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Identification of Weak Bus and Voltage Stability Enhancement

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Abstract: This paper describes sensitivity indicator method to identify weakest bus of the system. It also describes method of calculating the amount of reactive power to be injected at the load bus to avert the voltage instability as the load on the load bus increases. In this paper IEEE-57 BUS system has been considered. First, the weakest bus is identified using sensitivity indicator method. Then Load flow analysis is performed using the Newton-Raphson (N-R) method. When load flow doesn't converge after the demand has increased on a bus then it indicates that it requires reactive power compensation on that bus. The Additional capacitor that needs to be switched on is computed by an iterative procedure. Thereafter, in the actual usage, based upon the computed Table, given any load one may determine the level of compensation required to avert voltage collapse. By using Jacobian element additional compensation required to improve the bus voltage can be determined.

Key Words: weak bus, voltage instability, sensitivity indicator, load flow

I. INTRODUCTION

Modern transmission networks are more heavily loaded than ever before to meet the growing demand. One of the major problems associated with such a stressed system is voltage collapse or instability. There are many incidents of system blackout, due to voltage collapse. [1] Voltage stability is the ability of a power system to maintain steady acceptable voltages at all buses in the system under all operating conditions. Voltage control and stability problems are now receiving special attention in many systems as under heavy loaded conditions. There may be insufficient reactive power causing the voltage to drop. This drop may lead to drop in voltage at various buses. This sort of abnormal voltage drop is referred as voltage instability. A system enters the state of voltage instability when an increase in load demand or change in system condition causes a progressive and uncontrollable fall of voltage. Load variations or contingencies in general cause voltage collapse. [2]- [3] - [4] In this study voltage collapse due to load variations is considered.

$\frac{\partial Qi}{\partial Vi}$ Sensitivity index for weak bus identification

The application of N-R load flow method give following basic equations.

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix}=\begin{bmatrix}\frac{\partial P}{\partial \theta} & |V|\frac{\partial P}{\partial V}\\ \frac{\partial Q}{\partial \theta} & |V|\frac{\partial Q}{\partial V}\end{bmatrix}\begin{bmatrix}\Delta\theta\\ \frac{\Delta V}{|V|}\end{bmatrix} \quad (1)$$

The first term on right side of equation is Jacobian matrix. In formulating above equation we have assumed that all buses are PQ buses. For a PV bus only P is specified and the magnitude of V is fixed. Therefore, terms corresponding to ΔQ and ΔV would be absent for each of PV buses. Thus the Jacobian would have only one row and one column for each PV bus.

$$\begin{bmatrix}J11 & J12\\ J21 & J22\end{bmatrix}\begin{bmatrix}\Delta\theta\\ \Delta V\end{bmatrix}=\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} \quad (2)$$

We can therefore easily compute the expected small change in θ and v for small changes in P and Q. Hence, the real and reactive power sensitivities of the i^{th} bus are obtained as

$$\frac{\partial Pi}{\partial Vi}=\frac{J12}{|Vi|} \quad (3)$$

$$\frac{\partial Qi}{\partial Vi}=\frac{J22}{|Vi|} \quad (4)$$

Eq. (3) and (4) represents the real and reactive power sensitivities of the i^{th} bus. $\frac{\partial Qi}{\partial |Vi|}$ also indicates the degree of weakness for the i^{th} bus. As $\frac{\partial Qi}{\partial |Vi|}$ being high $\frac{\partial |Vi|}{\partial Qi}$ becomes low, indicating minimum change in |Vi| for variation in Q-status of the bus. Thus, $\frac{\partial Qi}{\partial |Vi|}$ being higher, the degree of weakness of the ith bus becomes lesser.

In this study, the load on a weakest bus is increased until the voltage collapse occurs. Then the minimum reactive power to be injected at the particular load bus is calculated by an iterative method. The same procedure is repeated for different load conditions and the corresponding kVAr to be injected has been calculated. This helps to form an expert system database, which can be used effectively to alleviate voltage instability.

Numerous methods have been proposed for alleviating voltage instability. These methods predominantly use Jacobian sensitivities for improving voltage stability margin [5]-[7].These methods consider the change in real and reactive power controllers to improve voltage stability margin. However they require lot of computation and time.

