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Voltage Collapse Prediction of IEEE 30-Bus system

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ABSTRACT

Voltage collapse in the power system occurs as a result of voltage instability, thus which lead to a blackout, and this is a constant concern for network workers and customers alike. In this paper, voltage collapse is studied using two approved methods: the modal analysis method and voltage stability indices. In the modal analysis method, the eigenvalues were calculated for all the load buses, through which it is possible to know the stability of the power system, The participation factor was also calculated for the load buses, which enables us to know the weakest buses in the system. As for the Voltage stability Indices method, two important indices were calculated, which are: Fast Voltage Stability Index (FVSI) and Line stability index (Lmn). These two indices give a good visualization of the stability of the system and the knowledge of the weakest buses, as well as the Maximum load-ability of the load buses. The above mentioned two methods were applied using software code using MATLAB \ R2018a program to the IEEE 30-Bus test system. In the modal analysis, the buses which have the maximum participation factor are 26, 29, and 30 this indicates that they are the weakest in the system. as well as in the voltage stability indices. These buses have the lowest maximum load ability which demonstrates the possibility of using both methods or one of them to study the voltage collapse.

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التنبؤ بانهيار الفولتية في نظام IEEE 30-Bus

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الخلاصة

انهيار الفولتية في نظام القدرة يحدث نتيجة لعدم استقرار الفولتية وقد يؤدي الى الانطفاء التام للمنظومة, وهذا يشكل مصدر قلق دائم للعاملين في مجال النقل والمستهلكين على حد سواء. في هذه البحث تم دراسة انهيار الفولتية باستخدام طريقتين وهما طريقة التحليل النمطي وطريقة مؤشرات انهيار الفولتية. في طريقة التحليل النمطي تم حساب القيم الذاتية لكل عموميات الحمل حيث تعد مؤشرا على استقرار النظام وكذلك تم حساب عامل المشاركة لنفس العموميات والتي تمكننا من معرفة العمومي الأضعف في المنظومة. اما في طريقة مؤشرات انهيار الفولتية فتم استخدام مؤشرين وهما مؤشر استقرار الجهد السريع (FVSI) ومؤشر استقرار الخط (Lmn) . الطريقتين المذكورتين سابقا تم تطبيقهما باستخدام برنامج MATLAB \ R2018a على نظام (IEEE 30-bus). في طريقة التحليل النمطي كانت العموميات ذات اعلى عامل مشاركة هي 26 و 29 و 30 مما يدل على انها العموميات الأضعف، كما في طريقة مؤشرات انهيار الفولتية حيث ان هذه العموميات تملك اقل قدرة تحميل. وهذا يبرهن على إمكانية استخدام كلتا الطريقتين او احدهما لدراسة انهيار الفولتية.

الكلمات الدالة: انهيار الجهد، التحليل النمطي، مؤشرات استقرار الجهد، Lmn، FVSI، عامل المشاركة.

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1. INTRODUCTION

In the few past decades, the power system's voltage stability becomes very close to the limits of system design, planning, and operation. This causes numerous destructions of overall power system stability limits, and it results in voltage collapse occurrences from place to place in the world with high-cost insinuations to both companies and consumers . Voltage collapse is the most important problem, which occurs when a disturbance on the system causes a voltage drop and uncontrollable gradually [1], load suddenly increment, faults, external factors, and it can also occur when the demand for reactive power is greater than generated reactive power [2]. Voltage collapse causes a blackout, which is maybe partial or total blackout. At last power supply will be cut on consumers [3]. Power system networks must be still working in safety limits under stability conditions; this requires that the system should be able to return to stability conditions after a disturbance or at least very close to the value of pre-disturbances.

Voltage stability is defined as "the ability of a power system to maintain steady and acceptable voltages at all buses in the system at normal operating conditions and after being subjected to a disturbance" [4].

Many studies were submitted to solve the voltage collapse problem, one of these studies was used to predict voltage collapse before it occurs and save the system from it. Next, some of these researches.

Ashish Godra and et. al (2018) discussed the use of line voltage stability indices termed as fast voltage stability index (FVSI) and line stability index (Lmn) to determine the critical line [5].

Isaiah G. Adebayo and et. al (2018) present voltage stability assessment using a technique based on modal analysis of the reduced Jacobian. The participation factor (PF) of each load node is determined to evaluate the weakest bus. The effectiveness of the methodology presented on the IEEE 30 bus power system [6].

Srinivas Nagaballi and Vijay S. Kale (2019) view research as an assessment of various voltage stability indices to predict the proximity of the distribution line close to voltage collapse. The behavior of VSIs has been tested on two test systems, i.e. IEEE 12-bus and IEEE 33-bus systems. These indices are differentiated to resolve their effectiveness in identifying the weakest line in the system [7].

In the previous research, only one method was used (i.e. either modal analysis or voltage stability indices), while in this paper, voltage collapse prediction was introduced by using the two methods together. Predicting the voltage collapse point, weakest busses, and the most critical lines for each bus of the IEEE 30-Bus system standard system. This makes the planners and workers take appropriate actions to avoid the voltage collapse in emergency cases, as well as make them put compensators in suitable places to increase the network efficiency.

2. MODAL ANALYSIS

The Modal analysis generally is determined by the power flow solution, precisely depends on the reduced Jacobian matrix. This method was proposed in 1992 by Gao, Morison, and Kundur [8]. It can study voltage stability in complex power system networks as well as a simple system. It includes mainly the calculating of the lowest eigenvalues and eigenvectors of the Jacobian matrix that reduced which obtained from the power flow solution. The calculated eigenvalues are connected with a mode of voltage amplitude and reactive power variation, which can make available a relative measure of voltage instability proximity. Then, the weakest bus in the system can be found by calculating the participation factor [9].

Modal analysis can be summarized as follows:

1. If $\lambda_i = 0$, the ith modal voltage will collapse because any change in that modal reactive power will cause infinite modal voltage variation

2. If $\lambda_i > 0$, the ith modal voltage and ith 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 ith reactive power variation are along with the opposite directions, indicating that the system is voltage unstable.

