P-V, Q-V Curve – A Novel Approach for Voltage Stability Analysis

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ABSTRACT
Power transmission capability has traditionally been limited by either synchronous (or rotor angle) stability or by thermal loading capability of transmission line and equipment. Voltage stability is an important factor, which needs to be taken into consideration during the planning and operation of electrical power systems in order to avoid voltage collapse and subsequently partial or full system blackout. From the voltage stability analysis point of view, system operators need to know not only the severity of their system, but also the mechanisms that cause voltage instability. This paper presents study of different methods and techniques used to improve the voltage stability of electrical power systems. Conventional P-V curve and Q-V curve methods are taken as a basic analysis tool.

Keywords
Voltage stability, Voltage Collapse, P-V Curve, Q-V curve

1. INTRODUCTION
Security of power systems operation is gaining ever increasing importance as the system operates closer to its thermal and stability limits. Power system stability –the most important index in power system operation may be categorized under two general classes relating to the magnitude and to the angle of bus voltages. Power system voltage stability involves generation, transmission and distribution. It mainly focuses on determining the proximity of bus voltage magnitudes to predetermined and acceptable voltage magnitudes whereas angle stability focuses on the investigation of voltage angles as the balance between supply and demand changes due to occurrences of a fault or disturbances in the system. Voltage stability is slowly varying phenomenon while angle stability is relatively faster and deals with systems dynamics described mathematically by differential equations of generators in the systems.

Voltage stability concerned with the ability of a power system to maintain acceptable voltages at all buses in the system under normal conditions and after being subjected to a disturbance. A power system at a given operating state is voltage stable if, following the disturbances, voltages near loads are identical or close to the predisturbance values. A power system is said to have entered a state of voltage instability when a disturbance results in a progressive and uncontrollable decline in voltage. Following voltage instability, a power system may undergo voltage collapse, if the post disturbance equilibrium voltages near loads are below acceptable limits. Voltage collapse is also defined as a process by which voltage instability leads to very low voltage profile in a significant part of the system. Voltage collapse may be total (blackout) or partial. The main cause of voltage collapse may be due to the inability of the power system to supply the reactive power or an excessive absorption of the reactive power by the system itself.

The present transmission network are getting more and more stressed due to economic and environmental constraints .With growing size of power system networks, greater emphasis is being given to the study of voltage stability. The voltage stability can be studied either on static (slow time frame) or dynamic (long time frame) considerations[6,8]. The static voltage stability methods are mainly depends on steady state model in the analysis, such as power flow model or a linearized dynamic model. Dynamic stability analysis describes the use of a model characterized by nonlinear differential and algebraic equations which include generators dynamics, tap changing transformers etc. Since the steady state analysis only involves the solution of algebraic equations it is computationally less extensive than dynamic analysis. Thus, lot of work is carried out to determine voltage stability on static analysis method. Several methods have been used in static voltage stability analysis such as the P-V and Q-V curves, model analysis, optimization method, continuation load flow method, etc.

In this paper, various methods for improving voltage stability have been studied and a two bus system has been investigated for the purpose of voltage stability of power system using one of the basic static analysis method- conventional P-V,Q-V curve method.

2. POWER SYSTEM STABILITY
2.1 Basic Concepts And Definitions
Power system stability may be defined as that property of a power system that enables it to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to disturbances[10]. Traditionally the stability problem has been the rotor angle stability, i.e. maintaining synchronous operation. Instability may also occur without loss of synchronism in which case the concern is the control and stability of voltage. Power system is voltage stable if voltages after a disturbance are close to voltages at normal operating conditions. A power system becomes unstable when voltages uncontrollably decrease due to outage of equipment, increment of load, etc.

For good understanding of the stability problem, Power system stability is broadly classified as rotor angle stability-steady state stability and transient state stability, frequency stability and voltage stability-short term and long term voltage stability and it is load driven.

2.2 Voltage Stability And Rotor Angle Stability
Voltage stability and rotor angle stability are interlinked. Transient voltage stability is often interlinked with transient rotor angle stability, and slower forms of voltage stability are

interlinked with small disturbance rotor angle stability. However, rotor angle stability as well as Voltage stability is affected by reactive power control. Voltage stability is basically load stability and rotor angle stability is basically generator stability.

It can be said that, if there is voltage collapse at a point in a transmission system remote from loads, it is an angle stability problem. If the voltage collapses in a load area it is probably mainly a voltage instability problem.

3. POWER SYSTEM VOLTAGE STABILITY

Voltage is considered as an integral part of power system and is considered as an important aspect in system stability and security. In recent years the problem of voltage instability got a considerable attention because of many voltage collapse incidents.

