CORRECTIVE SCHEMES FOR VOLTAGE STABILITY ANALYSIS USING TWO DIFFERENT INDICATORS

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Abstract: This paper discusses the steady state voltage stability analysis of two power systems: Ward and Hale 6-bus system and IEEE 30-bus system by using four different correction schemes: transmission path, reactive power compensation, generation voltage and reactive path, and reactive shedding. These correction schemes can improve voltage stability with the help of two indicators: L-index value and V-Q sensibility value. Results of tests carried on the above mentioned systems are provided and discussed. *Copyright © 2005 IFAC*

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1. INTRODUCTION

Voltage control and stability problems are considered in many countries as one of the major concerns in power system planning and operation. In recent years, voltage instability has been found responsible for several major network collapses. The following accidents are some examples for voltage instability and voltage collapse:

- New York Power Pool disturbances of September 22, 1970;
- Florida system disturbance of December 28, 1982;
- Northern Belgium system disturbance of August 4, 1982;
- Swedish system disturbance of July 23, 1987.

As a consequence, the terms "voltage instability" and "voltage collapse" are appearing more frequently in the literature and in discussions of system planning and operation.

Voltage instability is concerned with the ability of power system to maintain acceptable levels at all buses in the system under normal conditions and after being subjected to a disturbance.

Voltage collapse is the process by which the sequence events accompanying voltage instability lead to a low unacceptable voltage profile in a significant part of the power system, voltage collapse may be manifested in several different ways.

In planning and operation of power systems, the analysis of voltage instability for a given system involves the examination of two aspects:

(a) proximity: how close is the system to voltage instability?

(b) mechanism: when voltage instability occurs, what are the contributing factors, what are the voltage-peak points and what are the area involved?

Proximity gives a measure of voltage security whereas mechanism provides information useful in determining system modifications or operating strategies, which could be used to prevent voltage instability, as in Kundur (1994).

In order to deal with both the margin and mechanism aspect of the voltage stability problem, the majority of the existing methods are based on full or reduced Jacobian matrix analysis.

The main factor causing voltage instability is the incapacity of the power system to meet the demand for reactive power. From Byerly et all. (1982), the following are the principal causes of voltage instability:

- The load on the transmission lines is too high.
- The voltage sources are too far from the load centers.
- The voltage source voltages are too low.
- There is insufficient load reactive compensation.

In this paper, a discussion on the steady state voltage stability analysis of two power systems: Ward and Hale 6-bus system and IEEE 30-bus is presented. Such analysis is conducted by using four different correction schemes: active transmission path, reactive compensation, generation voltage and reactive transmission and load shedding. These correction schemes are used to improve voltage stability problems with the help of two indicator techniques: L-index and V-Q sensitivity value. Results of test carried on the above-mentioned systems are provided and discussed.

2. SOLUTION METHODOLOGY

Voltage stability is indeed a dynamic phenomenon and can be studied using extended transient/midterm stability simulation. However, such simulations do not really provide sensibility information for the degree of stability. They are also time consuming in terms of CPU and time requirements for analysis of the results. Therefore, the application of dynamic simulations is limited to investigation of specific voltage collapse situations, including fast or transient voltage collapse and for coordination of protection and controls, as in Gao et all. (1992). It has also been observed that the voltage magnitude at nodes may not give a good indication of the proximity to the stability limit. In this paper, two different efficient local indicators are used: the L-index and the V-Q sensitivity.

2.1 L-Index Indicator

L-index is a local indicator that covers the whole power system and evaluates it at each individual bus. It shows the buses that are in the unstable region for a specified threshold. This indicator uses the bus voltage and network information provided by the load flow program, as in Belhadj et all. (1996). The numerical calculation of this indicator is simple and fast and can be obtained as follows:

$$\left[\underline{I}_{bus}\right] = \left[\underline{Y}_{bus}\right] \cdot \left[\underline{V}_{bus}\right] \qquad (1)$$

After segregation of the load buses (PQ-buses) from the generator buses (PV-buses), equation (1) becomes:

$$\begin{bmatrix} [\underline{V}_L] \\ [\underline{I}_G] \end{bmatrix} = \begin{bmatrix} [\underline{H}_1] & [\underline{H}_2] \\ [\underline{H}_3] & [\underline{H}_4] \end{bmatrix} \cdot \begin{bmatrix} [\underline{I}_L] \\ [\underline{V}_G] \end{bmatrix} \qquad (2)$$

where $[\underline{V}_L]$ and $[\underline{I}_L]$ are the voltages and currents for PQ-buses; $[\underline{V}_G]$ and $[\underline{I}_G]$ are the voltages and currents for PV-buses; $[\underline{H}_1]$, $[\underline{H}_2]$, $[\underline{H}_3]$ and $[\underline{H}_4]$ are submatrices generated from $[\underline{Y}_{bus}]$ partial inversion.

