ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
Volume 7, Issue 1, July 2017

Voltage stability margin improving by controlling power transmission paths

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Abstract**—*****This paper present a method to improving voltage stability margin depending on power transmission paths. Weak buses and lines are determined by using voltage stability indices, some comparison between these indices are made to determined weakest buses, the voltage stability margin is illustrate using the P-V curves and Q-V curves. After defined the weak buses and the degree of stress in each path depending on the indices values, voltage stability marginimprove by two methods. The first one adding a parallel line in the systemwhiles the second one by adding a device to supply only active power, reactive power and complex power. The results on IEEE 30 buses sample system shows extending and improving in the margin of voltage stability.***

Index Terms**—Voltage stability margin, Voltage collapse, voltage stability indices, Matlab-Simulink, *****P-V curves and Q-V curves.***

I. INTRODUCTION

Power system voltage stability is a very complex subject that has been challenging the power system engineers in the past two decades. Due to the continuous expansion of power systems to cater the needs of growing population, power system stability problems also are a continuous and fascinating area of study. When a bulk power transmission network is operated close to the voltage stability limit, it becomes difficult to control the reactive power demand for that system. As a result the system voltage stability will be prevented. Voltage stability is a problem in power systems which are heavily loaded, faulted or have a shortage of reactive power. The problem of voltage stability concerns the whole power system, although it usually has a large involvement in one critical area of the power system. [1]

Voltage stability is defined as the ability of power system tomaintain steady voltages at all buses in the system after beingsubjected to some form of disturbances, which leads to voltage collapse [2]. In recent years, along with the deepening of power interconnection and of electric power demand, led power systems to operate very close to their limits. Thus, voltage-instability and even voltage-collapse situations became very likely to occur, imposing important limitations to power-system operation. Then, the power system operation managers will find a visualized voltage stability evaluation index to measure the extent of voltage-stability.

Voltage stability margin is an index to measure a level of voltage-stability of the current power system. It means thatin power injection space, the distance from the current operating point to collapse of voltage according to the increase load in a given direction. In general, it is also called load margin because the distance can formulate by additional load on the transmission power. The load margin directly reflects the ability of current power system to maintain steady voltages under a disturbance. Compared with other indexes, the widely use indexare loads margins because of its strong intuitive and good linearity. Therefore, a key to obtain the load margin index is calculating the voltage stability bifurcation of system [3]

Voltage analysis can be done using dynamic or staticstability analysis. Even though dynamic stability analysisproduces more interruptions to the system, however, the staticvoltage stability analysis is still widely accepted.In most of the research works, the voltage stability has been considered as static phenomenon. This is due to slow variation of voltage over a long time observed in most of the incident until it reaches to the maximum loading point and then it decreases rapidly to the voltage collapse. Static voltage stability can be analyzed by using bifurcation theory.

Many voltage stability indices are based on the Eigen value analysis or singular value decomposition of the system power flow Jacobian matrix. The prominent methods in voltage stability analysis are those that find system load margin, especially when system contingency is considered P-V curve and Q-V curve are most considerable method to find active power margin and reactive power marginto proximityto voltage collapse while the other methods developed voltagestability indices as indicators. These voltage stability indices are derived referred either to a bus or a line in power system. [4] and [5].

The P-V curves are the most used method of predicting voltage security where it used to determine the loading margin of a power system. These curves are produced by running a series of load flow cases and relate bus voltages versusload within a special region. This methodology has the benefit of providing an indication of proximity to voltage collapse throughout the range of load levels. If thepower transfer increases in a special region, the voltage profile will become lower until a point of collapse is reached.Whilethe Q-V curve is possible, for the operators, to know which is the maximum reactive power that can be achieved or added to the weakest bus before reaching minimum voltage limit. The reactive power margin is the *MVar* distance from the operating point to the bottom of the Q-V curve. The Q-V curve can be used as an index for voltage instability. The point where dQ/dV is zero is the point of voltage stability limit [6] and [7].

