A Novel Approach for Reducing Proximity to Voltage Instability of Multibus Power System with Line Outage Using Shunt Compensation and Modal Analysis

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Abstract— Voltage instability is the phenomena associated with heavily loaded power systems. Due to deregulation of power system, the system has to cater for the load bids in open access. This may cause the increased transaction level leading to more stress on the power system. It has become the urgent need of today to address the voltage stability problems to keep the voltage profile under control. Several incidences of voltage instability have occurred worldwide recently. In the event of contingency, the most serious threat to operation and control of power system is insecurity. The estimation of the power system state under contingency is an essential task for the power system engineers. The contingency analysis technique is a prerequisite to predict the effects of various contingencies like failure of transformers, transmission lines etc.It helps to initiate necessary control actions to maintain power system security, reliability and stability. In the present work for a multibus and multi line power system the transmission lines are ranked based on reactive power performance index. Furthermore static voltage stability analysis by incrementing the load in proportion to the original load on load buses along with the most vulnerable line outage with and without addition of shunt compensation is carried out. The effect of line contingency on voltage stability and minimum eigen value with and without shunt compensations is brought out using modal analysis method. The concept of bus participation factor is used to identify the weak buses for effective use of shunt compensation for improvement of voltage stability.
Keywords- *Voltage Stability, Load Flow, Shunt Compensation, Modal Analysis*

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I. INTRODUCTION

Main challenging tasks for the power system engineers is maintaining power system security. The security assessment is indeed an essential task as it gives the knowledge about the system state in the event of a contingency. Contingency analysis technique is being widely used to predict the effect of outages like failure of equipment, transmission line etc, and to take necessary actions to keep the power system secure and reliable. But only selected contingencies will lead to severe conditions in power system. The process of identifying these severe contingencies is referred as contingency selection and this can be done by calculating some kind of performance indices for each contingencies. In order to indicate the severity of the contingency, two performance indices, namely the line flow performance index and voltage performance index, are calculated in [1].The simplest AC security analysis can be carried out by running an AC power flow analysis for each possible generator, transmission line and transformer outage. The approximate changes in the line flow due to an outage in generator or transmission line is predicted based on distribution factors [2, 3]. The application of ANN for determining the voltage stability margin under contingency situation has been discussed in [4]. The sensitivity analysis framework can determine the voltage stability status of the power system as well as instability depth due to the occurrence of each contingency. A severity index is obtained for each voltage contingency and so the contingencies can be ranked [5]. In [6], based on real-time network connectivity, a re-definition function is suggested which takes into account the actual response of protection subsystem on the power system equipment and identifies the breakers required for isolating the contingency equipment. This provides additional accuracy of post contingency results and provides important data to ensure that the remedial action schemes are employed correctly. Each contingency is simulated in contingency analysis by opening these breakers to evaluate their impact to the system. A novel approach for contingency filtering and assessment in sense of power quality and voltage instability is proposed in [7]. The approach consists of two-block technique. First block filters out dangerous contingency, and then second block assesses it for severity based upon performance index. The main motivation of the present work is to carry out the voltage stability analysis of a power system with most severe line outage. Firstly, contingency ranking is made based on calculation of performance index..During a transmission line contingency both the active power flow limit and the reactive power limit which in particular affects the bus voltage gets altered. Hence it is essential to predict these power flow and the bus voltages following a contingency. Firstly, an algorithm for contingency analysis using N-R Load Flow has been developed with the main focus on the contingency selection for line outage for multibus power systems. Under contingency condition of most severe line outage the voltage stability of the system is severely affected. Secondly, an analysis of voltage stability is carried out the under most vulnerable line outage and its improvement is illustrated by addition of shunt compensation on weak buses. A novel approach of increasing the load on load buses in proportion to original loading and providing additional shunt compensation on already identified load buses in proportion to the bus participation factor is presented. The effect of line contingency on voltage stability and minimum eigen value with and without shunt compensations is brought out using modal analysis method. The effectiveness of the methodology has been tested on IEEE 6-Bus system.