Begging from the power equation

$$S_i = V_i I_i^* \tag{1}$$

$$S_i^* = P_i - jQ_i = V_i^* \sum_{k=1}^{n} Y_{ik} V_k \text{ ; i=1,2……,n} \tag{2}$$

Real power and reactive power equations are

$$P_i = \operatorname{Re}\left\{ V_i^* \sum_{k=1}^{n} Y_{ik} V_k \right\} = V_i^* \sum_{k=1}^{n} V_k Y_{ik} \cos\left(\theta_{ik} + \delta_k - \delta_i\right) \tag{3}$$

$$Q_i = -\operatorname{Im}\left\{ V_i^* \sum_{k=1}^{n} Y_{ik} V_k \right\} = -V_i^* \sum_{k=1}^{n} V_k Y_{ik} \sin\left(\theta_{ik} + \delta_k - \delta_i\right) \tag{4}$$

Modal analysis can be derived in form of linearized power flow beginning from the Jacobian matrix as shown below

$$J = \begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V} \end{bmatrix} = \begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix} \tag{5}$$

The power flow equation is

$$\begin{bmatrix} \Delta \mathrm{P} \\ \Delta \mathrm{Q} \end{bmatrix} = \left[J \right] \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} \tag{6}$$

Meanwhile, voltage stability analysis be determined by the reactive power of the system Q, therefore, if the active power P is kept as a constant, then,

$$\begin{bmatrix} 0 \\ \Delta \mathrm{Q} \end{bmatrix} = \left[J \right] \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} \tag{7}$$

The reactive power incremental change of the load busses can be expressed as:

$$\Delta Q = J_{21} \Delta \delta + J_{22} \Delta V \tag{8}$$

$$\Delta \delta = -J_{11}^{-1} J_{12} \Delta V \tag{9}$$

Substituting 9 in 8 yields

$$\Delta \mathrm{Q} = [J_{22} - J_{21} J_{11}^{-1} J_{12}]\ \Delta \mathrm{V} \tag{10}$$

$$\Delta \mathrm{Q} = J_R \Delta \mathrm{V} \tag{11}$$

Where

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

Equation 11 can be written as

$$\Delta V = J_R^{-1} \Delta Q \tag{13}$$

Eigenvalue analysis of J_R results in the following:

$$J_R = \Phi \Lambda \Gamma \tag{14}$$

Where J_R: reduced Jacobian matrix, Φ: right eigenvector matrix of J_R, Γ: left eigenvector matrix of J_R, Λ: diagonal eigenvalue matrix of J_R

By inversing equation 10 yields:

$$J_R^{-1} = \Phi \Lambda^2 \Gamma \tag{15}$$

If Φ_i and Γ_i represent the right- eigenvectors and left-eigenvectors, for the eigenvalue λ_i of the reduced Jacobian matrix J_R, then the participation factor defined as

$$P_{ki} = \Phi_{ki}\, \Gamma_{ik} \tag{16}$$

Q-V curve is a method of calculating voltage stability. It represents the relationship between the bus voltage and reactive power. Many utilities of using Q-V curves such as voltage collapse proximity determination, this technique allowed the operators to make better decisions to avoid voltage instability. On the other hand, planners will know the maximum load ability of each bus bar. The maximum load ability refers to how can adding reactive power to the buses before reaching voltage collapse. Also, the maximum load ability limits could relate to the shunt capacitor size or static VAR compensator in the load area. It can be generated by varying reactive power and calculating voltage at each value of it at the weakest bus or the tested bus.

The flow chart of modal analysis can be shown in Fig. 1

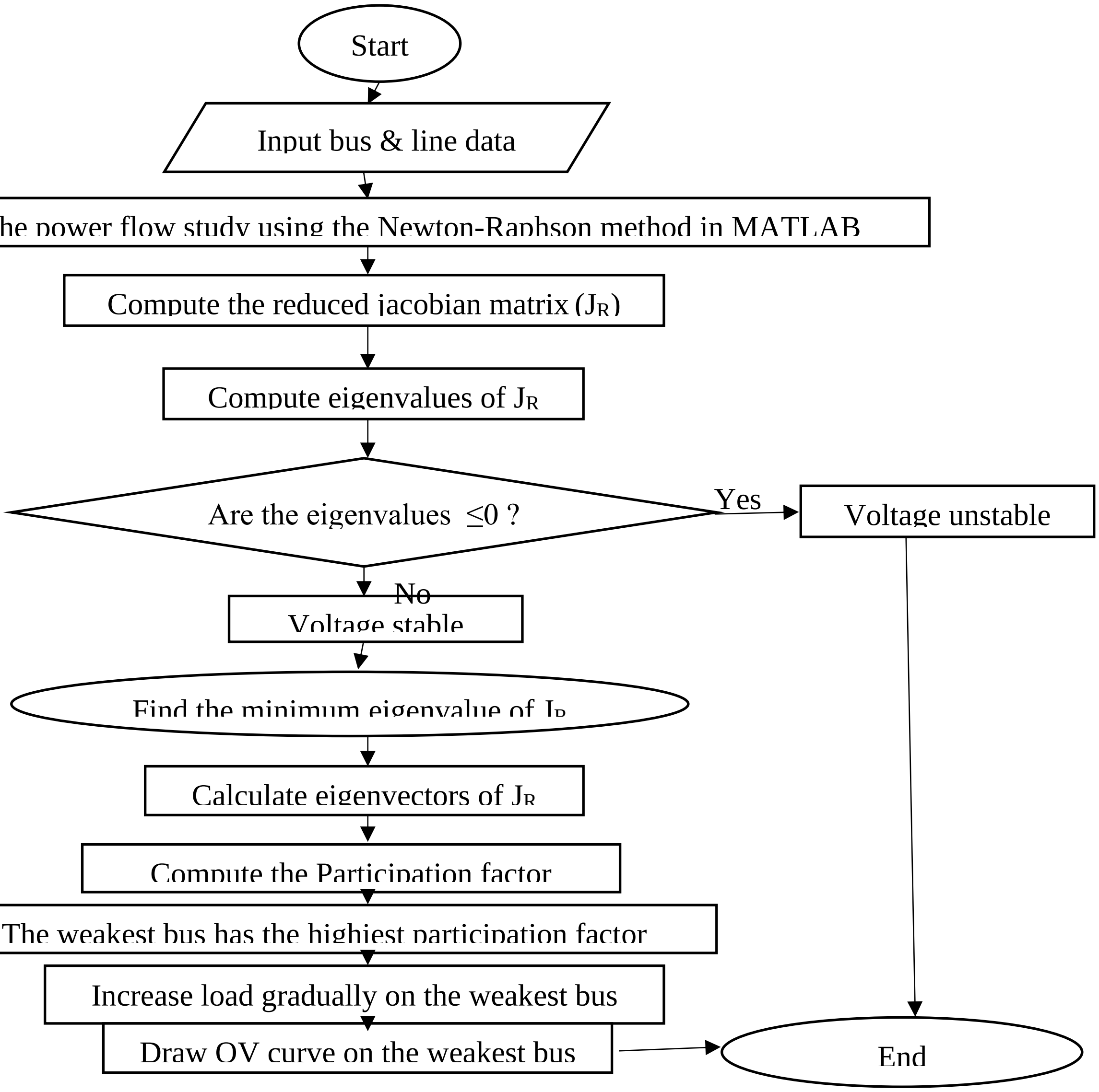


Fig.1: flow chart of modal analysis

3. VOLTAGE STABILITY INDICES

Voltage stability indices have a very large interest in voltage collapse studies because they detect the stability limits and how close each bus to voltage instability. Voltage stability indices are used for online/offline monitoring of the power system grid to voltage collapse prediction.