Hence, prediction of voltage collapse is essential and very important in power system planning and secure operation. An accurate knowledge of voltage collapse prediction can be gained by finding several voltage stability indices that is a very important task in voltage stability studies. These indices give important information about the proximity of voltage instability and identification of the weakest bus, line and area in the power network. Usually these indices values changes between 0(no load) and 1(voltage collapse) [8].

II. VOLTAGE STABILITY INDICES

Upon a time, many attempted had been made for voltage stability indices that can be summarized in the following review:

1. Line Stability Index (L_{mn})

The line stability index (L_{mn}) proposed in Ref. [9] where itformed based on a power transmission concept in a single line as given in equation (1). A single line in an interconnected network is shown in the following Figure (1).

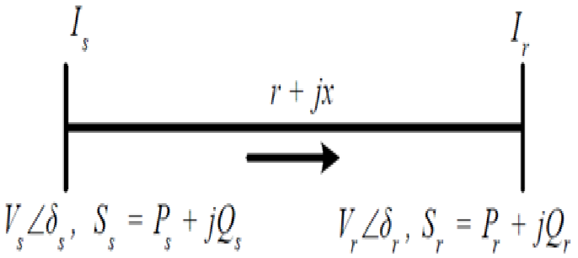

Fig (1)A single line in an interconnected network

$$L_{mn} = \frac{4xQ_r}{[V_s sin(\theta - \delta)]^2} \leq 1 \qquad ...(1)$$

Where, V_s and V_r are the sending and receiving end voltages respectively. $\delta_s$andδ_r are the phase angle at sending and receiving buses. Z- line impedance; r-line resistance; x-line reactance; θ-line impedance angle; P_r-active power at receiving end; Q_r-reactive power at receiving end. The line index is also directly related to the reactive power and indirectly related to the active power through the voltage phaseangleδ. A line in the system said to be close to instability when the L_{mn} is close to one (1). On the other hand, if the L_{mn} value is less than 1, then the system is said to be stable [9].

2. Fast Voltage Stability Index FVSI

The Fast voltage stability index, (FVSI) proposed in Ref. [10] based on a concept of power flow through a single line. The voltage stability index calculated for the interconnected transmission line by equation (2).

$$\frac{4Z^2 Q_r x}{V_s^2 x} \leq 1 \qquad ...(2)$$

The line of FVSI index-approaching unity indicates instability .So for any sudden voltage drop the system will be goes to collapse.

3. Line Stability Index NLSI

Line Stability IndexNLSI proposed in Ref. [11] by referring to the representation of a two buses power network model to formulate the index by equation (3).

$$\frac{P_r R + Q_r X}{0.25 V_s^2 cos^2\delta} \leq 1 \qquad ...(3)$$

4. Voltage Collapse Proximity Indicator VCPI

Voltage collapse point indicators (VCPI) proposed in Ref. [12] based on the concept of maximum power transferred through a line.

$$VCPI = \frac{P_r}{P_{r\,(max)}} \qquad ...(4)$$

$$P_{r\,(max)} = \frac{(V_s)^2}{Z_s} \frac{cos\emptyset}{4cos^2\left(\frac{\theta-\emptyset}{2}\right)} \qquad ...(5)$$

Where $\emptyset = tan^{-1}(P_r / Q$

The values of VCPI (power) increases slowly when power flow through transmission line increases. When the power flow reaches the maximum value,the VCPI will be unity and voltage collapse occurs. The VCPI values varies from zero (no load condition) to unity (voltage collapse).

III. DETERMINATION OF THE WEAKEST BUSES AND LINES IN THE SYSTEM USING LINE STABILITY INDICES

For any test power system, increasethe reactive power only in one bus with time and the loads on the other nodes remained constant. A program to calculate the stability index for each line has been developed then implemented the following steps:

1) Run the Newton-Raphson load flow program to find the steady state values.
2) Calculate the value of the line stability index, for the steady statefor all the lines of test system.
3) Gradually, increase the reactive power in one bus and keeping the loads on the other nodes constant until solution of the power flowstop converge.
4) Calculate the value of the line stability index for each variation of the load.
5) Calculate which line of the bus presents the greatest value. This line is called the most critical line of the bus.
6) Select another bus PQ and repeat steps 1 to 5. [13]

IV. TEST RESULTS AND DISCUSSION

An IEEE 30 buses is the test system of this work, shown in Figure (2), which consists of six generator buses (PV), twenty-four load busses (PQ) and forty-one interconnected branches. The load consists of only static load. This system used to verify the effectiveness of the line stability indices, determine the weakest buses, weakest lines and then improve the voltage stability margin.