3.1 Basic Concepts Of Voltage Stability

Voltage stability is the ability of a power system to maintain acceptable voltages at all buses in the system under normal conditions and after being subjected to a disturbance[11]. Power system is unstable when voltage decreases beyond particular limit because of outage of equipment, increase in load or decrease in controller's action. Voltage stability can be classified into two subclasses –

- Large disturbance voltage stability: It is mainly concern with system ability to control voltage after large disturbance like system fault, loss of generators or circuit contingencies occur.
- Small disturbance voltage stability: It is mainly concern with the system ability to control voltages following small disturbances like change in load.

3.2 Voltage Collapse

Voltage collapse typically occurs in power system which are usually heavily loaded, faulted and/or have reactive power shortages. Voltage collapse is system instability and it involves large disturbances (including rapid increase in load or power transfer) and mostly associated with reactive power deficits.

Voltage collapse is the process by which the sequence of events accompanying voltage instability leads to a low unacceptable voltage profile in a significant part of system. The main factors causing voltage instability are –

1) The inability of the power system to meet demands for reactive power in the heavily stressed system to keep voltage in the desired range

2) Characteristics of the reactive power compensation devices

3) Action and Coordination of the voltage control devices

4) Generator reactive power limits

5) Load characteristics

6) Parameters of transmission lines and transformer.

3.3 General Characterization Of Voltage Collapse

Voltage collapse may be characterized as follows:

1) The initiating event may be due to a variety of causes. Such as natural increase in system load or large sudden disturbances.

2) The heart of the problem is the inability of the system to meet its reactive demands.

3) The voltage collapse generally manifests itself as a slow decay of voltage.

4) Voltage collapse is strongly influence by the following significant factors as:

- Large distances between generation and load
- ULTC action during low voltage condition
- Unfavorable load characteristics
- Poor coordination between various control and protective system

5) The voltage collapse problem may be aggravated by excessive use of shun capacitor compensation.

4. VOLTAGE STABILITY ANALYSIS

The analysis of voltage stability[10] for a given system state involves the examination of two aspects:
1) Proximity to voltage instability: How close is the system to voltage instability?
2) Mechanism of voltage instability: How and why does thus instability occur? what are the key factors contributing to instability? What are the voltage weak areas? What measures are most effective in improving voltage stability?

Voltage instability is a non linear phenomenon. It is impossible to capture the phenomenon as a closed form solution. There are various types of dynamics associated with the problems, hence many aspects of the problem can be effectively analyzed by using static as well as dynamic analyzing techniques.
Following a disturbance, power simulations provide a method of study of a voltage instability problem. Two sets of graphs are used to study voltage instability. They are P-V curves and Q-V curves[7].

4.1 P-V Curve Analysis

P-V curve analysis is use to determine voltage stability of a radial system and also a large meshed network. For this analysis P i.e. power at a particular area is increased in steps and voltage (V) is observed at some critical load buses and then curves for those particular buses will be plotted to determine the voltage stability of a system by static analysis approach.
To explain P-V curve analysis let us assume two-bus system with a single generator, single transmission line and a load, as shown in Figure 1.

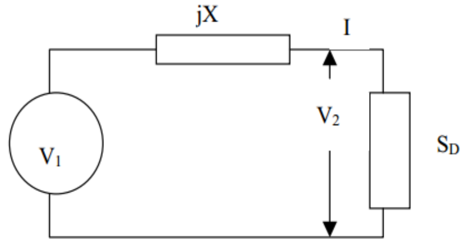

Fig 1: Two bus representation model

P-V curves are useful in deriving how much load shedding should be done to establish prefault network conditions even with the maximum increase of reactive power supply from various automatic switching of capacitors or condensers.

Here, the complex load assume is $S_{12} = P_{12} + jQ_{12}$ with V1 is the sending end voltage and V2 is receiving end voltage and $\cos\theta$ is load power factor.