For every PQ-bus from equation (2), we define:

$$\underline{V}_{ok} = \sum_{i-1}^{NG} \left(\underline{H}_2\right)_{ki} \cdot \underline{V}_i \qquad (3)$$

where NG is the number of generators.

Therefore, for any PQ-bus index can be defined as:

$$L_k = \frac{1}{\left\| 1 + \dfrac{\underline{V}_{ok}}{\underline{V}_k} \right\|} \qquad (3)$$

where L_k is the L-index indicator for bus k .

In practice the maximum value of L-index must be lower than a threshold value depending on the system configuration and on the utility policy. The value of L-index indicator varies from zero (for no load) to one. When the power system operates near the steady-state stability limit, the maximum value of L-index for the whole system increases sharply, in a nonlinear manner, exceeds 1, which indicates the risk of voltage collapse. The effectiveness and sensitivity of L-index to the system stability evaluations and limits have been investigated, established and used by Tuan et all. (1994), Kessel and Glavitsh, (1999).

2.2 V-Q Sensitivity Indicator

This is considered also as a local indicator. It gives voltage stability-related information from a system-wide perspective. It can clearly identify areas that have instability problems. The numerical formulation of this indicator can be derived from the linear relationship between the power and voltage which is given as:

$$\begin{bmatrix} [\Delta P] \\ [\Delta Q] \end{bmatrix} = \begin{bmatrix} [J_{P\theta}] & [J_{PV}] \\ [J_{Q\theta}] & [J_{QV}] \end{bmatrix} \cdot \begin{bmatrix} [\Delta \theta] \\ [\Delta V] \end{bmatrix} \qquad (5)$$

where $[\Delta P]$, $[\Delta Q]$, $[\Delta \theta]$ and $[\Delta V]$ are the increments in nodal powers, angles and magnitudes of bus voltages.

The voltage stability of the system is affected by both P and Q. However, at each operation point we keep P constant and evaluate voltage stability by considering the incremental relationship between Q and V. This is analogous to the Q-V curve approach. Therefore, if we let $\Delta P = 0$, equation (5) becomes:

$$\left[\Delta\theta\right] = -\left[J_{P\theta}\right]^{-1} \cdot \left[J_{PV}\right] \cdot \left[\Delta V\right] \tag{6}$$

and

$$\left[\Delta Q\right] = \left[J_{Q\theta}\right] \cdot \left[\Delta\theta\right] + \left[J_{QV}\right] \cdot \left[\Delta V\right] \tag{7}$$

After substituting $\left[\Delta\theta\right]$ in $\left[\Delta Q\right]$, we get:

$$\left[\Delta Q\right] = \left(\left[J_{QV}\right] - \left[J_{Q\theta}\right] \cdot \left[J_{P\theta}\right]^{-1} \left[J_{PV}\right]\right) \cdot \left[\Delta V\right] \tag{8}$$

or:

$$\left[\Delta Q_{load}\right] = \left[J\right] \cdot \left[R\right] \cdot \left[\Delta V_{load}\right] \tag{9}$$

where:

$$\left[J\right] \cdot \left[R\right] = \left[J_{QV}\right] - \left[J_{Q\theta}\right] \cdot \left[J_{P\theta}\right]^{-1} \left[J_{PV}\right] \tag{10}$$

$$\left[\Delta V_{load}\right] = \left[J\right] \cdot \left[R\right]^{-1} \cdot \left[\Delta Q_{load}\right] \tag{11}$$

$\left[J\right] \cdot \left[R\right]^{-1}$ is called reduced V-Q Jacobian matrix. Its i th diagonal element is the V-Q sensitivity at the bus i.

A positive V-Q sensitivity is indicative of stable operation. As stability decreases the sensitivity increases, becoming infinite at stability limit. This fact has been experimented and compared with other indicators for voltage stability cases for voltage stability cases and for several power systems. The marginal increase of the sensitivity value of voltage to reactive power ratio shows the system heading toward the singularity of $[J] \cdot [R]^{-1}$ and therefore toward voltage collapse, as in Elrazaz and Al-Olhay (1993). Conversely, a negative V-Q sensitivity indicates voltage instability. A smaller negative sensitivity represents a very unstable operation. In other words, the system is voltage stable if the voltage magnitude decreases as the reactive power injection decreases for at least one bus.