II. COMPENSATION

Compensation consists of injecting reactive power to improve power system operation. Reactive power

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compensation is often the most effective way to improve both power transfer capability and voltage stability. It also contributes to voltage stability margin enhancement. Compensation is provided by either capacitors installed in series with transmission lines or shunt elements connected to a particular load bus. More specifically, it keeps voltages close to nominal values, reduces line currents and hence network losses. In this study shunt compensation technique is adopted to improve the voltage stability margin.

III. SHUNT COMPENSATION

Shunt compensation is the simplest and most widely used form of compensation. To investigate its effect in some detail, a simple system is shown Fig. 1. It combines the effect of line charging susceptance B1 with that of an adjustable shunt compensation susceptance BC. The maximum deliverable power under power factor $\cos\varphi$ and the corresponding load voltages are given by following equations.

$$P_{max} = \frac{\cos\varphi}{1+\sin\varphi} \times \frac{E_{th}^2}{2X_{th}} \quad (5)$$

$$V_{maxp} = \frac{E_{th}}{\sqrt{2}} \times \frac{1}{\sqrt{1+\sin\varphi}} \quad (6)$$

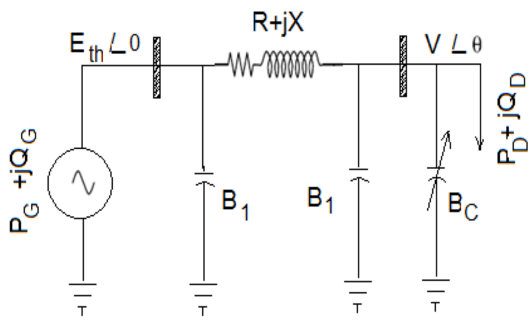

Fig 1 Simple Transmission Line Diagram [8]

By using Thevenin's theorem we get

$$P_{max} = \frac{1}{1-(B_c+B_1)X} \times \frac{\cos\varphi}{1+\sin\varphi} \times \frac{E^2}{2X} \quad (7)$$

$$V_{maxp} = \frac{E_{th}}{1-(B_c+B_1)X} \times \frac{E}{\sqrt{2}} \times \frac{1}{\sqrt{1+\sin\varphi}} \quad (8)$$

Where

$$E_{th} = \frac{E}{1-(B_c+B_1)X}$$

$$X_{th} = \frac{X}{1-(B_c+B_1)X}$$

Here line resistance is neglected. $\mathbf{P_{max}}$ and $\mathbf{V_{maxp}}$ increase by the same percentage when network capacitances are taken into account and/or capacitive compensation is added. Fig. 2 shows a PV curves for a power sysem.It can be seen that in order to keep the voltage within the limits shown by the dotted lines (typically 0.95p.u. and 1.05p.u. respectively) more shunt compensation has to be added with increase in load power. The resulting PV curve is shown in a thick line [9].Thus it is clear that addition of shunt compensation improves voltage stability margin of a power system. When the system is stressed, switching in more capacitive compensation helps to deliver more real power.

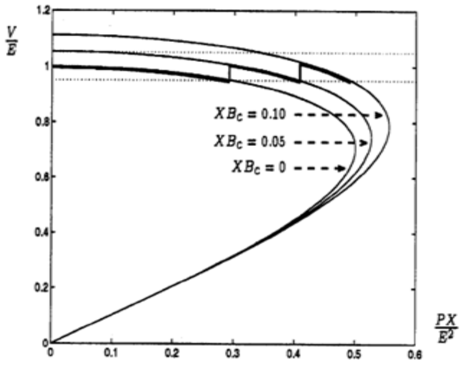

Fig 2 P-V Curve for Power System [8]

IV. METHODOLOGY

Sometimes, power system is operated at higher load than expected. In such situations, the extra load may cause voltage collapse. Inclusion of additional capacitive compensation may alleviate this situation. We follow below mentioned steps in the alleviation process. These steps are also shown as flochart in Fig.3.