From the figure,

$$S_{12} = P_{12} + jQ_{12}$$

$$P_{12} = |V_1|^2 G - |V_1||V_2|G\cos(\theta_1 - \theta_2) + |V_1||V_2|B\sin(\theta_1 - \theta_2)$$

$$Q_{12} = |V_1|^2 B - |V_1||V_2|B\cos(\theta_1 - \theta_2) - |V_1||V_2|G\,sin(\theta_1 - \theta_2)$$

Let G=0, Then

$$P_{12} = |V_1||V_2|B\sin(\theta_1 - \theta_2)$$

$$Q_{12} = |V_1|^2 B - |V_1||V_2|B\cos(\theta_1 - \theta_2)$$

Now we can get ,

$$S_D = P_D + jQ_D = -(P_{21} + jQ_{21})$$

$$P_D = -P_{21} = -|V_1||V_2|B\sin(\theta_2 - \theta_1)$$

$$= |V_1||V_2|B\sin(\theta_1 - \theta_2)$$

$$Q_D = -Q_{21} = -|V_2|^2 B - |V_1||V_2|B\cos(\theta_2 - \theta_1)$$
$$= -|V_2|^2 B + |V_1||V_2|B\cos(\theta_1 - \theta_2)$$

Define $\theta_{12} = \theta_1 - \theta_2$,

$$P_D = |V_1||V_2|B\sin\theta_{12}$$

$$Q_D = -|V_2|^2 B + |V_1||V_2|B\cos\theta_{12}$$

From figure we can also express,

$$S_D = |V_2||I|e^{j\emptyset}$$

$$= |V_2||I|(\cos\emptyset + j\sin\emptyset)$$
$$= P_D(1 + j\tan\emptyset)$$
$$= P_D(1 + j\beta),\ \ Where\ \beta = \tan\emptyset$$
$$Now, Q_D = P_D\beta = -|V_2|^2 B + |V_1||V_2|B\cos\theta_{12}$$

Equating the expressions for P_D and Q_D, we have

$$(|V_2|^2)^2 + \left[\frac{2P_D\beta}{B} - |V_2|^2 + \frac{P_D}{B^2}[1 + \beta^2]\right] = 0$$

This is a quadratic equation in $|V_2|^2$, Eliminating θ_{12} and solving the second order equation ,we get

$$|V_2|^2 = \frac{1 - \beta P_D \pm \sqrt{[1 - P_D(P_D + 2\beta)]}}{2}$$

As seen from equation, the voltage at the load point is influenced by the power delivered to the load, the reactance of the line, an\d the power factor of the load. The voltage has two solutions; the higher one is the stable solution. The load at which the two solutions have one value indicates the steady state voltage collapse point. Using this equation we have plotted P-V curve using MATLAB program[9] for various power factors, lagging as well as leading as shown in fig.2.

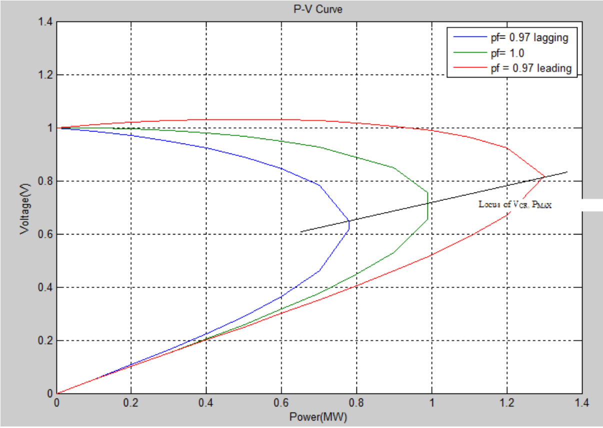

Fig 2: P-V Curve for various load power factors

The dotted line can be shown by connecting nose points of the P-V curve. Only the operating points above the critical points represent satisfactory operating condition. At the knee of the P-V curve, the voltage drops rapidly with the increase in loads. P-V curves are useful for conceptual analysis of voltage stability especially for radial systems.

4.2 Q-V Curve Analysis

Q-V curve is the relationship between the reactive power support (Q) and receiving end voltage (V_2) for different values of active power P [3].

We consider our simple (lossless) system again, with the equati ons,

$$P_D = |V_1||V_2|B\sin\theta_{12}$$

$$Q_D = -|V_2|^2 B + |V_1||V_2|B\cos\theta_{12}$$

Now, again assume that V_1=1.0, and for a given value of P_D and V_2, compute $\theta_{12}$from the first equation, and then Q from the second equation. Repeat for various values of $V_2$to obtain a Q-V curve for the specified real load P_D. The Q-V curve can be obtained from the P-V curve as shown in figure 3.

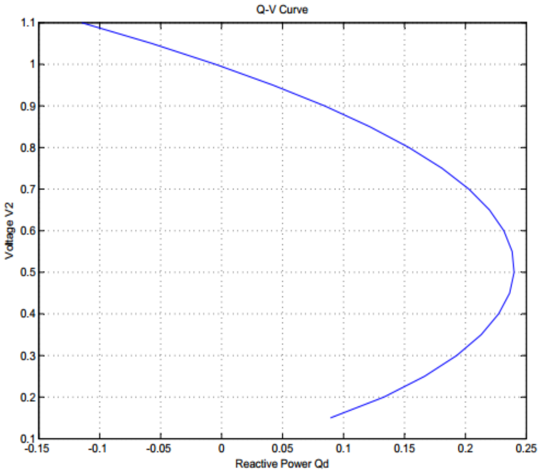

Fig 3: V-Q curve

One of the information that can be accessed from the curves is the sensitivity of the loads to the reactive power sources.