3. CORRECTION METHODOLOGY

Four different correction schemes are proposed below for solving the voltage stability problem. These are: active transmission path correction, reactive compensation, generation voltage and reactive path correction and load scheme.

3.1 Active Transmission Path Correction Scheme

Since the active power flow is strongly connected to the angle variation, a transmission path with decreasing angles can be identified. An active power transmission path is defined as a sequence of connected buses with declining phase angles. A transmission path starts from a generator bus with the highest angle value and ends at a load bus with the lowest angle value.

In general, a voltage collapse may occur at a load bus at the end of one of the identified transmission paths. Therefore, all identified transmission paths are considered for voltage instability, which is of vital importance for the collapse location and proximity identification. A load node is stable if the load bus is supplied with the required power through at least one stable path, otherwise that load bus is experiencing a voltage collapse.

A stable transmission path can be found by the Transmission Path Stability Index (TPSI). This index is the defined as the difference between the halved generator voltage phasor and the corrected voltage drop along the transmission path, is in Gubina, B. Strmcnic (1995):

$$TPSI = 0.5U_g - \Delta U'_d \tag{12}$$

where U_g is the generator voltage phasor and $\Delta U'_d$ is the voltage drop along a transmission path.

The TPSI index is expressed in pu [5]. When it reaches zero value, the power transfer on that transmission path becomes unstable due to voltage collapse. Therefore, a stable transmission path is required to meet the following condition:

$$2\Delta U'_d < U_g \tag{13}$$

This scheme is mainly applied for long-term correction. The following steps can summarize this corrective scheme:

1. Calculate L-index value for all buses, sort them in descending order and then check out all buses with values above a pre-specified threshold (critical) value. If any start the correction action.
2. Find the transmission path and calculate the TPSI for each path and sort them in descending order.
3. Select the transmission path with the smallest TPSI and start the reinforcement with branches that have the biggest losses in VARs.

The reinforcement in the third step can take place by reducing the branch impedance by adding series reactive compensators.

3.2 Reactive Compensation Scheme

Shunts reactive are another means by which the system voltage could be brought to a good profile. There are several types of compensation equipment that can maintain the desired voltage profile and control the steady state voltage stability. A brief description of such compensation equipment is presented in section 1.

This scheme is mainly applied at system planning stage or for long-term correction. The following steps can summarize this corrective scheme:

1. Calculate the L-index value for all buses, sort them in descending order and then check out all buses that are larger than the pre-specified threshold (critical) value. If any start the correction action
2. Use V-Q sensitivity to determine the amount of VARs needed to be absorbed or injected.
3. Use the existing reactive compensator to absorb or inject the required VARs near the buses having the instability problem.
4. If the existing reactive compensators are not sufficient, install new compensators in accordance with the Q-V sensitivity value and starting from the worst critical buses as indicated by the L-index largest value.

3.3 Generation Voltage and Reactive Pat Correction Scheme

This scheme consists of two main correction tools: through the generator voltage (immediate action) and/or through the reactive transmission path (long-term action). Since the reactive power flow is strongly connected to the voltage magnitude, a reactive transmission path with decreasing voltage magnitudes can be identified. A reactive power transmission path is defined as a sequence of connected buses with declining voltage magnitudes.

A reactive transmission path starts from a generator bus with the highest voltage magnitude value and ends at a load bus with the lowest voltage magnitude. In general a voltage collapse may occur at the load bus at the end of the identified transmission paths.

A stable transmission path can be found by the use of the TPSI defined in equation (13). The following steps can summarize this corrective scheme:

1. Calculate the L-index value for all the buses, sort them in descending order and then check out all buses that are larger than the pre-specified threshold (critical) value. If any start the correction.
2. Select the generator bus near to bud having the worst problem, increase the generator voltage without exceeding the generator VARs limits. Keep doing this for the next worth buses. In the instability problem is resolved STOP, otherwise go to next step.
3. Find all the reactive transmission paths and calculate the TPSI for each path and then sort them in descending order.
4. Select the transmission pat with the smallest TPSI and start the reinforcement with branches that have the biggest loses VARs.

The reinforcement in four steps can take place by reducing the branch impedance by adding series reactive compensators.

