Chapter-9

VOLTAGE INSTABILITY AND CASCADED FAILURE

9.1 Introduction

Power systems fall victim to two kinds of instability viz. power angle instability and voltage instability [70,93]. Power angle instability is caused by mismatch of active power between the electrical and the mechanical ports. Voltage instability is caused by mismatch of reactive power generation and absorption [71,72]. Unacceptable voltage sags are created by the mismatch [94]. Short term voltage instability has effects on synchronous and induction machines [75].

Power angle instability, both transient and dynamic, have received large scale attention of the power system researchers, but not voltage instability which is of comparatively recent origin and is a result of large scale interconnections of long EHV lines. Recently many eminent researchers have concentrated on this phenomenon and its adverse effects on the system [64,67,68]. A method for evaluating composite power system vulnerability to cascading failures has been proceeded by C. Quan et al [65]. Regular load flow studies should be conducted to reduce the vulnerability of the system [77].

Almost all electrical loads, setting aside a few exceptions, absorb lagging VAR. Hence, under normal operating conditions, the power systems run at lagging p.f. The over-all lagging VAR demand is met by the alternators. The high tension transmission lines are generally more capacitive than inductive. They act as VAR-generators and at lean load hours push the system p.f. to leading zone, reducing the power angle margin. Verbie has proposed a protection scheme against voltage collapse using local phasors [64].

Load flow studies on large systems at peak and lean hours reveal the possibility of voltage collapse for specified network configurations and loading conditions. A load-dependent model is commonly used. Recently some works dynamic load-models for voltage stability studies have been reported [64,69,104].

At any cost, the voltage profile of the system is found to be unacceptably poor. To avoid such unhappy situation, VAR compensators are interposed at vulnerable points. These points are found out by load-flow studies. They may be either capacitive, used to improve the p.f. at peak hours, or inductive, to partially offset the VAR generation caused by long lines and avoid the VAR-in phenomenon. Series compensation is used to reduce the voltage drop in the line and to increase the power flow [104].

9.2 Voltage stability defined

A power system should be operationally stable at all times, fulfilling all criteria and at the same time be secure against any probable contingency. Now-a-days, the power systems are being operated closer to their stability limits for economic reasons and environmental constraints. Maintenance of stable and secure operation of a power system under such stringent conditions is a very important and challenging issue.

Recently, the power system researchers and planners are considering voltage instability as a major source of power system insecurity. It is a phenomenon in which the receiving end voltage falls much below its normal value and is not restored even in the presence of mechanisms such as VAR compensators, or continues to oscillate against sudden disturbances due to poor damping. Voltage collapse is the process by which the voltage profile falls to a low, unacceptable value due to cumulative actions [63,92]. Dynamic optimization of reactive power planning should be made in order to initiate slow recovery voltage and to avoid a grid collapse [80]. The assessment should be made using dynamic load models for accurate prediction [81,82].

Once upon a time, this phenomenon was associated with weak systems and with long lines. But now this problem exists even in highly developed networks due to heavier loading. The main factors causing voltage instability in a power system are now well-explored and well-understood. The methods of voltage stability analysis are well-developed- both conventional methods [93] and soft-computing techniques [34,124].

9.3 Classification of voltage stability

Voltage stability is classified as short-term and long-term according to the time span of the disturbance. Automatic voltage regulators (AVR) and excitation control, turbine and its governor influence the short-term dynamics. The time span is only a few seconds. Induction motors, electronically operated loads and HVDC lines are also in this category. For a stable system, the short-term disturbance dies away and the system gradually enters into a slow long-term dynamics. Components influencing the long-term dynamics are transformer tap changers, limiters, boilers etc. This time frame is from a few minutes to tens of minutes. A long-term voltage stability problem is mainly due to large electrical distance between the generator and the load –it depends on the topology of the power system [33].

There is little scope for the operator to intervene in the process of transient voltage instability- he can only rely on the automatic emergency devices incorporated in the system to avoid voltage instability. The corrective actions are automatically taken by protective devices which keep the larger part of the system in operation by isolating the unstable part.

Long-term voltage instability problems generally occur in heavily loaded systems where the electrical distance is large between the generator and the load. The instability may be triggered by high power imports from remote generating stations, a sudden large disturbance, or a large load buildup (during morning or evening peak). Operator intervention is possible if the time scale is long. Reactive power compensation or load shedding may prevent this type of voltage instability, if timely applied [32,72].