The observation of the voltage collapse of the power system network is an important function for the system's safe operation, due to using these indices to predict and find the system voltage stability state. These indices are used to know if the system is near to voltage collapse and to take actions to avoid the collapse. Voltage stability indices in a power system can be classified as either referring to a bus or line voltage stability indices. The following table shows the classification of the voltage stability indices.

Table 1
Classification of voltage stability indices [10]

Line voltage stability indices		Bus voltage stability indices		Jacobian Matrix-based	
Name	**Abriv.**	**Name**	**Abriv.**	**Name**	**Abriv.**
Lmn Index	Lmn	L Index	L	Impedance Ratio Indicator	IRI
Line Voltage Factor	LQP	Power Stability index	PSI	Minimum Eigenvalue and Right eigenvector method	RE
Line Index	L	Voltage Deviation Index	VDI	Minimum Singular value	MSV
Voltage Collapse Proximity Indicator	VCPI	Stability Index	SI	Predicting Voltage Collapse	PVC
Novel Line Stability Index	NLSI	Voltage Collapse Prediction Index	VCPI	Test Function	TF
Fast Voltage Stability Index	FVSI	Sensitivity Analysis	SA	Tangent Vector Index	TVI
Critical Voltage	Vcr	Bus Participation Factor	BPF	Second-Order Index	i
Power Transfer Stability Index	PTSI	Voltage Stability Index	VSI	Integral Steady-State Margin	ISSM
Line Voltage Stability Index	LVSI	Equivalent Node Voltage Collapse Index	ENVCI		
Critical Boundary Index	CBI	Voltage Collapse Index	VCI		
Line Voltage Stability Index	LVSI	Improved Voltage Stability Index	IVSI		
Integrated Transmission Line Transfer Index	ITLTI	Voltage Stability Factor	VSF		
		Voltage Instability Proximity Index	VIPI		

In this paper, two different types of voltage stability indices are used which are FVSI and Lmn. Moreover, the calculations were performed using MATLAB.

3.1 Fast Voltage Stability Index (FVSI)

This index is derived by Musirin (2002), it is based on notions of load flow through lines [11] as shown in fig. 2

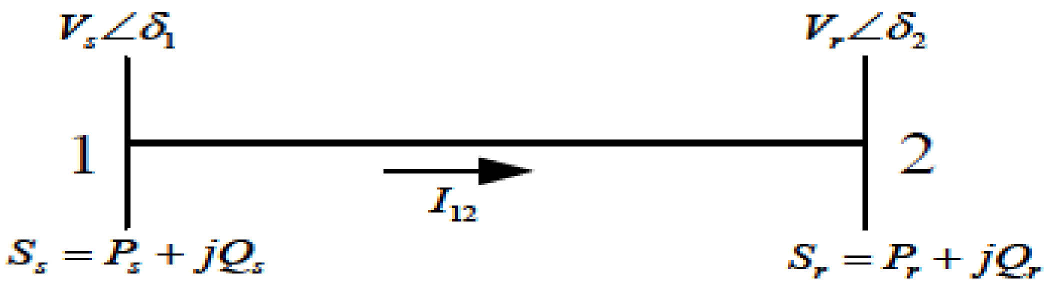


Fig. 2: single line diagram of the transmission line

It was derived based on reactive power and voltage. FVSI value of a line must be less than one, when its value is close to unity that means that the line is closest to its stability limit. This case may lead to system instability [12].

Fast Voltage Stability Index (FVSI) is calculated by the following formula.

3.2 Line Stability Index (Lmn)

Moghavvemi and Omar (1998) proposed this index. It is also based on the concept of load flow of a one-line as shown in fig. 2. The load flow using π nominal model exemplification for a 2-bus system is used and the discretion of the voltage quadratic equation must be above or equal to zero. If it is less than zero, the roots will be imaginarily suggesting that there is instability in the system [13]. Line Stability Index (Lmn) is calculated by the following formula.

$$FVSI = \frac{4Z^2 Q_r}{V_s^2 X} \leq 1$$

(17)

Where Z: line impedance, X: line reactance, Qr: reactive power flow to the receiving end, and Vs: sending-end voltage.

$$Lmn = \frac{4XQ_r}{|V_s|^2 \sin^2(\theta - \delta)} \leq 1$$

(18)

where X: line reactance, Q_r: reactive power flow to the receiving end, V_s: sending-end voltage, Ɵ: transmission line angle, and δ: phase angle.