II. The Strategy of Analysis

A. Contingency Analysis Using AC Power Flow

In power systems the voltage magnitudes are the critical factor in assessing contingencies. In systems, where VAR flows predominate, such as underground cables, an analysis of only the MW flows will not be adequate to indicate overloads. The method of contingency analysis using AC power flow is preferred as it gives the information about MVAR flows and bus voltages in the system. The method using AC power flow will determine the overloads and voltage limit violations accurately

B. Contingency Selection

Since contingency analysis process involves the prediction of the effect of individual contingency cases, the above process becomes very tedious and time consuming when the power system network is large. In order to ease the above problem contingency screening or contingency selection process is used. Practically it is found that all the possible outages does not cause the overloads or under voltage in the power system. The process of identifying the contingencies that actually leads to the violation of the operational limits is known as contingency selection. The contingencies are selected by calculating a kind of severity indices known as Performance Indices (PI) [1]. These indices are calculated using the conventional power flow algorithms for individual contingencies in an off line mode. Based on the values obtained the contingencies are ranked in a manner where the highest value of PI is ranked first. The analysis is then done starting from the contingency that is ranked one and is continued till no severe contingencies are found. There are two kind of performance index which are of great use, these are **active power performance index (PIP)** and **reactive power performance index (PIV)**. PIP reflects the violation of line active power flow and is given by (1).

$$PIP = \quad (1)$$

Where, Pi = Active Power flow in line *i*, Pimax = Maximum active power flow in line *i*, n = specified exponent, L = total number of transmission lines in the system, M_P = weighting factor. If *n* is a large number, the PIP will be a small number if all flows are within limit, and it will be large if one or more lines are overloaded. Here the value of n has been kept unity. This index provides a measure of the severity of the line overloads for a given state in a power system. The value of maximum power flow in each line is calculated using (2).

(2)

Where, Vi = Voltage at bus i obtained from N-R load flow solution, Vj = Voltage at bus j obtained from N-R Load Flow solution, X = Reactance of the line connecting bus i and bus j.
Another performance index parameter which is used is reactive power performance index corresponding to bus voltage magnitude violations. It is mathematically given by (3).

$$PIV = M_V \sum_i^{N_l} \quad (3)$$

Where, Vi = Voltage of bus i Vimax and Vimin are maximum and minimum voltage limits, Vinom = average of Vimax and Vimin, Npq = total number of load buses in the system.,M_V = weighting factor. When all of the voltage level deviations from rated voltage are within limit the voltage performance index PIV is small. The PIV index measures the severity of the out of limit bus voltages, for a set of contingencies. This index provides a direct value of comparing the relative severity for different outages on the system voltage profile.

C. Modal Analysis

Voltage stability characteristic of the system can be identified by computing eigen values and eigen vectors of reduced Jacobian matrix J_R given by (4).

$$J_R = \xi \, \mathbf{\Lambda} \, \eta \quad (4)$$

Where ξ = Right eigenvector matrix of J_R
η = Left eigen vector matrix of J_R
$\mathbf{\Lambda}$ = Diagonal eigen value matrix of J_R
The final equation relating vector of modal voltage variations with the vector of modal reactive power variations is given by (5)

$$v = \Lambda^{-1} q \quad (5)$$

Where
v =Vector of modal voltage variations
q = Vector of modal reactive power variations
Λ^{-1} = A diagonal matrix
Therefore for i^{th} mode modal voltage and modal reactive power is related by (6)