Asynchronous links are commonly used now-a-days to avoid large scale synchronous coupling and the associated stability problems. Though, it improves the system damping and enhances power angle stability, highly stressed HVDC links degrades the transient voltage stability [97,104].The tools and techniques used to analyze the voltage stability are also different for small and large-disturbance. Steady state voltage stability deals with small perturbation, In such cases the system can be analyzed by linearizing around the quiescent point. Steady state stability analysis helps to get a qualitative picture of the system e.g. the stress on the system or the margin against instability.

Large-disturbance stability deals with phenomena like loss of generation, loss of load or loss of transmission line. To analyze the large-disturbance stability, a much longer time-frame has to be chosen and the system dynamics is to be computed for the whole time frame. It is pre-requisite to develop a suitable model of the system for detailed dynamic analysis over a long time [68].

9.4 Tools for voltage stability analysis

There are different methods for carrying out a steady state voltage stability analysis. The conventional methods can be broadly classified into the following types[33,89].

i. P-V curve method.

This is one of the widely used methods of voltage stability analysis. This gives the available amount of active power margin before the point of voltage instability. For radial systems, the voltage of the critical bus is monitored against the changes in real power consumption. For large meshed networks, P can be the total active load in the load area and V can be the voltage of the critical or representative bus. Real power transfer through a transmission interface or interconnection also can be studied by this method.

ii. V-Q curve method and reactive power reserve.

The V-Q curve method is one of the most popular ways to investigate voltage instability problems in power systems during the post transient period. Unlike the P-V curve method, it doesn’t require the system to be represented as two-bus equivalent. Voltage at a test bus or critical bus is plotted against reactive power at that bus. A fictitious synchronous generator with zero active power and no reactive power limit is connected to the test bus. The power-flow program is run for a range of specified voltages with the test bus treated as the generator bus. Reactive power at the bus is noted from the power flow solutions and plotted against the specified voltage. The operating point corresponding to zero reactive power represents the condition when the fictitious reactive power source is removed from the test bus.

Voltage security of a bus is closely related to the available reactive power reserve, which can be easily found from the V-Q curve of the bus under consideration. The reactive power margin is the MVAR distance between the operating point and either the nose point of the V-Q curve or the point where capacitor characteristics at the bus are tangent to the V-Q curve. Stiffness of the bus can be qualitatively evaluated from the slope of the right portion of the V-Q curve. The greater the slope is, the less stiff is the bus, and therefore the more vulnerable to voltage collapse it is. Weak busses in the system can be determined from the slope of V-Q curve.

iii. Methods based on singularity of power flow Jacobian matrix at the point of voltage collapse.

The power flow Jacobian matrix becomes singular at the point of voltage collapse. A number of methods have been developed on this basis. The modal analysis of the Jacobian matrix is one of the most popular methods in this group [33,34].

iv. Continuation power flow method.

It is numerically difficult to obtain a powerflow solution near the voltage collapse point, since the Jacobian matrix becomes singular at this point. Continuation power flow is a technique by which the power flow solutions can be obtained near to or at the point of voltage collapse.

9.5 Static Voltage Stability

This is a stability phenomenon, where the power system loses its ability to control load bus voltage due to various reasons. This phenomenon can lead to failure of the total or partial power system due to interventions of various control and protection actions.The reasons for voltage instability could be [69,73,92] any one of the following:

- Failure to provide necessary power support to the loads as a consequence of power transfer limit. The power transfer limit is determined not only by the bus voltage phase angle, but also by bus voltage magnitude
- Failure to meet power requirements due to equipment reaching their control and operating limits. Examples are transformer tap limits, generator reactive power supply capabilities.
- Inconsistency in the load power requirements as function of bus voltage and power supply characteristics.

9.6 Some recent works in this area

S Mei, Y. Ni, G. Wang, S. Wu, in one of their papers, developed a novel model with AC-OPF and AC grid upgrade to study the cascading failures and blackouts in power systems from the perspective of self-organized criticality [73]. This model overcomes some shortcomings of existing blackout models. The proposed model contains two types of dynamics, one is fast dynamics which simulates the serial blackouts in power systems, the other is slow dynamics which reflects the tendency of the power systems time evolution. This model also has voltage stability analysis function and can reveal critical characteristics from reactive power and voltage viewpoint. Simulation results on IEEE 118-bus system with this model showed that the fast dynamics could capture the cascading process Furthermore, the voltage stability criticality status could be detected from the eigenvalue with the smallest magnitude through reactive power and voltage relevant nodal analysis.