Flow chart of voltage stability indices methods can be shown in fig. 3

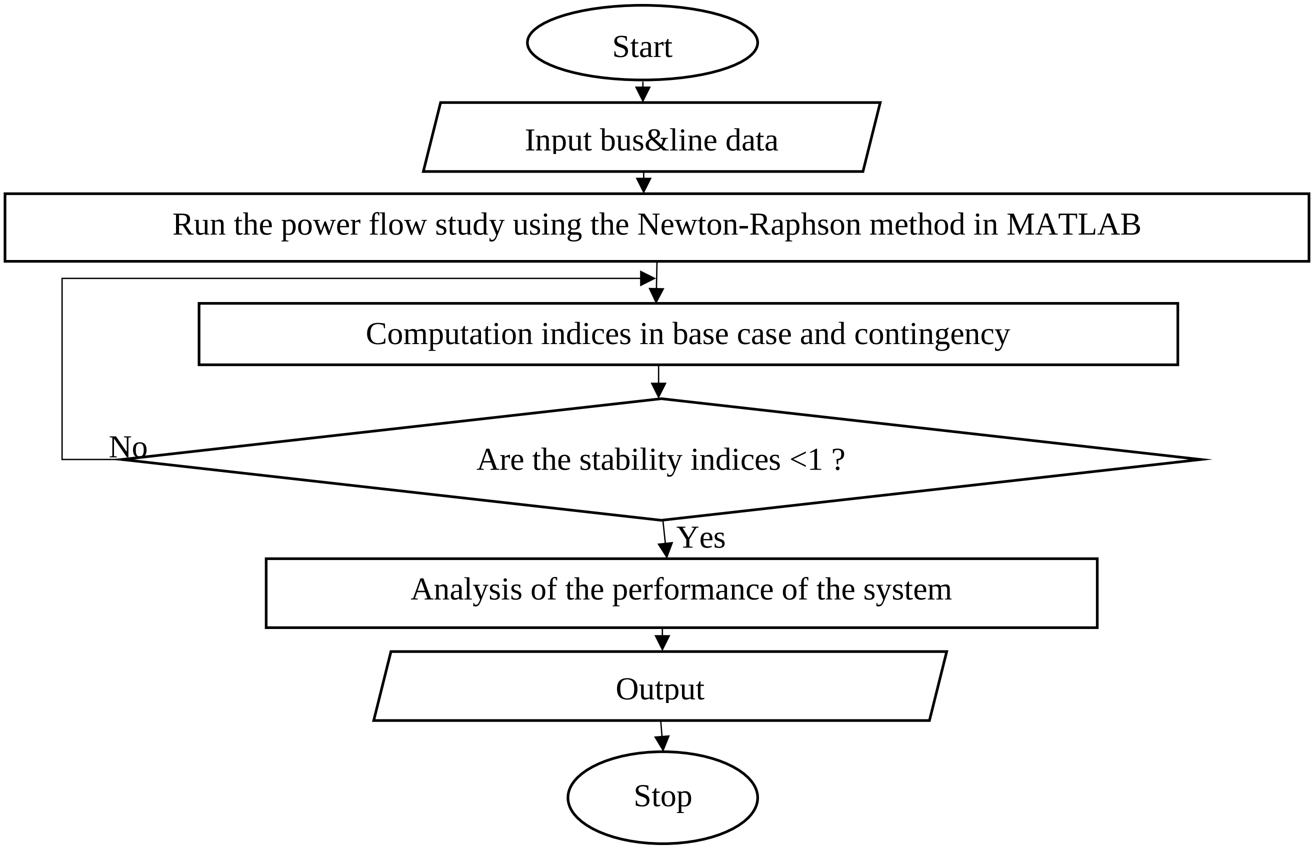


Fig. 3: flow chart of voltage stability indice

4. RESULTS AND DISCUSSION

When using the modal analysis method, if the eigenvalues of all load busses are greater than zero that means the system is stable, then the participation factor must compute. The weakest buses are the buses that have the highest participation factor. While by using voltage stability indices, there are advantages of using each type of indices, for example, the Fast Voltage Stability Index (FVSI) is the fastest index to reach the result, also the Line Stability Index (Lmn) is the most accurate from the indices. In this research, MATLAB was used to predict the voltage collapse on IEEE 30 bus standard system by using both Lmn and FVSI indices. The IEEE 30 bus standard system has five generator buses (PV), and twenty-four load buses (PQ), and forty-one branches or interconnected lines. Out of the generator buses, bus (1) chased as slack bus bar [14]. The single-line diagram shown in fig. 4

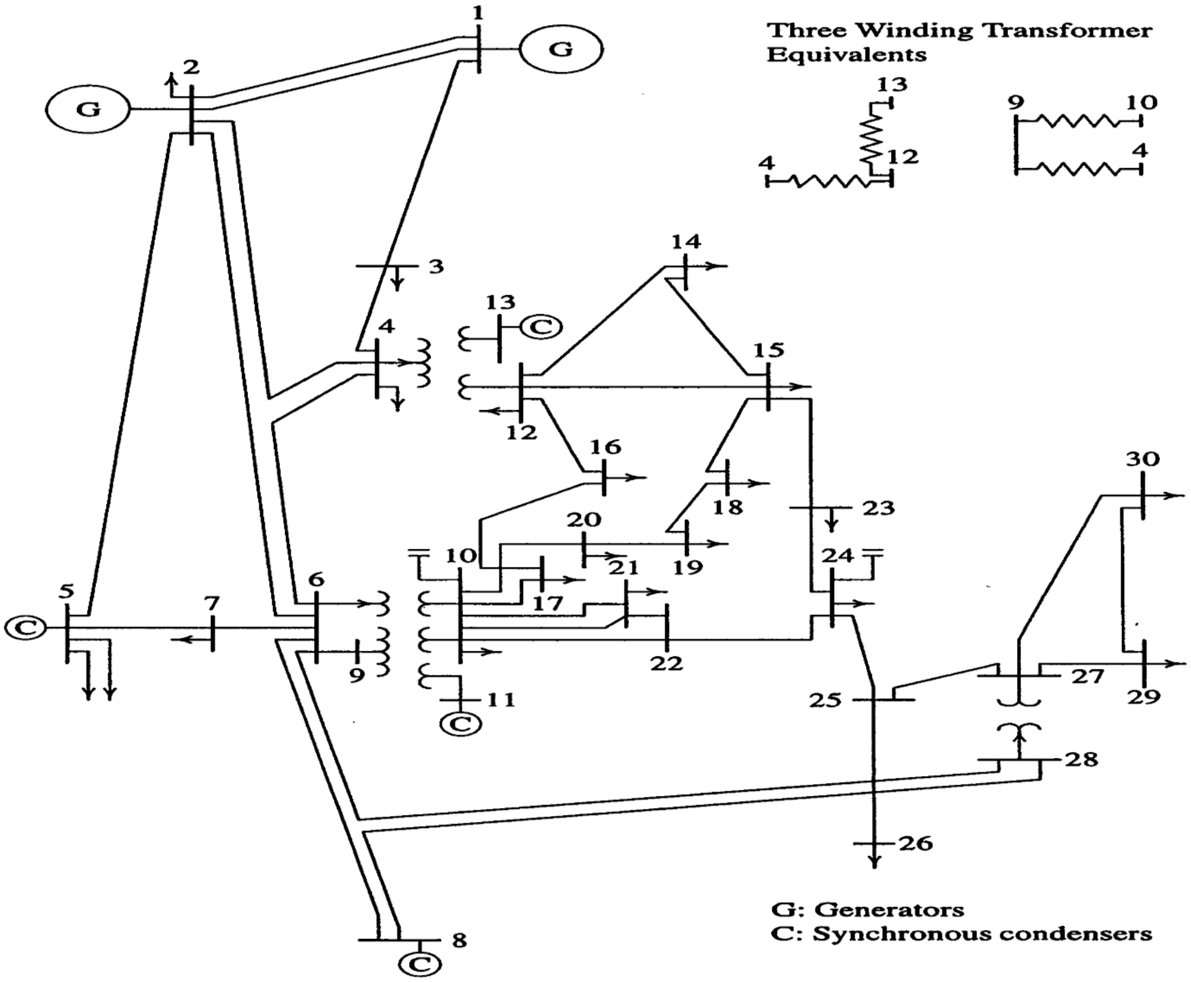


Fig. 4: single line diagram of the IEEE 30 bus system [14]

