Assessment of Voltage Instability through Multiple Load Flow Solutions

S.N.Chpahekar, Member IEEE and V.V.Khatavkar, Member IEEE

Abstract-The conventional stability studies of the power systems deal with real power dispatch, voltage profile, line losses etc. under stable operating conditions. In the last decade, in addition to power system stability, voltage stability has become important due to ever increasing load demand. Several voltage instability phenomenons are observed in electric power systems where receiving voltage oscillates remarkably above or at much lower value than the nominal value.

In developing countries like India power systems are always heavily loaded. There is always shortage of generation as compared to the rapidly increasing load demand. Heavy loading of the system or tripping of any one of the lines in the grid causes the reduction of receiving end voltage resulting in voltage instability.

Thus the voltage instability is a state of power system encountering an unacceptable voltage level. The phenomenon of the voltage instability can be approached in many ways as steady state instability, load flow feasibility, static bifurcation of equilibrium, multiple load flow solution problem etc. The analysis of voltage instability is considered in this paper.

An assessment of voltage instability in the system under different contingencies can be studied using application of multiple load flow solutions approach resulting in feasible solutions for Pune city.

I. INTRODUCTION

For every country, power system is the heart of industrial growth and welfare as well as socio-economic development. In developing countries like India, there is always shortage of the generation as compared to the rapidly increasing load demand. In other words, power systems are always heavily loaded. However NO POWER condition in any country will bring everything to a halt. Heavy loading of the system or tripping of any one of the lines in the grid causes the reduction of the receiving end voltage. If this voltage is decreased beyond the limit, voltage instability may be observed.

Thus the voltage instability is a state of the power system encountering an unacceptable voltage level. The various methods that have been developed to analyse the phenomenon of voltage instability can be summarized below

II. VOLTAGE INSTABILITY METHODS

The various methods that have been developed to analyze the voltage instability problem are mainly classified into two categories-

Static methods-These methods are divided into two forms

[1] Load flow feasibility methods-These methods include maximum power transfer , load flow feasibility, multiple load flow solutions and singular value of Jacobian matrix

[2] Steady state methods-These methods include Eigen value of linearised dynamics, positive definite of Jacobian matrix, Sensitivity method.

Dynamic methods-These methods are called as nonlinear stability methods.

III. PROBLEMS OF VOLTAGE INSTABILITY

The continuing interconnections of bulk power systems brought about by economic and environmental pressures have led to an increasingly complex system that must operate closer to the limits of the stability. Voltage control problems are treated a some of the most fundamental and important problem in addition to the consideration of power stability. The voltage control problem becomes severe when the voltage drop occurs at the consumer end due to the reactive power imbalance between generation and demand. Voltage problems are compounded when the reactive demand increases and the reactive power is transmitted over the lines, which are already heavily loaded.

In India the loads are concentrated in and around the metropolitan cities like Mumbai, Calcutta, Delhi, and few less important cities than in rural areas. This results in non-uniform loading through out the country. Also the generation sources are generally far away from the load centers and power is transmitted through medium and long EHV lines from these generating stations to the load centers. Hence the power in our country is characterized by frequent unbalances in power generation which falls short and demand which is ever increasing, erratic outages, low system short circuit strength and lower transmission capacities and consists of radial configurations of lines connecting the distant sources of generation to the load centers. Such type of the power system is known as longitudinal power systems.(LPS)

These systems suffer from the lack of modern control centers with centralized control, advanced computational tools, trained manpower, adequate number of EHV/UHV lines etc. Moreover LPS systems commonly face financial constraints. Load growth is non-uniform and unpredictable. All these factors result in poor system reliability. Being electrically weak and running with minimum stability margin, LPS systems are very sensitive to real and reactive power changes. This leads to a series of static and dynamic problems like frequency disturbances, power and voltage oscillations etc.

In addition to EHV lines these systems consist of numerous generators, transformers, reactors etc. that are needed for supplying uninterrupted electric supply to the consumers at desired voltage level and at various locations.