1. First add more load as desired to the specified bus.
2. Solve the load flow equations using fast Newton Raphson's load flow method.
3. Determine whether a converged solution is obtained or not.
4. If the solution is converged, then there is no need for capacitive compensation.
5. If there is no feasible solution for the power flowequations, then corrective action is taken by providing reactive power injection computed by iterative method.
6. If necessary select an appropriate value of additional capacitive compensation to enhance voltage stability at the desired bus.
7. Go to step 2 and repeat steps 2 to 6.

The algorithm given below is simple. It uses the Newton Raphson load flow algorithm for the solution of power flow equations. This makes the proposed algorithm computationally efficient.

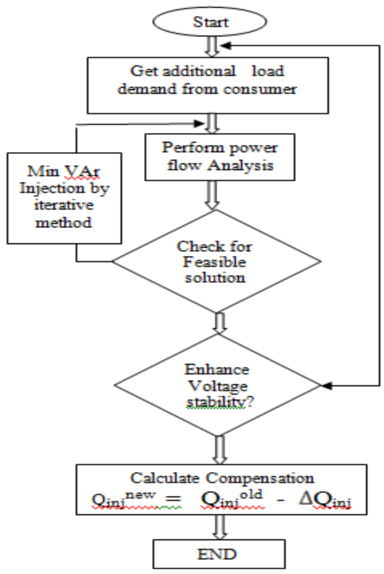

Fig. 3: Flowchart of the Proposed Method

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$$B_{II} = \frac{\Delta Q_I}{\Delta V_I} \quad (9)$$

Where BII is the i^{th} diagonal element of B" matrix. This allows simple computation of required Q to improve the bus voltage. The change in bus voltage is taken as 0.1 p.u. Thus at each iteration of step 6 the reactive power injection is increased by the following equation:

$$Qinj^{new} = Qinj^{old} - \Delta Qinj \quad (10)$$

V. RESULTS AND DISCUSSION

TABLE-I
VAr CALCULATION BY ITERATIVE METHOD

Real power demand at bus 31 $P_{D(31)}$ MW p.u.	VAr to be injected at bus 31 to avoid voltage collapse (MVAr p.u.)		
	When $Q_{D(31)}$ is 0.15 MVAr p.u	When $Q_{D(31)}$ is 0.16 MVAr p.u.	When $Q_{D(31)}$ is 0.17 MVAr p.u.
0.130	0	0	0
0.135	0	0	0.003
0.140	0	0	0.006
0.145	0	0	0.009
0.150	0	0.002	0.012
0.155	0	0.006	0.016
0.160	0	0.009	0.019
0.165	0.003	0.013	0.023
0.170	0.006	0.016	0.026

The algorithm was tested on the standard IEEE 57-bus system. By sensitivity indicator method it is found that $\frac{\partial Q}{|\partial V|}$ is 2.035 and it is lowest for bus no. 31. Hence it is identified as the weakest bus in the power system. Load was increased at Bus Number 31.

The real power demand was increased from a value of 0.130 p.u. to 0.170 p.u. in steps of 0.05 p.u. The reactive power demand at the same bus was kept at three different values viz. 0.15 p.u., 0.16 p.u. or 0.17 p.u.. For various values of reactive power demand and real power demand the reactive power compensation was computed. This result is documented in Table I.

Thereafter, the curve is obtained for the relationship between the real power demand and the reactive power compensation. The equation of the curve is obtained by the mathematical modeling. The equation is represented in equation number (11). The resulting curve is graphically shown in Fig. 4 for bus No.31.

The values of the coefficients of the equation are obtained for this curve. The values of the coefficients α and β, for this case in which reactive power demand is 0.15p.u. are 0.6 and -0.096 respectively.