4.1. Load flow solution

The load flow simulation was completed on the IEEE 30-bus standard system. Fig. 5 shows the graph of voltage magnitude versus bus number (voltage profile). Voltage magnitude at all buses is between (0.995 to 1.082). The buses that exceed the permissible voltage levels are buses 9, 11,12, and 13 have voltage magnitudes of 1.051, 1.082, 1.057, and 1.071 p.u respectively. These buses are considered to have violated the ±5% tolerance margin of voltage criterion. This high voltage is an indication that the network is prone or susceptible to possible voltage instability.

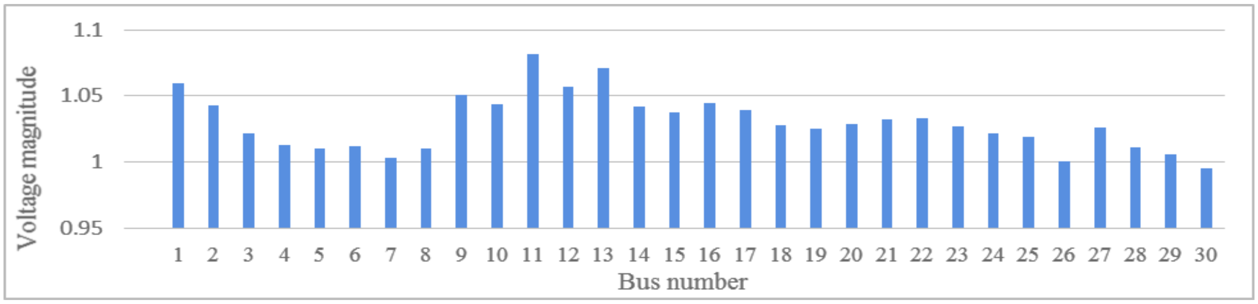


Fig. 5: The bar chart of voltage profiles for the IEEE 30-Bus System

4.2. Simulation Result using modal analysis

In the IEEE 30-Bus system, there are one swing bus and 5-generation buses, so the number of the eigenvalues obtained from the reduced Jacobian matrix must be equal to 24. Table 2 shows the eigenvalues of IEEE 30-bus. Where all eigenvalues are greater than zero, which means the system voltage is stable. The smallest eigenvalue is 0.518, which is the most critical mode.

Table 2

Eigenvalues and the participation factor of IEEE 30-bus

bus No.	eigenvalue	Participation Factor
3	110.4594	0.0004
4	101.3378	0.0005
6	66.116	0.0005
7	60.1211	0.0002
9	38.0069	0.0035
10	35.5183	0.0112
12	23.5405	0.0036
14	23.2494	0.0079
15	19.272	0.0108
16	19.8532	0.0075
17	18.2208	0.0108
18	16.771	0.0159
19	13.9795	0.0171
20	13.7211	0.0164
21	11.1013	0.0166
22	0.518	0.0179
23	1.0573	0.0233
24	1.7984	0.0384
25	8.8372	0.1069
26	3.6327	0.1734
27	4.0901	0.1064
28	7.664	0.0027
29	5.5481	0.1953
30	6.3075	0.2129

Since all eigenvalues are greater than zero, that means the voltage is voltage stable. The smallest eigenvalue is 0.518, which is the most critical mode. After that, the participation factors can be computed. Buses 26, 29, and 30 have the maximum participation factors for the critical mode i.e. the weakest busses in IEEE 30-Bus are the busses determined above. Fig. 6 shows a bar chart for the participation factor in the IEEE 30-Bus system and the highest of them.

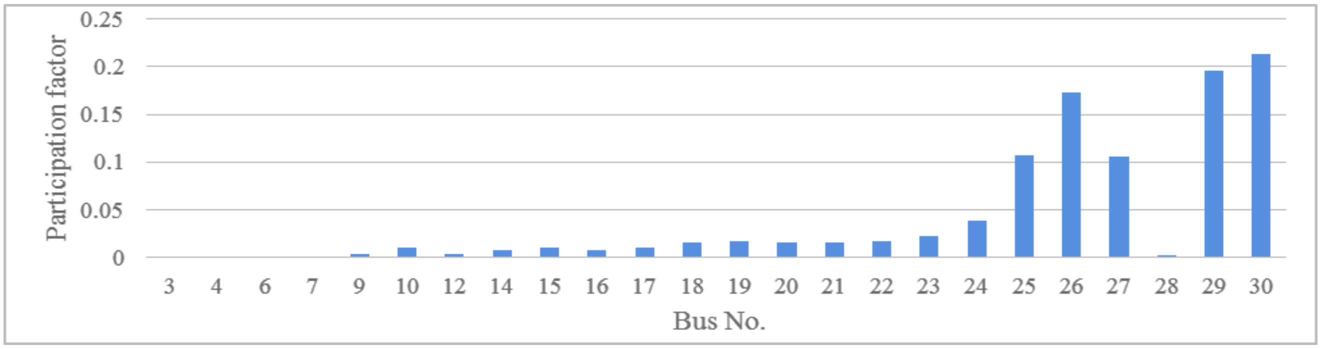


Fig. 6: Bar chart participation factor for IEEE 30-Bus system

For the weakest nodes, the Q-V curves were considered in the IEEE 30 Bus system as predictable by the modal analysis method. The weakest buses are 26, 29, and 30, the curves are presented in fig. 7 where any more increase in the reactive power demand in that bus will cause a voltage collapse, where three curves represent the change of voltage with the change in reactive power in the three weakest buses that were mentioned previously, it is noticed that the special curve of bus 26 is the shortest, which indicates that this bus is the weakest in this system, then bus 30 comes second because it has the second-longest curve, and finally, Bus 29 comes in third place because it has the longest curve among the three mentioned buses