3.4 Load Shedding Correction Scheme

This scheme provides a low-cost means of preventing widespread system collapse. It is considered as an economical and immediate solution to the voltage stability problem, as in Taylor (1992). The maximum limit for a load that can be shed at each bus is 80% to ensure a minimum emergency service to the costumers. The load to be shed should be done gradually, in steps.

The amount of the load to be shed can be determined either experimentally or by fast calculation. Using sparse vector technique, sensitivities between indicator changes and the amount of the load to be shed could be determined as:

$$\Delta B_j = \left(SBP_{jj} + SBQ_{jj} \cdot \tan \phi_j \right) \cdot \Delta P_j \qquad (14)$$

where: $\tan \varphi_j$ is the load factor at the bus j;

SBP and SBQ are the sensitivities between indicator changes and the load power to be shed;

B_j is the indicator value at the bus j;

P_j is the active power to be shed at bus j.

The following steps can summarize this corrective scheme:

1. Calculate L-index value for all buses, sort them in descending order and then check out all buses that are larger than the pre-specified threshold (critical) value. If any start the correction action.
2. Start the shedding of the load according to the technical and priority list, if any, taking into account the allowable shedding limit.

4. RESULTS AND DISCUSSION

This section implements the four corrective schemes on two different power systems: Ward and Hale system and the IEEE 30-bus, for the voltage stability analysis. For every system, the voltage instability is studied and analyzed and then corrected by using each of the four corrected schemes.

In each study case, L-index indicator is used to sort out the buses that have the greatest instability problems. The corrected solution by each scheme is considered perfect when the voltage profile of all buses in the system is within the standard range (0.95-1.05 pu). Some of the corrective schemes use the VQ-sensitivity indicator to assess the correction. The corrected solution of each study case can also be viewed by checking the L-index value of the buses after the correction.

4.1 Wale & hale 6-bus system

The network configuration and the system basic parameter of this 6-bus system are given in Al-Ghamdi et all. (1994). The L-index indicator whose threshold (critical) value has been selected as 0.25 has checked the instability of this system. After sorting L-index value of all buses, buses 3, 5 and 6 have been traced as the buses with possible low-voltage profile. Bus 5 is the worst bus (the one with the largest L-index value). Using the four corrective schemes the voltage problem was solved. Because bus #1 and #2 are the generator buses, they are not accounted for corrections.

Correction by active power scheme The correction of instability using this scheme starts by finding all active transmission path of this system and then sorts their TPSI values in descending order. Two paths are calculated. The line connections of each path along with its TPSI value are given in Table 1.

Table 1 Line connections and TPSI values

Transmission path	Line connections (from bus to bus)	TPSI
1	1-6, 6-4, 4-3, 5-4	0.395
2	5-4	0.360

The second transmission path in Table 1 has the smallest TPSI value. The best solution was obtained by decreasing the impedance of the line connection (1-6 and 2-5) by 30% and line connection (6-4) by 10%. The values of L-index and voltage profiles before and after the correction are shown in Fig. 1.

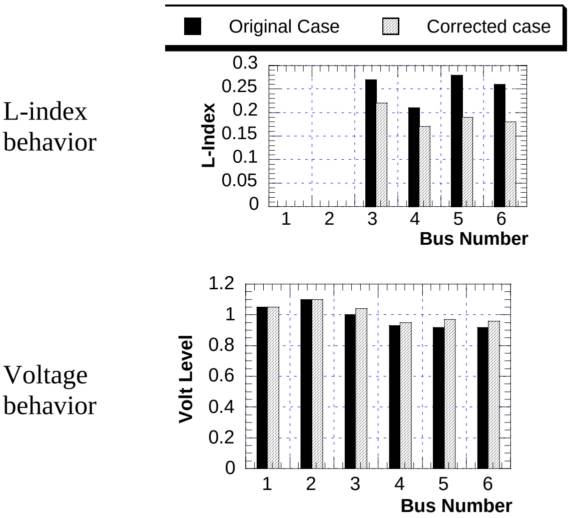

Fig. 1: L-index and voltage before and after the correction by active power scheme

Correction by Reactive Compensation Scheme: This correction scheme uses VQ-sensitivity to determine the amount of VARs needed to be absorbed or injected. This has to be done by using first the existing reactive compensators at buses 1, 4 and 6.