The frequency is used as a measure of the balance between the generation and real load through out the power system. Transmission voltage levels indicate the balance between the supply and reactive power demand. Although under a specific operating condition, frequency is uniform throughout the power system, voltage levels can vary at different points of the transmission network due to excessive reactive lagging power demand problem.

Voltage control problem in its extreme stage may cause voltage instability, which is basically due to reactive power mismatch in power system.

The longitudinal power transmission line due to limited availability of reactive power may lead to system voltage collapse. A sudden increase in reactive power demand in such a typical system is generally due to contingency in transmission network. For example, tripping of the heavily loaded EHV line causing an increase in the load burden of the adjacent lines in order to maintain the constant system load dispatch. The additional reactive demand caused by the disturbance is generally compensated by the system‘s reactive power reserves, if available allowing the system to settle down at a reduced level of the transmission voltage. On the other hand when the reserves cannot cope up with the sudden rise of the reactive power demand, the system voltage instability occurs. This collapse takes place even though the system’s real power requirement is met and the frequency is stabilized.

IV. CAUSES OF VOLTAGE INSTABILITY

In the operation of the power system, there is a continuous control of voltage levels. For major system reactive disturbances, large demands are met with the reactive reserves with automatic control providing short-term correction of the voltage levels. Even though such measures are taken to reduce voltage instability, there are many causes, which affect the voltage levels of the system.

A. Heavy Loading of the Lines

In power systems, long lines with voltage uncontrolled buses at the receiving ends create major voltage problems during heavy loading conditions. In case of the heavy loading of the transmission line condition, high reactive power demand causes increased voltage depression due to lower charging capacity and higher reactive current intake in the induction motor loads.

B. Loss of Transmission Line

In the power system, most of the EHV networks are composed of radial transmission lines. Any loss of an EHV line in the network causes an enhancement in system reactance. A small increase in the load puts system in an unstable state if there is further increase in reactive power required by the load.

C. Shortage of Local Reactive Power

The disorganized combination of the outages and maintenance schedule may cause localized reactive power shortage and lead to voltage instability.

D. Less Reactive Dispatch Capability

This problem occurs in the system where there is common trend to use local generators to supply reactive loads and losses.

E. Tap Changing Operation of Distribution Transformer

Immediately after any EHV line tripping, there would be a considerable voltage reduction at the adjacent load centers thereby causing a significant load reduction. In case, the system does not have enough reactive power reserve, a voltage reduction following a disturbance will be observed at all segments of the network down to the loads at distribution level.

V. CALCULATIONS OF MULTIPLE LOAD FLOW SOLUTIONS FOR POWER SYSTEMS

For any given power system, voltage instability can be analysed by using static and dynamic methods. The determination of load flow distribution is one of the most important and basic power system problems. The load flow calculations provide power flows and voltages for a specified power system subject to the regulating capability of the generators, condensers and tap changing transformers as well as specified net interchange between individual operating systems. This information is essential for the continuous evaluation of the current performance of a power system and for analyzing the effectiveness of the alternative plans for system expansion to meet the increased load demand. This analysis requires the calculation of numerous load flows for both normal and emergency operating conditions. The mathematical formulation of the load flow problem results in a system of algebraic nonlinear equations. These equations cannot be solved in single step. They require iterative method. Since N-R method is advantageous to use the same has been used to analyse voltage instability problem for Pune city.

The solution obtained by N-R method is called as flat start solution. However if a load flow solution cannot be found from the iterative method it does not necessarily means that no solution exists for the power systems. Also even if solution is obtained, it does not necessarily mean that the solution is the only solution for the power system. Hence it can be understood that for a given power system, multiple load flow solutions exist. The basic algorithm for finding the multiple load flow solutions is a kind of exhaustive search from 2^{n-1} initial values. The initial values are found out by combining the solution of voltages obtained by the iterative methods and voltage obtained by solving the quadratic equation at each node. Thus the multiple load flow makes use of solution of N-R method for analyzing the problem in this paper.