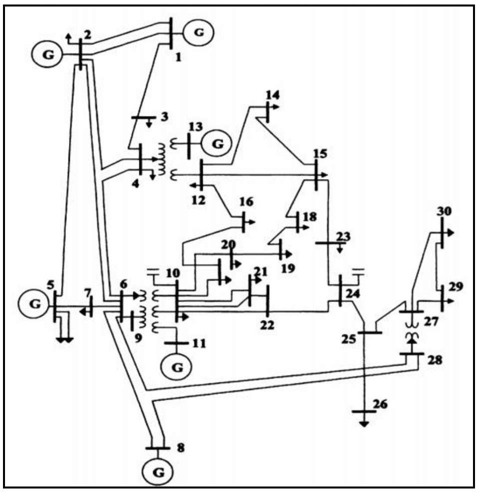

Fig (2) Sample system of IEEE 30 buses

The simulation results and discussion for all cases can be summarizedin the following points:

1. *Determine the weak buses and lines*

As shown in theTables(1A),(2A) and(3A) in Appendix (A), buses# 14, 26, 30 are chosen to evaluate each voltage stability index performance under three cases; reactive power load changes, real power load changes and simultaneous reactive and real power load changes. The Figures (3), (4) and (5) are illustrating the comparison between the indices at line#25-26 when applying the three cases at bus#26.

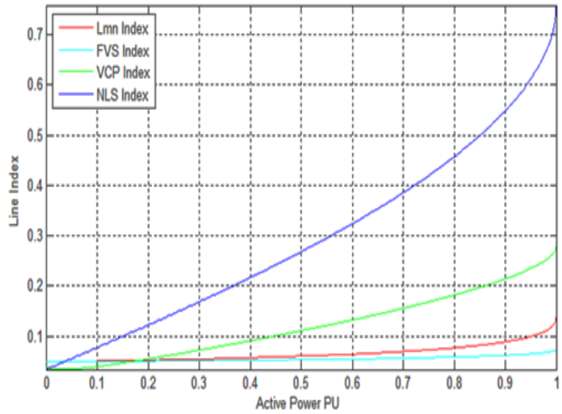

Fig (3)Line index at line#25-26 vs. real load variation at bus#26

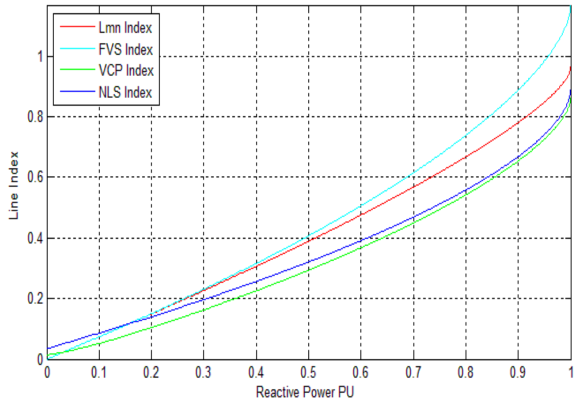

Fig (4)Line index at line#25-26 vs. reactive load variation at bus#26

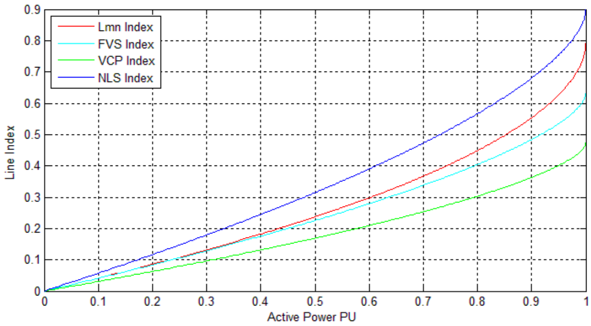

Fig (5)Line index at line#25-26 vs. real load variation at bus#26

The simulation results shown the NLSI index have the best performance because of it prone to all cases of load change. The L_{mn} index is the best prone to reactive load changes. TheL_{mn} index also used to determine the weakest bus in the system and it is based on the maximum permissible load. It is observed, in the Table (1B)in Appendix (B), that buses# 26, 30, 29, 25 and 27 have the minimum values of maximum permissible reactive load, respectively.