The correction of instability in this system is achieved by installing compensators. The best solution obtained, after using all existing compensators, is to add shunt compensators at buses 4 and 6 only to inject more VARs. The amounts of the extra VARs required, as determined by the VQ-sensitivity, are found to be about 7 MVAR at bus 4 and 15.5 MVAR at bus 6. The results of L-index values and voltage profiles before and after correction are shown in Fig. 2.

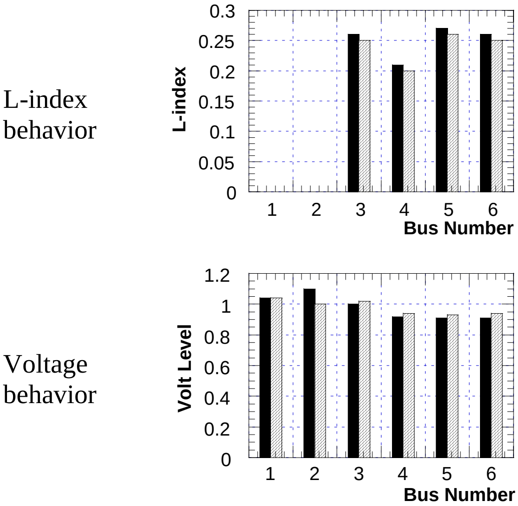

Fig. 2: L-index and voltage before and after the correction by reactive compensation scheme

Correction by Generating Voltage and Reactive Path Scheme: The correction of the instability by this scheme has been tried first by using the immediate solution step in which the generator voltages at buses 1 and 2 increases without exceeding the VAR limit. The voltage profile of all buses has been improved except bus 5.

The next step then is to calculate the reactive transmission path of the system and sort them according to their TPSI value. Two paths are found. The line connections of each path along with its TPSI value near to those given in Table 1. The correction of the instability has been tried over for many scenarios and the best solution obtained is by decreasing the impedance of line (2-5) by 10% only. The L-index values and voltage profiles before and after correction are shown in Fig. 3.

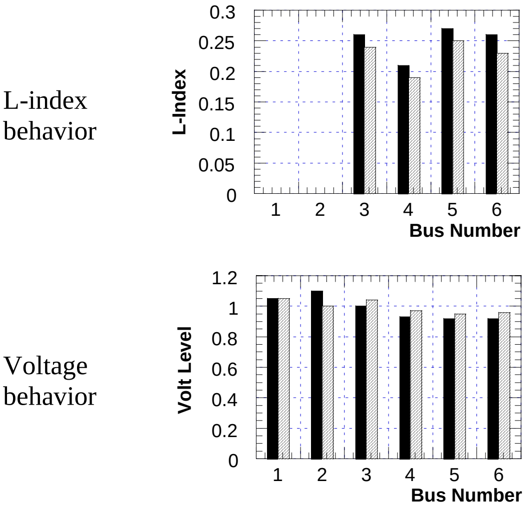

Fig. 3: L-index and voltage before and after the correction by Generating Voltage and Reactive Path Scheme

Correction by Load Shedding Scheme: This scheme allows load shedding maximum at 80% and this should be done gradually in steps of 10% (starting by 20%). The correction of instability has been started from bus 5, which has the worst voltage profile.

After a sequence of trails, the best solution that has been reached is by shedding 10% of the load at buses 5 and 3, and 5% of the load at the bus 6. The L-index values and voltage profiles before and after correction are shown in Fig. 4.

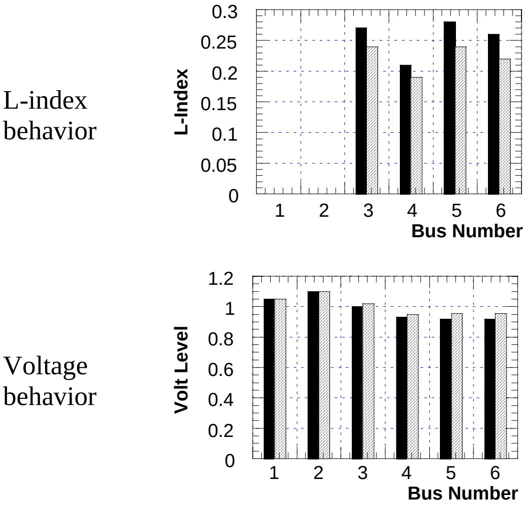

Fig. 4: L-index and voltage before and after the correction by Load Shedding Scheme

4.2 IEEE 30-bus system

The network configuration and the system basis parameters of this 30-bus system are given in Al-Ghamdi et all. (1996). The instability of this system has been cheeked by the L-index indicator whose threshold (critical) value has been selected as 0.13.