Thus P-V curve play a measure role in understanding and explaining voltage stability. However, it is not necessarily the most efficient way of studying voltage stability since it requires a lot of computations for large complex networks.

5. METHODS OF IMPROVING VOLTAGE STABILITY

The power system voltage instability can be improved using the following methods

1. Generator AVRs
2. Under-Load Tap Changers
3. Load shedding during contingencies
5. Reactive Power Compensation

5.1 Generator AVRs

Generator AVRs are the most important means of voltage control in a power system. Under normal conditions the terminal voltages of generators are maintained constant. When there exist voltage stability problem due to reactive power demand, generators can supply more power to system in the range of field current limits. AVRs act on the exciter side of synchronous generators. The exciter supplies the field voltage in the field winding. Within the capability limits of the generator, it can regulate the bus voltage.

5.2 Under-Load Tap Changers

Transformers enable utilization of different voltage levels across the system. In addition to voltage transformation, transformers are often used for control of voltage and reactive power flow. From the power system aspect, changing the ratio of transformer is required to compensate for variations in system voltages. The ULTC is used when the ratio has to be changed frequently due to simultaneous changes in load such as- daily variations. Therefore, in order to maintain voltage stability ULTCs are often used. Generally, taps allow the ratio to vary in the range of ±10% to ±15%.

5.3 Load Shedding During Contingencies

The risk of collapse due to voltage instability can be reduced by load shedding. Under voltage load shedding during contingencies is the cheapest way to prevent voltage instability. Load shedding may be manual or automatic. System planners conduct numerous studies using V-Q curve and other analytical method to determine the amount of load that needs to be sheds to retain voltage stability during contingencies. Voltage collapse is most probable under heavy load conditions. Therefore, amount of load to be shed depends on system load peak and generation sources.

5.4 Reactive Power Compensation

Voltage instability is basically the effect of reactive power imbalance between generation and demand. Load bus is most susceptible to voltage instability. Therefore, localized reactive support may be use to improve voltage stability. The following methods are use to give the reactive power support:

- Shunt Capacitors
- Series Capacitor
- shunt reactors
- synchronous condensers
- Static Var Systems
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Shunt capacitors are used to compensate for the reactive power requirement in transmission and to ensure acceptable voltage levels during heavy loading conditions. Capacitor banks of appropriate sizes are connected either directly to bus or tertiary winding of the main transformer. Switching of capacitor banks provides a convenient means of controlling transmission bus voltages. They are normally distributed throughout the system in order to minimize losses and voltage drops. Series capacitors are connected in series with the transmission line to compensate for the inductive reactance of the line. This reduces the reactance of the transmission line between the generation and load bus. Therefore, the maximum power that can be transferred increases and it reduces the reactive power requirement of the line. Since series capacitors permit economical loading of long transmission lines they are used frequently in power systems. Shunt reactors are used to compensate for the effects of line capacitance. They absorb reactive power from system. In case of unacceptable voltage rises they are activated so as to limit voltage rise. A synchronous condenser is a synchronous machine running without a prime mover or a mechanical load. By controlling the field excitation, it can be made to either generate or absorb reactive power. They can automatically adjust the reactive power output to maintain constant terminal voltage with a voltage regulator.

Static var compensators are shunt-connected static generators or absorbers whose outputs are varied so as to control specific parameters of the electric power system. Static var systems are capable of controlling individual phase voltages of the buses to which they are connected. Generally, thyristor controlled circuits are used in these systems. A static var system is ideally suited for applications requiring direct and rapid control of voltage.

Reactive power compensation is often the most effective way to improve both power transfer capability and voltage stability.

6. CONCLUSION

Simple analytical expression for real power and reactive power at receiving end and sending end of simple two bus system has been formulated and had been used to obtain voltage V_2 at load point. The same voltage expression is used to draw P-V curve of a radial transmission line. It is observed that real power transfer increases from lagging to leading power factor. Using the Q-V curves the sensitivity of the load to the reactive power sources can be obtained.

Thus basic voltage stability analysis tools i.e. P-V curve and Q-V curve are found to be effective tools to understand static voltage stability analysis.

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