$$v_i = q_i / \lambda_i \quad (6)$$

Comment on Stability: If q increases and v increases or vice versa then $\lambda_i > 0$ and i^{th} modal voltage variation and i^{th} modal reactive power variation are along same direction indicating voltage stability
If q increases and v decreases or vice versa then $\lambda_i < 0$ and i^{th} modal voltage variation and i^{th} modal reactive power variation are in opposite direction indicating voltage instability.
When the system reaches the voltage stability critical point, modal analysis is helpful in finding voltage critical areas and the elements which participates in this mode. The most critical mode is then identified where the eigen value is minimum. The magnitude of eigen values can provide the relative measure of proximity to instability at current operating point. It also indicates the requirement of shunt compensation at the buses. The advantage of modal analysis is that it clearly identifies groups of buses which participate in the instability by finding bus participation factors [8]. The application of modal analysis helps in determining how stable the system is and how much extra load or power transfer level the system can sustain without losing voltage stability [9].
Bus participation factor gives the information on how effective reactive power compensation at a bus is required to increase the modal voltage at that bus. It is given by (7).

$$P_{ki} = \xi_{ki}\,\eta_{ik} \qquad (7)$$

Thus P_{ki} determines the contribution of λi of mode i to V-Q sensitivity at bus k. A bus with high participation factor indicates that it has large contribution to this mode. The size of bus participation in a given mode indicates effectiveness of remedial action applied at that bus.

D. Local capacitive Shunt Compensation

When power system is subjected to a sudden increase of reactive power demand following a system contingency, additional demand is met by the reactive power reserves carried by the generators and compensators. If sufficient reserves are there, the system settles to a stable voltage level. However because of a combination of events it is possible that additional reactive demand may lead to voltage collapse. The reason for this is the shortage of reactive power support at the buses. Since the transmission of reactive power is difficult at heavy loads, local reactive support may be more effective in enhancing voltage stability margin. Placement of shunt capacitors at critical buses may provide local reactive support to maintain bus voltages [8].The most inexpensive way of providing reactive power and voltage support is the use of shunt capacitors. They can be used up to a certain point to enhance the voltage stability margin. They can also be used to free up spinning reactive support in generators and thereby prevent voltage collapse. It can also be concluded that providing local shunt compensation at weaker buses not only extends the maximum loadability point further thereby increasing maximum loadability of the system but also helps in improving the bus voltage.

III. ANALYSIS

Following are the algorithmic steps followed for the analysis.

1. Identify the most vulnerable line by calculation of PIV
2. Simulate the line outage.
3. Set the shunt compensation to original.
4. Perform Load Flow analysis.
5. Check for divergence of Load Flow.
6. Increase the load proportionately on selected load buses.
7. Find bus participation factors at critical load, in least stable mode. (Least stable mode corresponds to minimum eigen value of reduced Jacobian matrix).
8. Find the maximum Loadability and the bus voltages.
9. Increase total shunt compensation and distribute it in proportion with the bus participation factor.
10. Repeat from step 4 till maximum total shunt compensation is reached.

The analysis has been carried out for IEEE 6 bus system shown in Figure 1.

Following cases are analyzed and studied.

1. Base Case Without line outage
2. Base Case With most vulnerable line outage
3. Proportionate Load Increase without Line Outage
4. Proportionate Load Increase with most vulnerable line outage
5. Proportionate load increase with most vulnerable line outage with shunt compensation.

IV. RESULTS

Table 1 show the contingency ranking based on voltage performance index PIV.

TABLE1 PERFORMANCE INDICES AND RANKING

Line outage	PIP	PIV	Ranking
9	1.61	**10.12**	**1**
7	1.3	4.88	2
3	2.61	3.03	3
6	1.29	2.17	4
11	1.32	2.04	5
10	1.33	1.86	6
1	1.99	1.83	7
4	1.32	1.62	8
8	1.32	1.57	9
5	2.16	0.89	10
2	5.11	0.64	11

Load is increased proportionately on buses 4, 5 and 6.Table 2 depicts bus voltages and maximum loadability for various cases studied. Table 3 gives the details of the shunt compensations added on the weak buses. Table 4 depicts the bus voltages and maximum loadability of system for various shunt compensations added with most vulnerable line outage. Figure 2 and Figure 3 shows the variation in minimum eigen value with total load without and with shunt compensation. Figure 4 shows relationship between maximum loadability and shunt compensation. Figure 5 and Figure 6 shows the PV curves without and with addition of shunt compensation.