After sorting L-index values of all buses, buses 26, 29 and 30 have been traced with possible low-voltage profile. The worst bus (the one with the largest L-index value) is found to be the bus 30.

Correction of this 30-bus system has been performed by using the four corrective schemes as follows. It is worth mentioning here that buses 1, 2, 5, 8, 11 and 13 are the generator buses, therefore they are not accounted for corrections.

Correcting by Active Path Scheme The correction of instability using this scheme starts by finding all active transmission path of this system. Then their TPSI values are sorted in descending order. Six transmission paths have been calculated (as expected) and their first transmission path has been found to have the smallest TPSI value.

The line connections of each path along with its TPSI value are given in Table 2.

Table 2**: Line connections and TPSI value**

Path	Line connections (from bus to bus)	TPSI
1	1-3, 3-4, 4-12, 12-15, 15-18, 18-19, 19-20, 20-10, 10-22	0.37
2	2-6, 6-4	0.49
3	5-7	0.485
4	8-6	0.482
5	11-9	0.487
6	13-6, 16-17, 17-11, 11-21, 21-22	0.46

The correction of the instability in this system has been tried over for many scenarios and the best solution obtained was by decreasing the impedance of all line connections (25-17 and 27-28) by 50%. The L-index values and voltage profiles before and after correction are shown in Fig. 5.

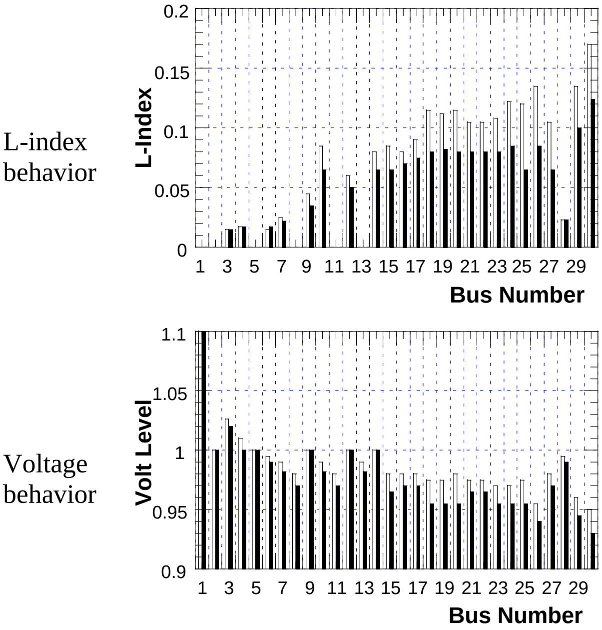

Fig. 5: L-index and voltage before and after the correction by active power scheme

Correction by Reactive Compensation Scheme: This corrective scheme uses VQ-sensitivity to determine the amount of VARs needed to be absorbed or injected. This has been done by using first the existing reactive compensators at buses 10and 24. The existing amounts of VARs are set as 19MVAR for bus 10 and 15MVAR for bus 24.

The correction of instability in this system could not been achieved without installing additional compensators. The best solution obtained, after using all existing compensators, is by installing additional shunt compensators at buses 19, 26, 29 and 30 to inject more VARs. The required amount of VARs, as determined by the VQ-sensitivity, are found to be about 16MVAR at bus 19, 7MVAR at bus 26, 4MVAR at bus 29 and 6MVAR at bus 30. The L-index values and voltage profiles before and after correction are shown in Fig. 6.

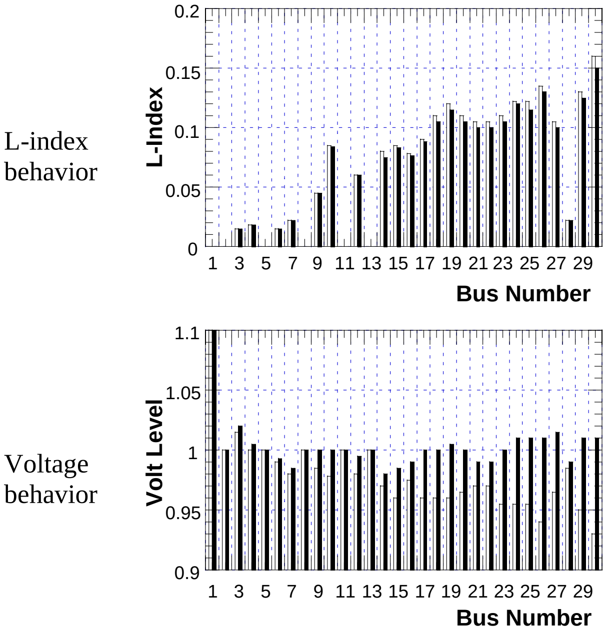

Fig. 6: L-index and voltage before and after the correction by reactive compensation scheme