2. *PV and QV curves*

The results PV and QV curves for the weakest bus#26are shown in Figures (6) and (7).

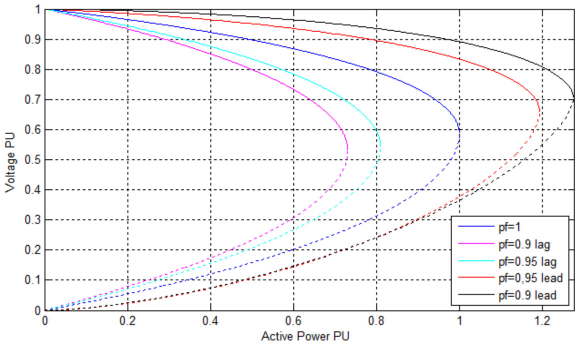

Fig (6) P-V curves at bus#26

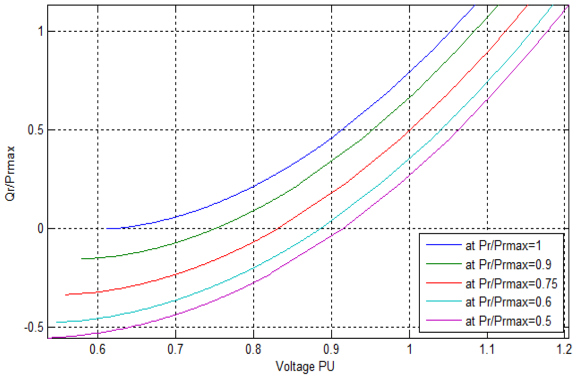

Fig (7) Q-V curves at bus#26

3. *Determine the average of the stress of the lines at the weak region*

The average of the L_{mn} values were took as a rate of stress of the lines in weak region. The values were took from the result of analysis of the weakest five buses as shown in the Table (1C) in Appendix (C) and demonstrated in Figure (8).

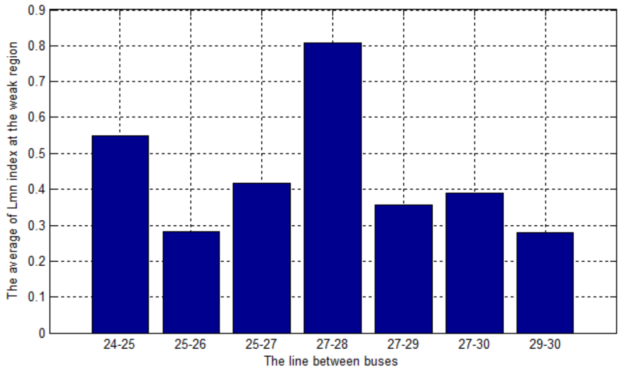

Fig (8)L_{mn} average values for lines in the weak region

The results shown that the most critical line at the weak region is the line#27-28 and the last critical line is the line#29-30. This results will took as a base to improving the voltage stability at all weak regions.

4. Improving voltage stability by controlling transmission paths

Voltage stability can improve either at weakest buses or at the overall weak region. Tables (1B), in Appendix (B), show the weakest five buses that represent the weak region. Thus, must improve it either at one weakest bus or at overall these buses as follows:

a) Improve voltage stability margin by Adding a new line:

First, adding a line to improve the voltage stability at one of the weakest buses. The bus#30 was chosen and the addition line was putted in parallel with the most critical lines. Figure (9) shows the P-V curves results for this casewhere the best benefit occurs when the location of the added line will be in parallel with the most stressed line (have the biggest L_{mn} index).