The steps involved in calculation of the multiple load flow solutions are

[1] Obtain the load flow solution V^0 for the system using the Newton-Raphson method with optimum multiplier (Equation 1&2).

[2] Calculate V_p (p=2,3, ….n) at all the buses and store as V^1

[3] Make up the initial values by combining the V^0 and V^1.

[4] Compute the load flow from each initial value to obtain the multiple solutions using Newton-Raphson method with optimal multiplier.

The important equations used for obtaining the results are reproduced here for the sake of convenience. The power flow equations at bus ‘P’

$$P_p = \sum_{q=1}^{n} \{e_p (e_q G_{pq} + f_q B_{pq}) + f_p (f_q G_{pq} - e_q B_{pq}) \} \text{ ------ } 1$$

$$Q_p = \sum_{q=1}^{n} \{ f_p (e_q G_{pq} + f_q B_{pq}) - e_p (f_q G_{pq} - e_q B_{pq}) \} \text{-------}2$$

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} H & L \\ J & N \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta V/V \end{bmatrix}$$

$$\delta^{k+1} = \delta_p{}^{k} + \Delta \delta_p{}^{k}$$

$$V^{k+1} = V_p{}^{k} + \Delta V_p{}^{k}$$

The other solution V^1 is obtained from

$$G_{pp}(1+\alpha^2)e_p{}^2 + (2\alpha\beta G_{pp} + A_p + B_p\alpha)e_p + G_{pp}\beta^2 + B_p\beta$$

$$+ (G_{pp}\beta^2 + B_p\beta - P_p) = 0 \quad \text{-------3}$$

VI. ASSESSMENT OF VOLTAGE INSTABILITY THROUGH MULTIPLE LOAD FLOW SOLUTIONS

The relationship between voltage instability and multiple load flow solutions can be found out by application of different criterion.

A. Sign of the Jacobian Determinant in the Load Flow using N-R method.

(dQi/dVi) at load bus indicates the index for the steady state stability considering the reactive power sensitivity to the voltage. Then the criterion for the system stability can be represented by

dQi/dVi > 0 ----------- Stable System
dQi/dVi < 0 ---------- Unstable System
dQi/dVi = 0 -----------At the limiting stage of stability

B. Load flow sensitivity for the node injection and system parameters

The magnitude of the voltage at the bus gets affected due to variation of the reactive power injection at that bus. This variation in the voltage of the multiple load flow solutions is compared with the original solution of the system to get the feasible solution of the system. The comparison is done with the help of sensitivity matrix.

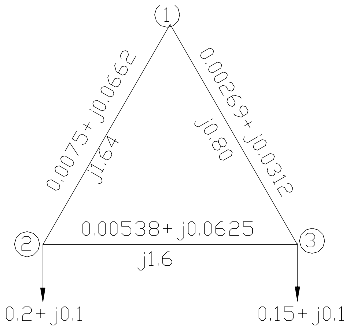
C. Stored energy of the elements L and C in the electric power system

The energy for each of the multiple solutions is given by
$E = T_L + T_C$
Then the sign of ($\partial E / \partial F$) is observed
If, $\partial E / \partial F > 0$ system is stable,
$\partial E / \partial F < 0$ system is unstable

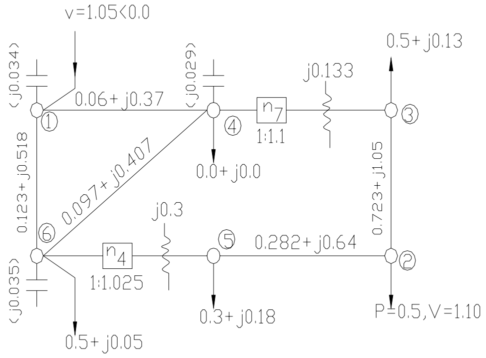
This criterion is not concerned with reactive power but with real powers.