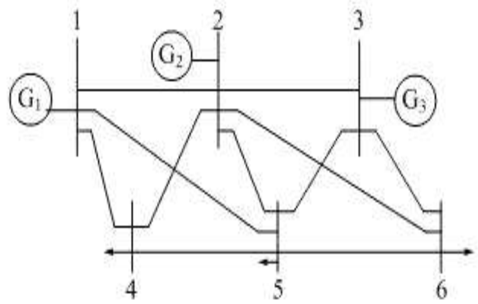

Figure 1 IEEE 6 bus system

TABLE 2 BUS VOLTAGES AND MAXIMUM LOAD FOR VARIOUS CASES WITHOUT ADDITIONAL COMPENSATION

Cases Analyzed	Bus Voltages (Pu)			Maximum Load (Mw)
	V4	V5	V6	
Base Case Without Line Outage	1.08	1	0.99	200
Base Case Without Line 9 Out	1.01	0.99	0.95	200
Proportionate Load Increase Without Line Outage	0.65	0.59	0.7	1095
Proportionate Load Increase With Line 9 Out	0.92	0.8	0.52	575

ISSN: 2321-8169
010– 014

TABLE 3 DETAILS OF SHUNT COMPENSATION ADDED

Bus No.	BPF	Shunt Compensations							
		1	2	3	4	5	6	7	8
6	0.945	0	10	19	28	38	46	57	67
5	0.0537	0	1	2	3	3	5	4	4
	Total (MVAR)	0	11	21	31	41	51	61	71

TABLE 4 BUS VOLTAGES AND MAXIMUM LOADABILITY WITH SHUNT COMPENSATION

Total Comp.(MVAR)	Bus Voltages (Pu)			Max.Load (Mw)
	V4	V5	V6	
0	0.923	0.798	0.582	575
11	0.916	0.786	0.572	600
21	0.91	0.778	0.571	620
31	0.904	0.771	0.576	640
41	0.9	0.769	0.593	655
51	0.894	0.759	0.588	675
61	0.887	0.748	0.579	695
71	0.883	0.746	0.598	710