Many researchers presented papers on **c**ascading failure which is one of the main causes of blackout [66,83]. The authors proposed an integrated approach to assess the risk of power system cascading failure considering hidden failures in protection system. Two probability models of protection system hidden failures were used to demonstrate their effects on power system risk. The mechanism and scheme of protection system were analyzed for their contribution to cascading failures after occurrence of the fault. The risk of power system cascading failure was assessed by bus isolated risk, load isolated risk, grid break-up risk and integrated system risk. On this basis, the preventive measures to reduce the risk of cascading failure were put forward. A Monte Carlo simulation approach was used and the software for prevention and assessment of the risk of cascading failure was developed. The results of applying the proposed method to IEEE 118-bus system illustrated the feasibility of this method and effectiveness of the developed software [93].

I. Dobson, A. Carreras David E., have discussed in a paper, the probabilistic nature of load-dependent cascading failure of a complex power system with many components [82]. They have developed an analytically solvable probabilistic model in which the failing components interact with other components, thereby increasing their load and hence their chances of failure. The generalized model has been approximated as a saturating branching process and this has led to a criticality condition for the propagation of cascading failure. It has been shown that the probability of failure depends on the size of the sample-the criticality condition shows how the component interactions radically control the proximity to catastrophic failure. The transmission system design to avoid such cascading failure leading to blackouts has also been discussed.

9.7 Case-studies

The case studies have been made on a fictitious small power system. The line data have been kept unchanged for all the cases. The bus-data have been gradually changed towards more and more reactive power mismatch. Load flow study has been made for three gradually worsening conditions. The computer print-outs of the study converted to word-format are given below.

9.7.1 Load Flow Study of a fictitious 6-bus system

A fictitious 6-bus system is being considered in which no of interconnections = 7. The line data for the system in p.u. is given in table 9.1

Table 9.1

Line data for 6-bus system

Node- P	Node-Q	R	X_L	Y/2
1	4	0.080	0.370	0.015
1	6	0.123	0.518	0.021
2	3	0.723	1.050	0.000
2	5	0.282	0.640	0.000
3	4	0.000	0.133	0.000
4	6	0.097	0.407	0.015
5	6	0.000	0.300	0.000

where P,Q: Node numbers; $R+jX_L$ = Series impedance of the line; Y/2 = Capacitive susceptance at either end for π-representation.

Load-flow studies will be conducted on this fictitious system for three different loading conditions. All the loadings are characterized by reactive power mismatch.

9.7.2 Bus Data File, condition-I (bad) towards failure.

The bus-data have been chosen in a manner such that the system is in the verge of collapse i.e. by implementing reactive power mismatch. The bus-data for condition-I is given in table 9.2

Table 9.2

Bus-data for condition-I

Power Station	Type	No	Voltage	P_L	Q_L	P_G	Q_G	Q_{GMAX}	Q_{GMIN}
North	SB	1	1.06	0.00	0.00	0.90	0.00	0.60	-0.20
South	GB	2	1.05	0.00	0.00	0.50	0.00	0.20	0.00
East	LB	3	1.00	0.35	0.13	0.00	0.00	0.00	0.00
Mid	LB	4	1.00	0.25	0.10	0.00	0.00	0.00	0.00
Isle	LB	5	1.00	0.30	0.18	0.00	0.00	0.00	0.00
West	LB	6	1.00	0.50	0.05	0.00	0.00	0.00	0.00

The Gauss-Siedel iterative method has been used for the load-flow study. The solution has been obtained in 45 iterations using acceleration factor of 1.2 for both real and imaginary parts. The load flow study converges but the bus-voltages are unacceptably low. Voltage cannot be kept at the Generator-bus of the South station. So it has been considered as a load bus to get convergence.The voltages & power angle for different buses have been given in table 9.3