Correction by Generating Voltage and Reactive Path Scheme: The correction of instability by this scheme has been tried first by using the immediate solution step in which the generator voltages of all PV-buses in the system are increased without exceeding their VAR limit. The voltage profile of all buses could not be improved. The next step then is to calculate the reactive transmission paths of this system and sort them according to the TPSI value. Six paths are found (as expected). The line connections of each path along with its TPSI value come to be similar to those given in Table 3.

Table 3 Line connections and TPSI values

Path	Line connections (from bus to bus)	TPSI
1	1-3, 3-4, 4-12, 12-15, 15-23, 23-24, 24-22, 22-11, 11-20, 20-19, 19-18, 18-15	0.23
2	2-6, 6-10, 10-21, 21-22	0.32
3	5-7, 7-6, 6-4	0.40
4	8-28, 28-27, 27-30, 30-29, 29-27	0.32
5	11-9, 9-10, 10-17, 17-16, 16-12, 12-14, 14-15	0.25
6	13-12	0.31

The correction of the instability has been tried over for many scenarios and the best solution obtained is by decreasing the impedance of line connection (27-28 and 27-30) by 25% only. The L-index values and voltage profiles before and after correction are shown in Fig. 7.

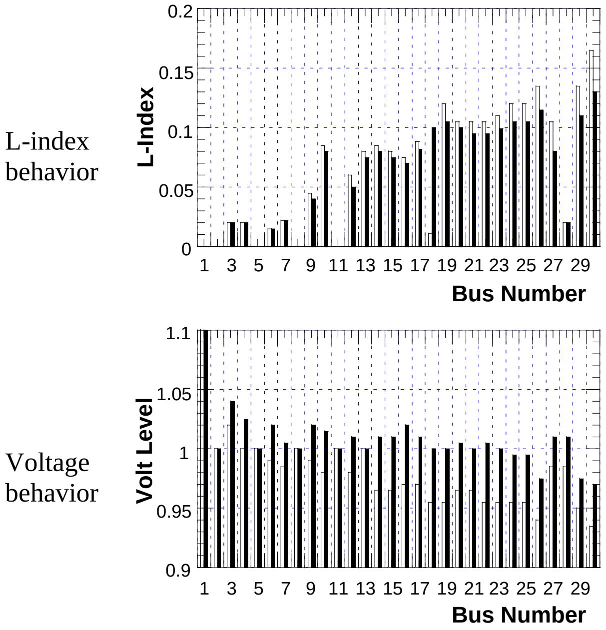

Fig. 7: L-index and voltage before/after correction by Generating Voltage and Reactive Path Scheme

Correction by Loading Scheme: This correction scheme, as explained previously, allows load shedding maximum at 80% and this should be done gradually by steps of 10% (starting by 20%). In this particular study case, the L-index critical case value has been set at 0.11 to see the effect of this supplementary stress on the results. In this case the buses that have problems are 19, 20, 24, 25, 26, 29 and 30.

After a sequence of trails, the best solution that has been reached is by shedding 50% of the load at the bus 30, 20% of the load at buses 26 and 29 and 10% of the load at buses 19 and 24. The results are presented in Fig. 8.

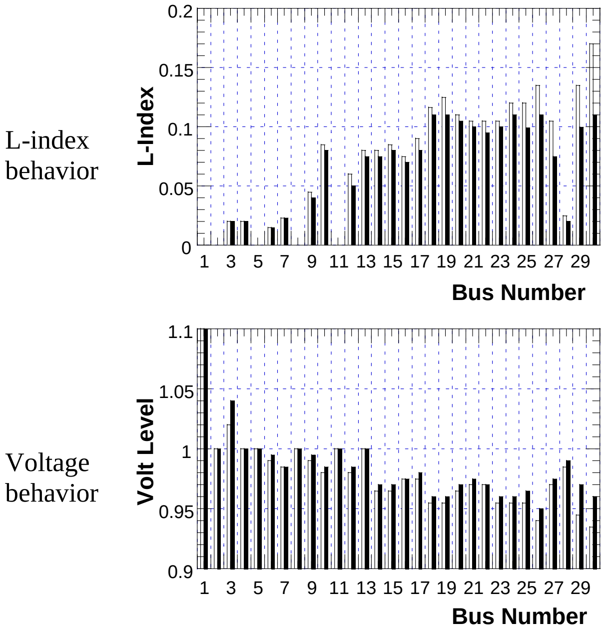

Fig. 8: L-index and voltage before and after the correction by Load Shedding Scheme