TABLE-II
ADDITIVE VAr COMPENSATION FOR ENHANCEMENT OF VOLTAGE MAGNITUDE

Sr. No	Reactive power Demand	Real power Dema-nd $P_D(31)$	Voltage after min VAr inj. in volt p.u.	VAr inj For enhance Voltage magni-tude In MVAr p.u.	Voltage after VAr inj in volt p.u.
1	When $Q_D(31)$ is 0.15 MVAr p.u	0.130	0.627	- 0.203	1.063
2		0.135	0.617	- 0.204	1.061
3		0.140	0.606	- 0.206	1.060
4		0.145	0.594	- 0.207	1.058
5		0.150	0.579	- 0.206	1.055
6		0.155	0.561	- 0.203	1.050
7		0.160	0.533	- 0.196	1.042
8		0.165	0.527	- 0.199	1.041
9		0.170	0.517	- 0.200	1.039
1	When $Q_D(31)$ is 0.16 MVAr p.u	0.130	0.589	- 0.189	1.052
2		0.135	0.575	- 0.188	1.049
3		0.140	0.557	- 0.185	1.044
4		0.145	0.531	- 0.176	1.034
5		0.150	0.511	- 0.170	1.026
6		0.155	0.524	- 0.185	1.036
7		0.160	0.518	- 0.188	1.035
8		0.165	0.527	- 0.199	1.041
9		0.170	0.517	- 0.200	1.039
1	When $Q_D(31)$ is 0.17 MVAr p.u	0.130	0.518	- 0.151	1.007
2		0.135	0.519	- 0.157	1.024
3		0.140	0.518	- 0.162	1.026
4		0.145	0.516	- 0.167	1.027
5		0.150	0.511	- 0.170	1.027
6		0.155	0.524	- 0.185	1.036
7		0.160	0.518	- 0.188	1.035
8		0.165	0.527	- 0.199	1.041
9		0.170	0.517	- 0.200	1.039

It may be observed that as the real power demand increases for a constant reactive power demand, the capacitive compensation is not required until a particular real power demand value is reached. It may also be observed from the graph shown in Fig.4 that as the reactive power demand increases, the capacitive compensation value increases for the same real power demand. Table II shows the values of required additive reactive power compensation given to bus No.31 for enhancement of voltage magnitude for different real power demands and reactive power demands. For example take a case No. 2 in which real power demand is 0.135 MW p.u., reactive power demand is 0.17 MVAr p.u. and the voltage magnitude after providing minimum reactive power injection to avoid voltage collapse is 0.519 volt p.u., which is very low and requires some additional reactive power compensation. The additional reactive power compensation for this case (which is calculated by equation number (9) and (10) is - 0.157 MVAr p.u.) It is seen that now with the enough compensation the voltage has come up to the specified level and its value is 1.024 volt p.u.

Actually, the voltage magnitude at some of the load buses are below specified limit after increase in real power loading for different reactive power demands at particular bus. Therefore by providing additional reactive power compensation at particular bus the voltage magnitude at all buses has come up to specified limit. The relation between the required capacitive compensation QC_i and the expected increased real power demand PD_i for a given reactive power demand QD_i may be expressed from a generic equation as:

$$QC_i = \alpha(QD_i) * PD_i + \beta(QD_i) \quad (11)$$

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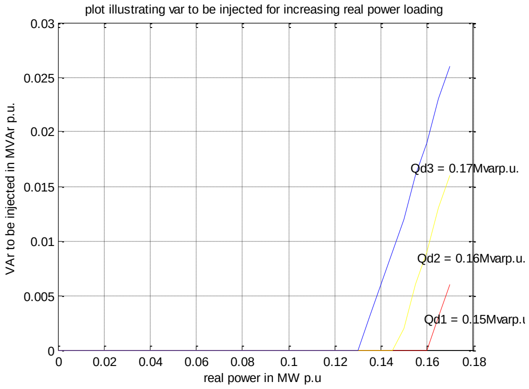

Fig. 4 Relation between Real Power Demand and Required Capacitive Compensation for Bus No. 31

VI. CONCLUSION

We have used sensitivity indicator method to findout weakest bus for the IEEE-57 bus test system. A method used for weak bus identification using voltage stability sensitivity indicator is very simple and fast because in this method, it neglects the effect of power angle δ . This study reports an iterative approach to determine the minimum shunt VAr compensation required for maintaining voltage stability of a power system working under different stressed conditions. The study also provides a method to determine the VAr compensation required to maintain voltage level of the system for any real and reactive power load at a particular load bus of the system. The reactive power compensation (VAr calculations) is carried out for different conditions on IEEE 57-bus system and the results are presented.

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