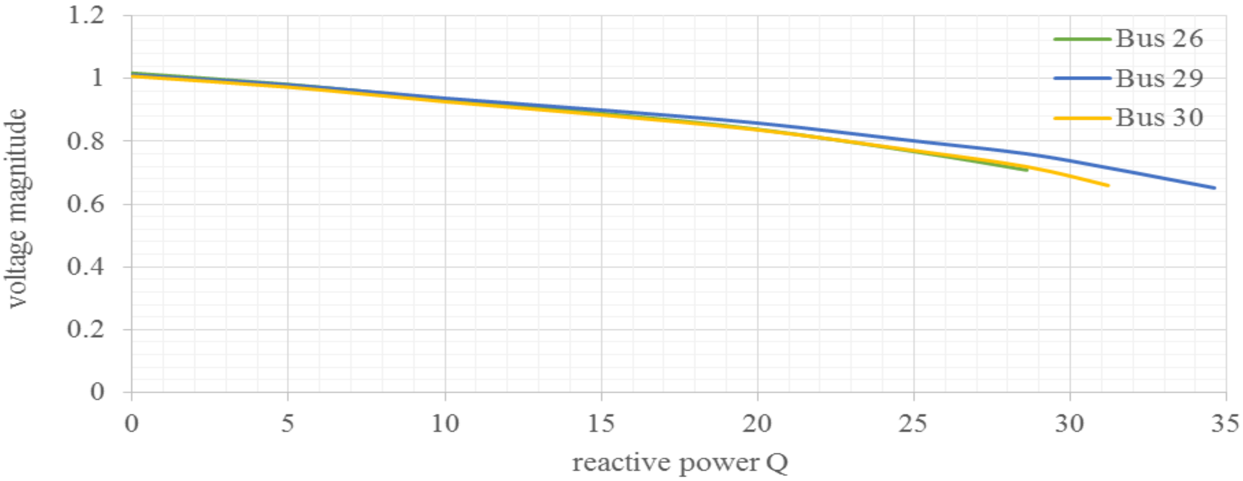


Fig.7: Q-V curves for the weakest buses in the IEEE 30-bus system.

4.1. Simulation Result using voltage stability indices

The simulation of the IEEE 30 bus system is discussed by using two line stability indexes which are: FVSI and Lmn as below. At the base case, the values of these indices were computed by using equations 1 and 2, and the results are shown in table 3, which illustrates that the IEEE 30 bus system is stable and secure because none of the line indices are not close to one. Fig. 8 shows a bar chart of voltage stability indices at the base case

Table 3
Results for the IEEE 30-bus test system

Line NO.	from bus	to bus	Lmn	FVSI
1	1	2	0.0543	0.0504
2	1	3	0.0392	0.0358
3	2	4	0.0202	0.0191
4	2	5	0.0145	0.0131
5	2	6	0.0075	0.0069
6	3	4	0.0053	0.0051
7	4	6	0.0312	0.0306
8	4	12	0.1476	0.1462
9	5	7	0.0544	0.0553
10	6	7	0.0068	0.0067
11	6	8	0.0067	0.0067
12	6	9	0.0596	0.0595
13	6	10	0.0143	0.0142
14	6	28	0.0245	0.0243
15	8	28	0.0204	0.0205
16	9	11	0.1179	0.1179
17	9	10	0.0269	0.0269
18	10	20	0.0332	0.0328
19	10	17	0.0157	0.0157
20	10	21	0.0331	0.0329
21	10	22	0.0307	0.0305
22	12	13	0.0515	0.0515
23	12	14	0.0279	0.0275
24	12	15	0.0415	0.0408
25	12	16	0.0296	0.0293
26	14	15	0.0113	0.0112
27	15	18	0.0178	0.0176
28	15	23	0.0278	0.0276
29	16	17	0.0122	0.0121
30	18	19	0.0047	0.0047
31	19	20	0.0085	0.0086
32	21	22	0.0018	0.0018
33	22	24	0.0267	0.0264
34	23	24	0.0164	0.0164
35	24	25	0.0266	0.0268
36	25	26	0.0507	0.0502
37	25	27	0.0079	0.008
38	27	29	0.0345	0.0337
39	27	30	0.0508	0.0488
40	28	27	0.0851	0.0848
41	29	30	0.0141	0.0139

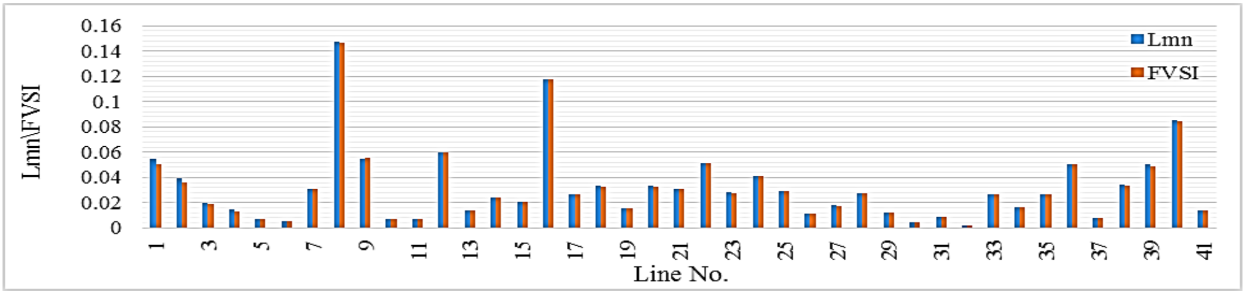


Fig. 8: bar chart of voltage stability indices at the base case

To check the weakest bus, the reactive power of load buses must increase until having FVSI or Lmn close to one, this condition is obtained. Table 4 shows the maximum load ability for each load bus of the IEEE 30-bus system and the voltage stability indices of the lines connected to each bus, and the bar chart of results shown in fig. 9.