5. CONCLUSION

This paper has introduced four different corrective schemes to approach the phenomena of voltage instability problems and the way to correct it. Two power systems: Ward & Hale 6-bus and IEEE 30-bus have been tested and corrected by using two different indicators which are of help in selecting the location of the unstable voltage buses and the amount of VARs required for the correction. These two indicators are L-index and the VQ-sensitivity.

From the study and analysis presented, one can understand and suggest different solutions for voltage instability problems based on the nature and situation of the problem. So, from the four alternative corrective schemes a best solution could be selected based on many factors, such as, technical and economical reasons.

During the emergency situation immediate actions such as load shedding scheme and/or increasing the generators' voltages could take place. On the other hand, active and reactive transmission path schemes and reactive compensation schemes could be considered for long-term planning.

A further expression of this work to investigate the effectiveness and the coordination of the four introduced corrective schemes would consider contingencies of a different type. A loss of line(s) or loss generation would have serious impact of the voltage stability profile and would change the classification of active and reactive transmission paths. The amount of reactive reserve would be affected and reduced. The load shedding priority picture would change.

A knowledge base where human knowledge and experience coded in logical manner is planed for an on-line monitoring for power system voltage stability. Priorities and system variables are included. A data acquisitions system for feeding the knowledge base is essential. The expert system will take coordinated actions to come with a complete solution or a partial alleviation of the voltage stability problem.

6. REFERENCES

Kundur, P. (1994) "Power System Stability and Control", Mc.Graw-Hill, New York, 1994.

Byerly, R.T , Poznaniak, D.T. and Taylor, E.R (1982) "Static Reactive Compensation for Power Transmission System", IEEE Trans. on Power Apparatus and Systems, Vol.PAS-101, No. 10, Oct. 1982, pp. 3997-4005.

Gao, B., Morison, G.K. and Kundur, P. (1992) "Voltage Stability Evaluation using Model Analysis", IEEE Trans. on Power Systems, Vol.7, No. 4, Nov. 1992, pp.1529-1542.

Belhadj, C., Mohamedi, R., Lefebvre, S., Lagace, P.J., Do, X.D. (1996) "Voltage Instability Modeling and Real-Time Monitoring using Expert System for Operation Assistance", IEEE Trans. on Power Systems, Vol.11, No. 2, May 1996, pp. 1037-1045.

Tuan, T.Q , Fandino, J., HadjSaid, N., Sabonnadiere, J.C. and Vu, H. (1994) "Emergency and load Shedding to Avoid Risks of Voltage Instability using Indicators", IEEE Trans. on Power Systems, Vol.9, No. 1, Feb. 1994, pp. 341-348.

Kessel, P. and Glavitsh, H. (1999) "Estimating the Voltage Stability of Power System", IEEE Trans. on Power delivery, Vol.PWRD-1, No.3, No.3, March 1999, pp. 346-354.

Elrazaz, Z., Al-Olhay, A., (1993) "Criterion for reactive compensation location to enhance System Steady State Stability", IEEE Trans. on Power Systems, Vol.8, No. 11, Nov. 1993, pp. 1545-1549.

Taylor, C.W. (1992) "Concepts and Undervoltage load Shedding for Voltage Instability", IEEE Trans. on Power Systems, Vol.7, No. 2, April 1992, pp. 480-486.

Al-Ghamdi, A., Al-Tamini, H., Al-Ghamdi, K., Al-Roubaya, M. (1996) "Steady-State Voltage Stability and Design", Capstone Project, Project, KFUPM, Dhahran, Saudi Arabia, Dec. 1996

Gubina, F., Strmcnic, B. (1995) "Voltage Collapse Proximity Index Determination using Voltage Phasors Approach", IEEE Trans. on Power Systems, Vol.10, No. 5, May 1995, pp. 788-794.

Lof, P.A., Smed, T. and Andersson, G. (1992) "Fast Calculation of a Voltage Stability Index", IEEE Trans. on Power Systems, Vol.7, No. 1, Feb. 1992, pp. 54-64.