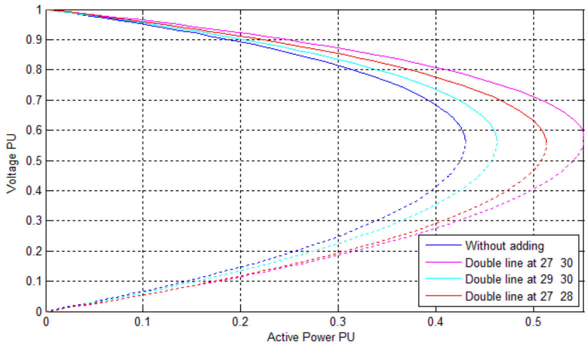

Fig (9) P-V curves at bus 30 before and after adding a line in parallel with the most critical lines

Second, when improving the voltage stability margin at overall weak region where Table (1C) in Appendix(C)show that line#(27-28) is the most stressed line for all weakest five busses. Now, to improve voltage stability at the weak region, adding a line in parallel with one of lines in the weak region with calculate the summation of maximum real load at the five buses and repeat this for all lines at the weak region. Finally, the state that give the biggest addition of real load is represent the best state of improving voltage stability as shown in Figure(10) and the Table (1D) in Appendix (D). The result of the analysis show the best location is at the most stressed line. The loads power factors are 0.95 lag.

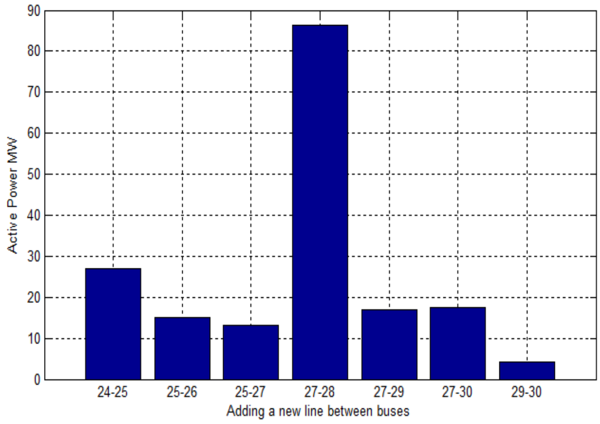

Fig (10) the addition in the summation of the maximum real load at the weakest five buses when adding a line in parallel with a line in the weak region

b) Improve voltage stability margin by adding a capacitor:

First, add a 10*MVar* capacitor to improve the voltage stability at one of the weakest buses. The chosen bus is bus#30 and the results of adding capacitor at the some buses shown in Figure(11).The results clear many state for improving voltage stability margin that different according to the location of the added capacitor and the best location nearest point to the bus that improve voltage stability margin. If the addition is not at the same bus, it must be at other bus that connected with the specific bus by least stressed path.

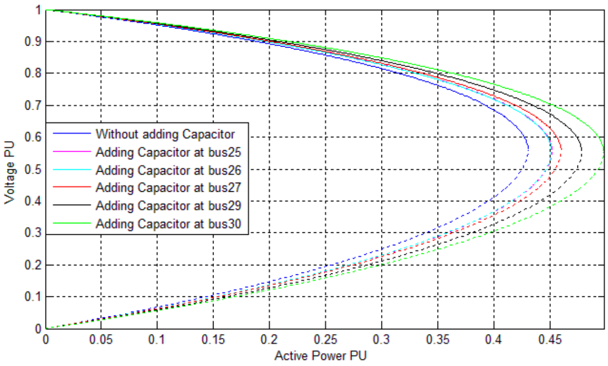

Fig (11) P-V curves at bus#30 before and after adding a capacitor at selection buses

Second when improving the voltage stability margin at overall weak region where Table (1C) in Appendix (C), show that the line (29-30) is the least stressed line for all weakest five busses. To improve voltage stability at the weak region, adding a 10*MVar* capacitor at one bus of the weakest five buses with calculate the summation of maximum real load at the five buses and repeat this for the weakest five buses. Finally, the biggest addition of real load is represent the best casefor improving voltage stability as shown in Figure(12) and the Table (1E) in Appendix (E). From the result of this analysis, it can be found that the best location to improve the voltage stability is at the bus that be close to the end of the least stressed path with respect to the weak region and this bus is connected with multi paths.