VII. CASE STUDY

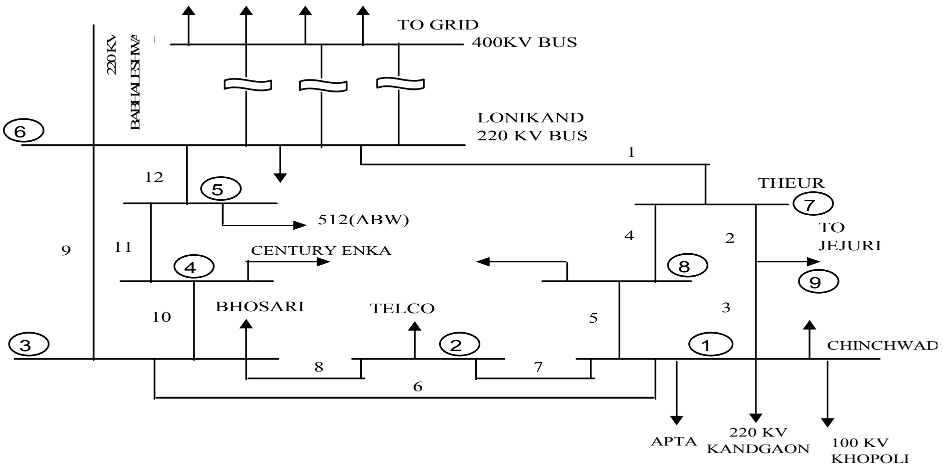
A. Klos and Kerner 3 Node System



B. Ward and Hale 6 Node System



C. 220 V Ring Main System around Pune city



The algorithm and the program can be developed for finding the multiple load flow solutions. The solutions are tested with respect to the sign of the Jacobian determinant, Watt loss and VAR loss.

For Klos and Werner 3 node system 4 solutions are found out. It can be concluded that the possible solution for stability of the system is only one.

For Ward and Hale 6 node system three solutions are obtained. However 2 are on the verge of instability

For 220 V ring main system around Pune city there are 6 solutions. They are checked for the sign of Jacobian determinant, watt loss and VAR loss.

220 kV Ring Main around Pune

Bus No	watt loss var loss	Det J	Solution V^0		Solution V^1	
			E	δ	e	f
2	0.034 -0.121	0.18×10^{36}	0.986	-0.329	0.0015	-0.0021
3			0.979	-0.34	0.0025	-0.0036
4			0.976	-0.374	0.0013	-0.0019
5			0.972	-0.08	0.0027	-0.0038
6			0.972	0.994	-0.0019	0.0199
7			0.967	-0.147	0.0069	-0.0099
8			0.983	-0.380	0.0029	-0.0053
9			0.972	-0.685	0.0058	-0.0099

Multiple Load Flow Solutions

INIT VALUE NO	BUS NO	e	δ	Det J	watt loss var loss
8	2	0.7686	-0.533	-0.15×10^{25}	8.35
	3	0.617	-0.677		50.46
	4	0.429	-1.57		
	5	0.010	-52.9		
	6	0.4812	4.998		
	7	0.556	0.737		
	8	0.805	-0.251		
	9	0.698	-0.744		
64	2	0.910	-0.308	-0.62×10^{27}	9.61
	3	0.853	-0.282		58.22
	4	0.824	-0.317		
	5	0.763	0.157		
	6	0.675	2.188		
	7	0.596	-0.368		
	8	0.0073	-67.02		
	9	0.725	-1.251		
72	2	0.738	-0.378	0.14×10^{17}	15.28
	3	0.567	-0.331		92.57
	4	0.394	-1.46		
	5	0.013	-50.05		
	6	0.288	13.26		
	7	0.278	0.668		
	8	0.0088	-60.56		
	9	0.511	-1.84		
128	2	0.874	-0.259	-0.69×10^{26}	9.29
	3	0.793	-0.182		56.45
	4	0.752	-0.201		
	5	0.663	0.441		
	6	0.533	3.479		
	7	0.420	-0.867		

