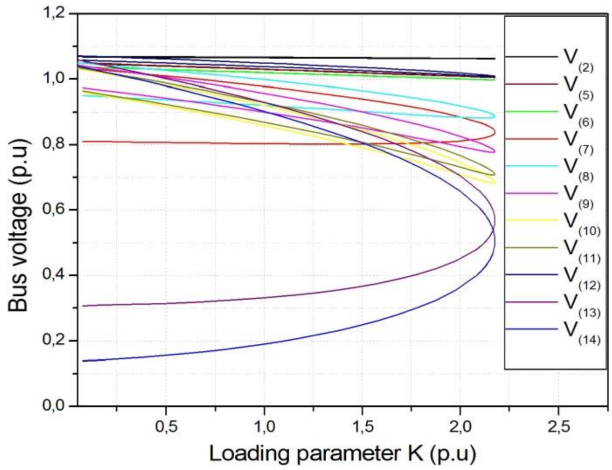

Figure 7. P-V curves of the western Algerian power system.

Fig. 7 shows that the weakest bus is bus 14 (Bechar). The next is bus 13 (Naama). This is due to the high steepness of the graph of both buses.
The point where K is 2.177 is the system critical point at specific operating states. The system then enters into an unstable state which may result in a voltage collapse.
Fig. 8 shows the buses the most sensitive to the load increase.

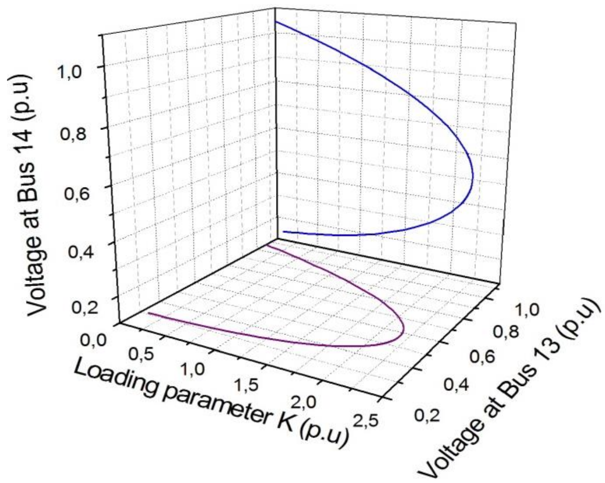

Figure 8. P-V curves for the two most sensitive buses of the western Algerian power system.

Bus 14 (Bechar) has the lowest voltage level, i.e. 0.5125 p.u, making it the weakest bus in the western Algerian power system. This result is the same as when using the V-Q Sensitivity and Modal analysis methods.

4 Conclusion

The modal analysis, V-Q sensitivity and CPF methods are used to investigate the stability of the western Algerian power system by identifying its weak buses.
Because the high X/R ratio of power the transmission network, the active power mostly depends on the phase angles, unlike the reactive power which mainly depends

on the voltage value. Finding this property interesting, the proper analysis of voltage stability is conducted, irrespective of the weak coupling between reactive power and voltage angle.

The V-Q sensitivity and modal methods are applied by taking into account the weak coupling between the reactive power and the voltage angle, i.e., by considering the reduced Jacobian matrix and those obtained by neglecting the coupling.

The biggest advantage of using sub-matrix J_{qV} instead of reduced Jacobian matrix J_R is its simplicity and the short computation time.

The major disadvantage of using J_R instead of J_{qV} is the inversion of the matrix in each load increase that takes a lot of time. A time increases as the number of the network buses increases.

The performance and accuracy of each case are assessed by comparing the results obtained when using the reduced Jacobian matrix and sub-matrix J_{qV} in terms of the weakest buses. The results of both cases are similar.

Using CPF confirms completeness of the result obtained when the modal analysis and V-Q sensitivity methods. The same buses are detected as the weakest and as such likely to give rise to a voltage collapse.

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