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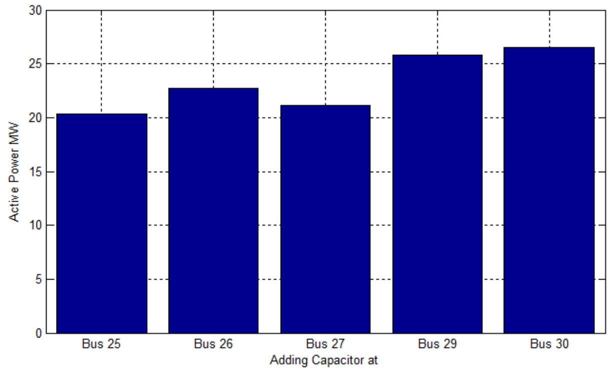

Fig (12) the addition in the summation of the maximum real load at the five buses of the weak region when adding a capacitor.

V. CONCLUSIONS

Voltage stability index are used to assess or detect the voltage collapse point of a system. In this paper, four-voltage stability index are derived from two bus-bar transmission line concept, compared and analyzed in terms of their performance during real and reactive power load changes. Based on the analyses, the NLSI is prone to all cases of load changes that lead to consider this index is the best index forassessment voltage stability. These indices used to identify the critical line referred to a bus and reveal the weakest bus of a power system. A line is considered critical if the line stability indices are close to one. The L_{mn} was chosen because the L_{mn}index has the best prone to reactive load changes. The simulations results shown that the bus#26 of IEEE 30 buses test system is considered the weakest bus in the system. By determine the weakest buses and lines we can improve the voltage stability at one of the weak buses or at overall this buses. This can be made either by adding a line in parallel with the most stressed line in the system or by adding a device to provide a power (active, reactive or both of them) at the same bus (forimproving voltage stability at one of the weak bus).It can be also addedin the end of the least stressed path with respect to the weak region (forimproving voltage stability at the overall weak region).

APPENDIX (A)

Table (1A) Line stability indices when increasing active powerloading only

Bus #	Active power of the load	Reactive power of the load	Line	L_{mn} index	FVSI index	VCP index	NLSI index
26	42.768	2.300	25 26	0.1365	0.0732	0.2771	0.7581
26	42.768	2.300	28 27	0.3932	0.3803	0.5875	0.3932
26	42.768	2.300	25 24	0.1363	0.1185	0.1769	0.3442
30	53.193	1.900	27 30	0.0905	0.0504	0.3374	0.6866
30	53.193	1.900	29 30	0.0414	0.0312	0.2318	0.4286
30	53.193	1.900	28 27	0.5188	0.4905	0.7372	0.5188
14	137.814	1.600	15 14	0.0000	0.0000	0.0766	0.6538
14	137.814	1.600	12 14	0.2966	0.1889	0.3964	0.7022
14	137.814	1.600	29 30	0.0139	0.0137	0.0275	0.0489

Table (2A) Line stability indices when increasing reactive powerloading only

Bus	Active power of the load	Reactive power of the load	Line	L_{mn} index	FVSI index	VCP index	NLSI index
26	3.500	33.482	25 26	0.9634	1.1680	0.8629	0.8898
26	3.500	33.482	28 27	0.5536	0.5496	0.5907	0.5536
26	3.500	33.482	25 24	0.4538	0.4601	0.3476	0.4355
30	10.600	35.570	27 30	0.9408	1.0021	0.7889	0.9182
30	10.600	35.570	29 30	0.7216	0.7584	0.6014	0.6774
30	10.600	35.570	28 27	0.7142	0.7096	0.7355	0.7142
14	6.200	100.728	15 14	0.9512	1.3619	0.7099	0.7605
14	6.200	100.728	12 14	0.9238	1.0459	0.9022	0.8590
14	6.200	100.728	29 30	0.0148	0.0145	0.0291	0.0517

Table (3A) Line stability indices when increasing both active and reactive power loading