INIT VALUE NO	BUS NO	e	δ	Det J	watt loss var loss
	8	0.746	-0.748		
	9	0.018	-59.25		
192	2	0.820	-0.242	$0.31x10^{18}$	15.56
	3	0.703	-0.115		94.29
	4	0.644	-0.147		
	5	0.515	0.813		
	6	0.325	7.271		
	7	0.167	-9.917		
	8	0.0094	-61.63		
	9	0.025	-59.81		

VIII. RELATIONSHIP BETWEEN REACTIVE POWER INJECTION AND VOLTAGE

If the loading conditions are varied i.e. if the reactive power injection is made in steps at particular bus, the voltage obtained is reduced for the flat start solution and increases for one of the multiple solutions against the expectation. For this solution Jacobian remains negative upto certain magnitude of Injection after which it becomes positive. At a specified injection a unique solution is obtained .After this point, no solution exists, as load flow does not converge.

Q_9	V_9^0	Det J	V_9^{128}	Det J
-0.35	0.972	$0.18x10^{36}$	0.018	$-0.69x10^{26}$
-3.0	0.922	$0.10x10^{36}$	0.060	$-0.10x10^{29}$
-6.0	0.858	$0.37x10^{35}$	0.125	$-0.97x10^{29}$
-9.0	0.778	$0.12x10^{35}$	0.205	$-0.56x10^{30}$
-12.0	0.667	$0.28x10^{34}$	0.317	$-0.22x10^{31}$
-13.0	0.605	$0.80x10^{33}$	0.379	$-0.55x10^{30}$
-13.5	0.557	$0.29x10^{33}$	0.427	$0.80x10^{31}$
-13.8	0.517	$0.23x10^{33}$	0.517	$0.23x10^{33}$

IX. EFFECT OF TRIPPING OF LINES ON VOLTAGE STABILITY

	BUS NO	e	δ	Det J	watt loss var loss
FLAT	2	0.9962	-0.3117	$0.15 X 10^{34}$	0.0661
START	3	0.8826	-1.3795		0.21812
	4	0.8828	-1.3687		
	5	0.8880	-0.9046		
	6	0.9036	0.5267		
	7	0.9100	-0.6510		
	8	0.9587	-0.6005		
	9	0.9348	-1.0538		
INT	2	0.0066	-54.28	$0.15 X 10^{34}$	12.26
VAL #1	3	0.8826	-1.3795		74.334
	4	0.8828	-1.3687		
	5	0.8880	-0.9046		
	6	0.9036	0.5267		
	7	0.9100	-0.6510		
	8	0.9587	-0.6005		
	9	0.9348	-1.0538		

It can be concluded that the start of voltage collapse begins at around 14-15 times normal reactive loading.

If the tripping of the line/s take place the voltage falls below the specified limits. Multiple load flow for Pune city in this case gives only one converging solution apart from flat start solution.

X. CONCLUSION

Multiple load flow is one of the static methods for studying the phenomenon of voltage instability. The relationship between voltage instability and multiple load flow solutions is judged by applying different criterion and feasibility of the solutions is verified. The variation in the bus voltages is observed under different contingencies like heavy loading on one of the bus, tripping of the transmission line etc. Under such conditions start of the voltage collapse can be observed.

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S.N.Chaphekar-She received B.E. (Electrical) from University of Pune 1994 and M.E.(Power Systems) from University of Pune in 1998. She is working as Assistant Professor in the Department of Electrical Engineering in Progressive Education Society's Modern College of Engineering, Pune. She has an industrial experience of 1 year and teaching experience of 10 years. She is a member of IEEE and life member of Indian Society for Technical Education. Her areas of interest are Electrical Machines and Power System Analysis.

V.V.Khatavkar-She received B.E. (Electrical) from University of Pune 1987 and M.E.(Power Systems) from University of Pune in 1998. She is working as Assistant Professor in the Department of Electrical Engineering in Progressive Education Society's Modern College of Engineering, Pune. She has an industrial experience of 6 months and teaching experience of 17 years. She is a member of IEEE and life member of Indian Society for Technical Education. Her areas of interest are Electrical Machines and Power System Analysis.