. **Table 9.3**

Voltage profile for condition-I

No	Power Station	Type	Voltage	Power angle
1	North	SB	1.0600	0.0000
2	South	GB (LB)	0.8788	3.7728
3	East	LB	0.8714	-13.199
4	Mid	LB	0.8268	-11.109
5	Isle	LB	0.7503	-13.465
6	West	LB	0.8115	-13.307

The bus voltages are below 0.95 p.u. except for the slack bus. The system is going towards collapse. So the voltage profile is unacceptable. The Line flow calculation is given in table 9.4

Table 9.4

Line flow for condition-I

P(1,4) = 0.5832	Q(1,4) = 0.5694	P(1,6) = 0.4861	Q(1,6) = 0.4140
P(2,3) = 0.1622	Q(2,3) = -0.0737	P(2,5) = 0.3379	Q(2,5) = 0.0739
P(3,2) = -0.1325	Q(3,2) = 0.1168	P(3,4) = -0.2174	Q(3,4) = 0.3252
P(4,1) = -0.5345	Q(4,1) = -0.3714	P(4,3) = 0.2174	Q(4,3) = -0.3008
P(4,6) = 0.0671	Q(4,6) = 0.0061	P(5,2) = -0.2942	Q(5,2) = 0.0253
P(5,6) = -0.0057	Q(5,6) = -0.1570	P(6,1) = -0.4393	Q(6,1) = -0.2542
P(6,4) = -0.0664	Q(6,4) = -0.0234	P(6,5) = 0.0057	Q(6,5) = 0.1698

Total active power loss in the line, P_{LOSS} = 0.1696

Total reactive power loss in the line, Q_{LOSS} = 0.5200

9.7.3 Bus Data File, condition II (worse)- towards failure.

In the next case study more reactive power mismatch has been implemented. The modified bus-data file is given in table 9.5

Table 9.5

Bus-data file for condition-II

Power Station	Type	No	Voltage	P_L	Q_L	P_G	Q_G	Q_{GMAX}	Q_{GMIN}
North	SB	1	1.06	0.00	0.00	0.90	0.00	0.60	-0.20
South	GB	2	1.05	0.00	0.00	0.50	0.00	0.20	0.00
East	LB	3	1.00	0.35	0.15	0.00	0.00	0.00	0.00
Mid	LB	4	1.00	0.25	0.10	0.00	0.00	0.00	0.00
Isle	LB	5	1.00	0.30	0.18	0.00	0.00	0.00	0.00
West	LB	6	1.00	0.50	0.10	0.00	0.00	0.00	0.00

In this case, the reactive load of station **EAST** has been increased from 0.13 to 0.15 p.u. and the reactive load of station **WEST** has been increased from 0.05 to 0.10 p.u. This time the solution is obtained in 115 iterations

The voltages and the power angles for different buses for this changed condition are given in table 9.6

Table 9.6

Voltage profile for condition-II

No	Power Station	Type	Voltage	Power angle
1	North	SB	1.0600	0.0000
2	South	GB (LB)	0.8048	6.3452
3	East	LB	0.8097	-14.128
4	Mid	LB	0.7786	-11.678
5	Isle	LB	0.6700	-14.669
6	West	LB	0.7494	-14.147

The corresponding line flow calculation is furnished in table 9.7. It may be noted that both active and reactive power loss have increased in this case.

Table 9.7

Line flow for condition-II

P(1,4) = 0.6074	Q(1,4) = 0.7043	P(1,6) = 0.5081	Q(1,6) = 0.5378
P(2,3) = 0.1638	Q(2,3) = -0.0773	P(2,5) = 0.3362	Q(2,5) = 0.0773
P(3,2) = -0.1272	Q(3,2) = 0.1305	P(3,4) = -0.2228	Q(3,4) = 0.2129
P(4,1) = -0.5441	Q(4,1) = -0.4375	P(4,3) = 0.2228	Q(4,3) = -0.1954
P(4,6) = 0.0713	Q(4,6) = 0.0310	P(5,2) = -0.2844	Q(5,2) = 0.0403
P(5,6) = -0.0156	Q(5,6) = -0.1819	P(6,1) = -0.4454	Q(6,1) = -0.3088
P(6,4) = -0.0702	Q(6,4) = -0.0440	P(6,5) = 0.0156	Q(6,5) = 0.2036

Total active power loss in the line= 0.2156

Total reactive power loss in the line= 0.6927

It may also be noted that the bus voltages have further deteriorated. The lowest bus-voltage has now come down to 0.67 p.u. However the program has converged to a solution.