Bus	Active power of the load	Reactive power of the load	Line	Lmn index	FVSI index	VCP index	NLSI index
26	28.889	18.984	25 26	0.7923	0.6330	0.4748	0.9009
26	28.889	18.984	28 27	0.4692	0.4596	0.5847	0.4692
26	28.889	18.984	25 24	0.2940	0.2728	0.2329	0.3977
30	48.018	8.607	27 30	0.3623	0.2227	0.3880	0.7654
30	48.018	8.607	29 30	0.2010	0.1576	0.2733	0.5013
30	48.018	8.607	28 27	0.5576	0.5321	0.7353	0.5576
14	116.752	30.130	15 14	0.1818	0.1093	0.1428	0.7470
14	116.752	30.130	12 14	0.5835	0.4235	0.4766	0.8014
14	116.752	30.130	29 30	0.0141	0.0138	0.0278	0.0494

APPENDIX (B)

Table (1B) the minimum values of maximum permissible reactive load

Rank	Bus#	Q_{max}	Line#	L_{mn} index
1	26	0.334880	25 26 28 27 24 25	0.9629 0.5530 0.4533
2	30	0.355700	27 30 29 30 28 27	0.9405 0.7213 0.7140
3	29	0.389740	27 29 28 27 27 30	0.9234 0.7743 0.6993
4	25	0.715500	28 27 24 25 27 25	0.9279 0.9144 0.7669
5	27	0.761900	28 27 24 25 25 27	1.0673 0.7067 0.5509

APPENDIX (C)

Table (1C) The average of the L_{mn} values at the lines in weak region

Bus #	L_{mn} at line 24-25	L_{mn} at line 25-26	L_{mn} at line 25-27	L_{mn} at line 27-28	L_{mn} at line 27-29	L_{mn} at line 27-30	L_{mn} at line 29-30
25	0.9143	0.1819	0.7668	0.9279	0.0777	0.0980	0.0319
26	0.4537	0.9633	0.3742	0.5535	0.0442	0.0580	0.0180
27	0.7056	0.1206	0.5497	1.0669	0.1317	0.1572	0.0550
29	0.3570	0.0750	0.2170	0.7743	0.9234	0.6993	0.5729
30	0.3105	0.0712	0.1811	0.7140	0.6070	0.9405	0.7213
Sum	2.7411	1.412	2.0888	4.0366	1.784	1.953	1.3991
Average	0.5482	0.2824	0.4178	0.8073	0.3568	0.3906	0.2798

APPENDIX (D)

Table (1D) The addition in the summation of the maximum real load at the weakest five buses when adding a line in parallel with a line in the weak region

Bus	Without adding	Add line at 2425	Add line at2526	Add lineat2527	Add line at2728	Add line at2729	Add line at2730	Add line at2930
25	79.0	93.9	79.2	86.6	96.6	79.2	79.3	79.1
26	35.8	38.1	50.7	37.5	39.2	35.8	35.9	35.8
27	89.6	96.9	89.7	92.7	136.7	90.0	90.4	89.8
29	43.0	44.5	43.1	43.6	53.1	56.0	47.2	43.8
30	43.1	44.2	43.1	43.5	51.4	46.5	55.2	46.3
Sum	290.6	317.7	305.8	303.8	376.9	307.6	308.0	294.9
Delta		27.1	15.2	13.2	86.3	17	17.4	4.3

APPENDIX (E)

Table (1E) the addition in the summation of the maximum real load at the five buses of the weak region when adding a capacitor at one of the busses

Bus	Without adding a Capacitor	Add Cap. at bus 25	Add Cap .at bus 26	Add Cap. at bus 27	Add Cap. at bus 29	Add Cap. at bus 30
25	79.0	86.1	85.5	84.1	84.0	84.0
26	35.8	38.4	41.8	37.6	37.5	37.5
27	89.6	95.7	95.4	97.6	97.3	97.3
29	43.0	45.5	45.4	46.4	49.8	48.4
30	43.1	45.2	45.2	46.0	47.9	49.8
Sum	290.6	310.9	313.3	311.7	316.4	317.1
Delta		20.3	22.7	21.1	25.8	28.5

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