Table 4
maximum load ability of the IEEE 30-bus system

From	To	Lmn	FVSI	Line Ranking	Qmax (MVAr)	Bus Ranking
Bus 3						
1	3	0.996104	0.935613	1	**270**	**20**
3	4	0.497593	0.470859	2		
Bus 4						
2	4	0.999804	0.972473	1	**470**	**23**
4	6	0.894575	0.842264	2		
4	12	0.705448	0.687170	3		
3	4	0.250937	0.245849	4		
Bus 6						
6	8	0.999106	0.947648	1	**665**	**24**
2	6	0.764997	0.708833	2		
6	9	0.498693	0.495608	3		
6	10	0.390006	0.384755	4		
6	7	0.393513	0.377008	5		
4	6	0.270431	0.265704	6		
6	28	0.246507	0.241906	7		
Bus 7						
5	7	0.930236	0.999851	1	**282**	**21**
6	7	0.744431	0.750718	2		
Bus 9						
9	11	0.988339	0.988339	1	**176**	**18**
6	9	0.619913	0.617824	2		
9	10	0.250117	0.249831	3		
Bus 10						
6	10	0.999057	0.991768	1	**173**	**17**
9	10	0.584036	0.583336	2		
10	20	0.211703	0.203797	3		
10	17	0.148598	0.146764	4		
10	22	0.0438771	0.043099	5		
10	21	0.0135013	0.013278	6		
Bus 12						
12	13	0.996202	0.996202	1	**207**	**19**
4	12	0.924661	0.914266	2		
12	16	0.231546	0.224410	3		
12	15	0.103133	0.099263	4		
12	14	0.0318274	0.031019	5		
Bus 14						
14	15	0.999589	0.826108	1	**74**	**6**

12	14	0.667242	0.706472	2		
Bus 15						
12	15	0.921492	0.989523	1	**149**	**13**
14	15	0.628253	0.737484	2		
15	18	0.490473	0.459844	3		
15	23	0.428931	0.408753	4		
Bus 16						
12	16	0.922179	0.985701	1	**112**	**12**
16	17	0.823352	0.771415	2		
Bus 17						
10	17	0.948435	0.999181	1	**155**	**15**
16	17	0.8854	0.929029	2		
Bus 18						
15	18	0.924594	0.989468	1	**87**	**8**
18	19	0.53861	0.509175	2		
Bus 19						
18	19	0.941508	0.992173	1	**119.8**	**10**
19	20	0.686406	0.640395	2		
Bus 20						
10	20	0.930028	0.983228	1	**88**	**9**
19	20	0.180681	0.185164	2		
Bus 21						
10	21	0.924866	0.983598	1	**167.5**	**16**
21	22	0.269518	0.264215	2		
Bus 22						
22	24	0.968131	0.862179	1	**153**	**14**
10	22	0.867759	0.925828	2		
21	22	0.236196	0.242494	3		
Bus 23						
23	24	0.991286	0.911812	1	**86**	**7**
15	23	0.854936	0.918127	2		
Bus 24						
22	24	0.89113	0.991798	1	**105**	**11**
24	25	0.806163	0.741631	2		
23	24	0.704489	0.747346	3		
Bus 25						
24	25	0.902712	0.983902	1	**60.5**	**5**
25	27	0.76097	0.705652	2		
25	26	0.121603	0.118810	3		
Bus 26						
25	26	0.886495	0.994887	1	**28.5**	**1**
Bus 27						
28	27	0.998114	0.994579	1	**57**	**4**
25	27	0.316214	0.324192	2		
27	30	0.116521	0.107341	3		
27	29	0.0754145	0.072071	4		
Bus 28						
8	28	0.956851	0.997459	1	**293**	**22**
6	28	0.745111	0.759712	2		
28	27	0.194441	0.192580	3		
Bus 29						
27	29	0.940525	0.999004	1	**34.6**	**3**
29	30	0.526457	0.480395	2		
Bus 30						
27	30	0.958021	0.989424	1	**31**	**2**
29	30	0.555443	0.570268	2		