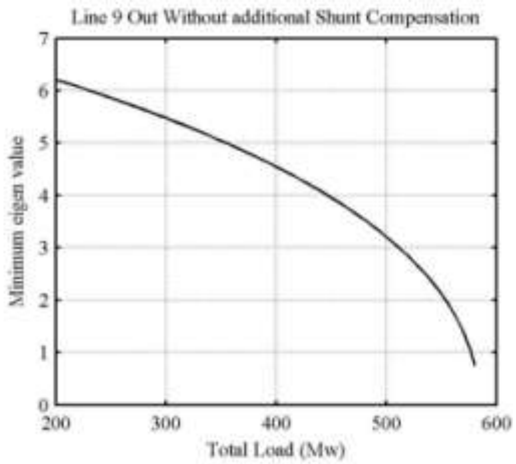

Figure 2 Va

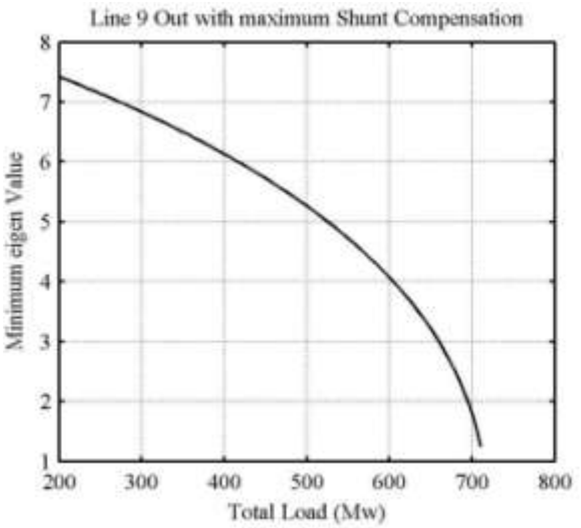

Figure 3 Variation of minimum eigen value with shunt compensation

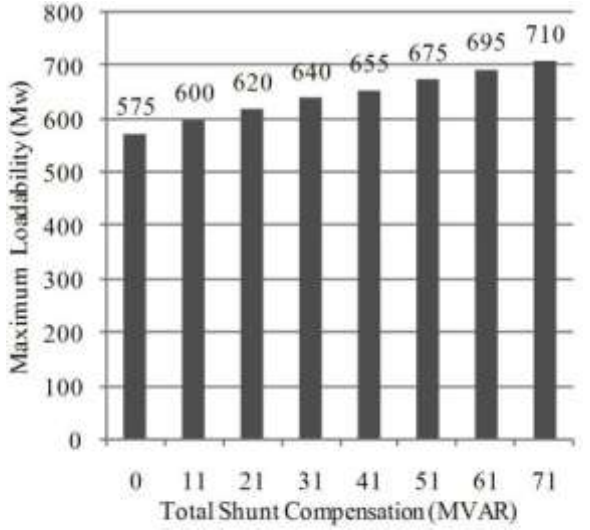

Figure 4 Maximum loadability with shunt compensation

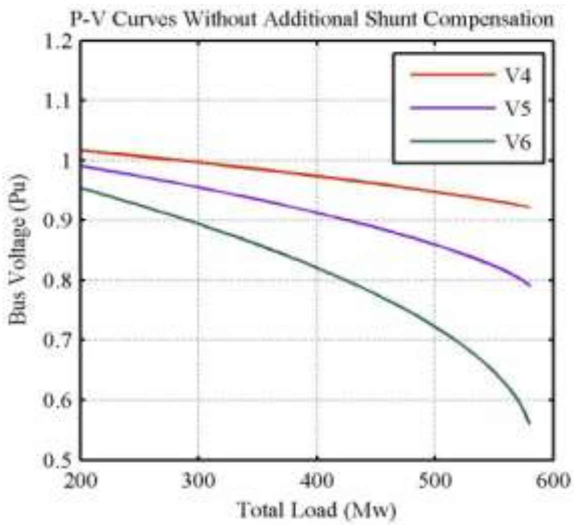

Figure 5 P-V curves without shunt compensation

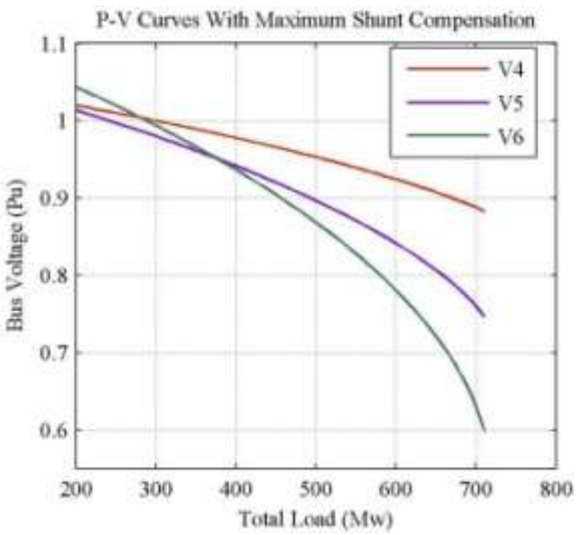

Figure 6 P-V curves with shunt compensation

V. CONCLUSION

From the results cited above it is evident that, the most severe line outage may jeopardize the system voltage stability. It is therefore necessary to identify the most vulnerable line contingency and then initiate the necessary action to maintain the voltage stability. Using the modal analysis the eigen values corresponding to most critical mode can be found for different loading conditions of the system. The eigen values provide the information of proximity to voltage instability. By adding the shunt compensation it is possible to raise the bus voltages and the system loadability which is a direct result of increased minimum eigen value. To bring the bus voltages to their nominal values would require large shunt compensation at the additional cost. But the local reactive power compensation can certainly prevent voltage collapse in case of line outages.

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