9.7.4 Bus Data File, condition-III (worst) towards failure.

In the next case study still more reactive power mismatch has been implemented. The modified bus-data file is given in table 9.8

Table 9.8

Bus data file for condition-III

Power Station	Type	No	Voltage	P_L	Q_L	P_G	Q_G	Q_{GMAX}	Q_{GMIN}
North	SB	1	1.06	0.00	0.00	0.90	0.00	0.60	-0.20
South	GB	2	1.05	0.00	0.00	0.50	0.00	0.20	0.00
East	LB	3	1.00	0.35	0.152	0.00	0.00	0.00	0.00
Mid	LB	4	1.00	0.25	0.10	0.00	0.00	0.00	0.00
Isle	LB	5	1.00	0.30	0.18	0.00	0.00	0.00	0.00
West	LB	6	1.00	0.50	0.112	0.00	0.00	0.00	0.00

In the next stage, reactive load of station EAST has been increased to 0.152p.u.and the load of station WEST has been increased to 0.112 p.u. This time the solution is obtained in 125 iterations with the same acceleration factors. The voltages & power angle for different buses for this changed data are given in table 9.9

Table-9.9

Voltage profile for condition-III

No	Power Station	Type	Voltage	Power angle
1	North	SB	1.0600	0.0000
2	South	GB (LB)	0.7698	7.8276
3	East	LB	0.7831	-14.654
4	Mid	LB	0.7575	-12.014
5	Isle	LB	0.6320	-15.428
6	West	LB	0.7219	-14.649

Now, the voltage profile has further worsened. The lowest bus voltage is now only 0.632. The line flow calculation for this condition is given in table 9.10. It is to be noted that the active and reactive power losses have increased further.

Table 9.10

Line flow for condition-III

P(1,4) = 0.6204	Q(1,4) = 0.7631	P(1,6) = 0.5200	Q(1,6) = 0.5928
P(2,3) = 0.1647	Q(2,3) = -0.0796	P(2,5) = 0.3353	Q(2,5) = 0.0798
P(3,2) = -0.1239	Q(3,2) = 0.1389	P(3,4) = -0.2260	Q(3,4) = 0.1711
P(4,1) = -0.5497	Q(4,1) = -0.4615	P(4,3) = 0.2260	Q(4,3) = -0.1552
P(4,6) = 0.0737	Q(4,6) = 0.0416	P(5,2) = -0.2787	Q(5,2) = 0.0485
P(5,6) = -0.0212	Q(5,6) = -0.1942	P(6,1) = -0.4488	Q(6,1) = -0.3275
P(6,4) = -0.0724	Q(6,4) = -0.0523	P(6,5) = 0.0212	Q(6,5) = 0.2222

Total active power loss in the line = 0.2406

Total reactive power loss in the line = 0.7874

All attempts to conduct load-flow study with additional reactive power burden have become unsuccessful. It has been noted that any further increase in reactive loading gives rise to voltage collapse. This is the limiting point[64,104].

9.8 Conclusion

Voltage stability of a power system is more important than its power angle stability. Modern power systems operate with low margins for economic reasons. The transmission lines are heavily loaded. Voltage instability occurs in heavily loaded lines, particularly if there be reactive power mismatch. The drop and rise in voltage along a transmission line depends much more on the line reactance and charging susceptance than on resistance or leakance. The effect of leakance is so small that very often it is neglected. Also, planned load flow could not be made for Indian power system due to various reasons. Ithas given rise to undesirable amount of reactive power flow, leading to unacceptable voltage profile for the system [138].

A no. of case-studies has been made on a fictitious power system with altogether 6-buses and 7 interconnections. Two of them are generator buses. One of them has been taken as the slack bus. Heavy active/reactive power loading has been made on this line. Also reactive power mismatch has been intentionally introduced into the system. Three case-studies have been made- one for bad, another worse and another worst possible conditions of reactive power mismatch. Load-flow studies conducted for these conditions have revealed that the voltage profile is unacceptable (all bus voltages are below 0.95 p.u.) and the profile worsen with more and more reactive power loading. This phenomenon has to be remembered while planning load flow for a system.

-------- x --------