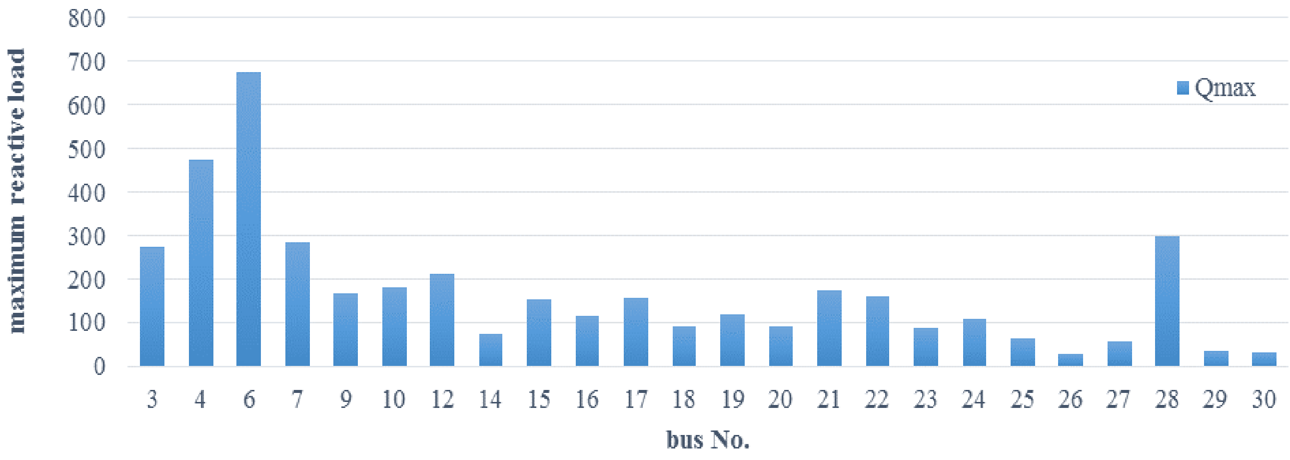


Fig. 9: bar chart of maximum load ability of the IEEE 30-bus system

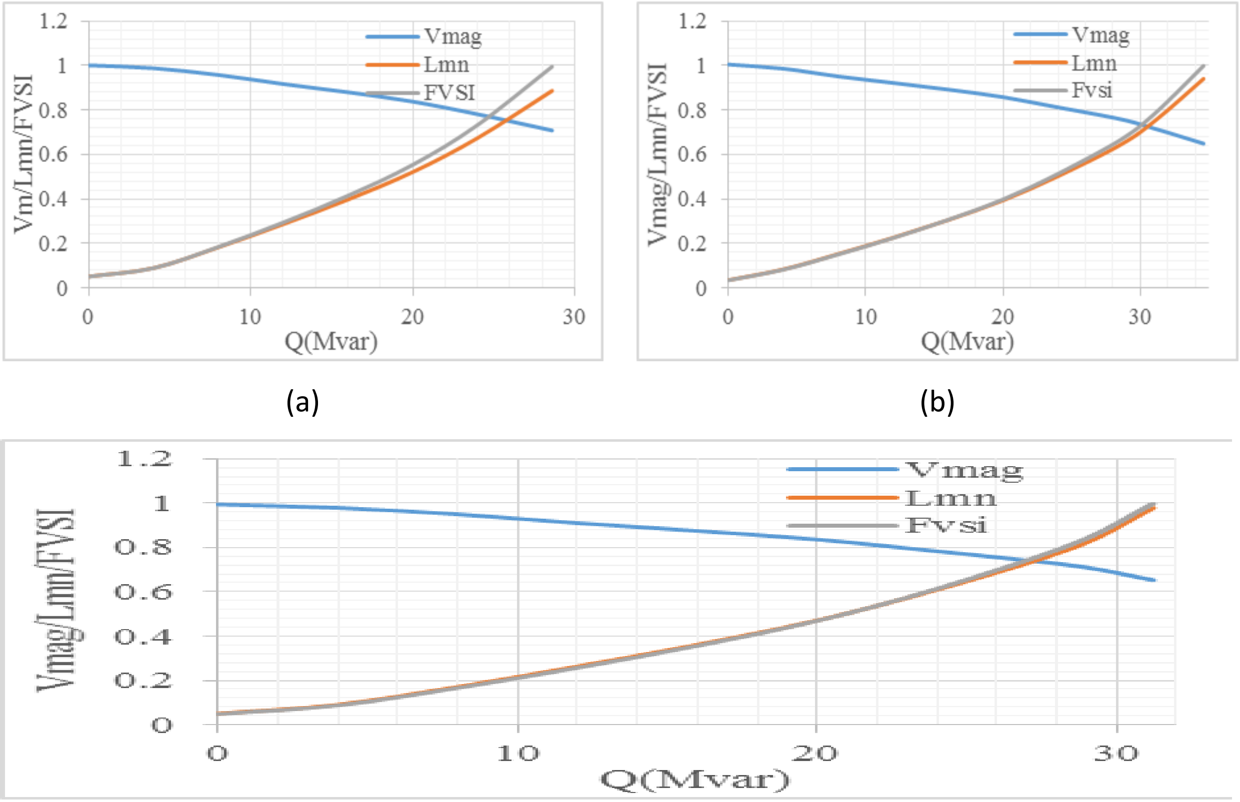
From Table 4 and Fig. 9 it's clear that the weakest buses of the IEEE 30-bus system are bus 26, 29, and 30 with maximum load ability 28.6, 34.6, and 31.2 Mvar respectively. These values mean that any addition in reactive power at these buses leads to voltage collapse. Also from the result, it is clear that buses 6 and 4 have the highest maximum load ability, which is 675 and 473 Mvar respectively. By studying buses 26, 29, and 30, varying reactive power load gradually, registering voltage stability indices and voltage magnitude for each value of reactive power load as shown in Table 5 and Fig. 10.

Table 5

reactive power variation on bus 26

Q Mvar	Bus 26			Bus 29			Bus 30		
	Vmag	Lmn	Fvsi	Vmag	Lmn	Fvsi	Vmag	Lmn	Fvsi
0	1.001	0.05067	0.05018	1.005	0.03449	0.0337	0.994	0.05084	0.04881
4	0.988	0.08849	0.08812	0.986	0.08303	0.08152	0.979	0.09083	0.08753
8	0.958	0.18155	0.18334	0.951	0.15218	0.15036	0.95	0.1713	0.16629
12	0.917	0.28592	0.29323	0.922	0.22527	0.22417	0.91	0.26341	0.25763
16	0.88	0.39686	0.41386	0.892	0.30504	0.30592	0.875	0.36136	0.35649
20	0.838	0.52051	0.55304	0.858	0.3934	0.39791	0.836	0.47132	0.46941
24	0.781	0.67361	0.73224	0.812	0.50229	0.5131	0.783	0.61013	0.61424
28.6	0.708	0.88649	0.99488	0.758	0.64506	0.6677	0.717	0.80204	0.81963
31.2	0.6445	1.067	1.22976	0.713	0.75829	0.79269	0.653	0.97908	0.9978
34.6	0.4954	1.46783	1.79359	0.649	0.94052	0.999	0.4715	1.56288	1.66983

From table 5 bus 26 has Qmax=28.6, any increment in reactive power leads to voltage collapse, which is obtained in red color. Bus 30 has the same condition where any increment above 31.2 Mvar leads to voltage collapse.



(a)

(b)

(c)

Fig. 10: reactive power variation in (a) Bus 26 (b) Bus 29 (c) Bus 30

5. COMPUTATIONAL TIMES

In this paper, there is a lot of calculations, since voltage stability analysis was done by using two different methods, and in each method, there are two cases (normal and contingency). The previous calculations were performed using MATLAB \ R2018a program, and the computational times were as shown in table 6.

Table 6:

computational times for voltage stability analysis

s	Calculations type	Computational time(s)
1	eigenvalues	0.525
2	Participation factor	1.23
3	Voltage stability indices at base case	0.343
4	Voltage stability indices at contingency case	0.426

The fast method to analyze voltage stability is the voltage stability indices method because it has the lowest computational time.

6. CONCLUSIONS

In this work, the voltage collapse problem is studied and the following can be concluded

- An associated software program for simulation and employment of voltage stability analysis was developed successfully and implemented in the MATLAB environment.

- The modal analysis method is used for this work. This method enables identifying the stability state of the system.
- The Voltage Stability Indices (Lmn and FVSI) are referred to as a line presented. These indices enable identifying the critical line in a system. A line is considered critical if the indices values are close to unity. This method has successfully reduced the calculation time for contingency analysis and ranking.
- Eigenvalues refer to system state at the normal operation as well as voltage stability indices at the base case and the results from these two methods are identical and each other strengthened
- The participation factor refers to the system at the loaded case as well as voltage stability indices at contingency case and those results lead to the same status and each other strengthened.
- The most stable buses are those that have more interconnected lines, and the weakest buses have less number of interconnected lines.
- The fast method to analyze voltage stability is the voltage stability indices method because it has the lowest computational time
- The two methods used can be applied to any power system.

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