Power System Voltage Stability and Control- A Review

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Abstract: At the recent years, power system becomes a large complex interconnected network that contains of hundreds of buses and generating stations. In addition, to provide the required power, new installation of power generators and transmission lines are required. Due to the environmental and economic constraints of installation of new generators and increasing demands, transmission line flows has been increased on the existing transmission lines which may increase the risk of losing voltage stability and blackouts in the system. This paper presents an overview on definition and principles of voltage stability. Furthermore, common proposed techniques in the literature to enhance the steady-state voltage stability, such as excitation control and FACTS devices are also addressed.

Key words: Dynamic stability control, power flow control, power system oscillation, power system stability

INTRODUCTION

Power system stability can be defined as the ability to recover a counterbalance state after the occurrence of disturbance in the system (Grigsby, 2007). Stability analysis of a system can be divided into two classes, steady-state stability and transient stability. Steady-state stability, which recently named as dynamic stability, is only a function of the operating condition, while transient stability is a function of both the operating condition and the disturbance (Venikov et al., 1975; Kwatny et al., 1986). Various types of disturbance such as changing power demand and short circuits are the main causes of power system dynamic. These disturbances may cause a broad range of dynamic changes and the loss of stability into some parts or the whole of system at a different time scale (Bose, 2003). Therefore, the dynamic changes and stability of the system depends strongly on the size of the disturbances (Agarwal, 1995; Pavella et al., 2000).

Over the past decades, stability issues, especially voltage instability, were the major challenging topic for the system planners. The rapid development of technology in field of power flow controller devices such as Flexible AC Transmission Systems (FACTS), Energy Storage System (ESS), and Distributed Generation (DG) is gradually reshaping the conventional power systems (Pal and Chaudhuri, 2005; Du et al., 2009). Most of these devices are based on power electronics technology, and operate by controlling the volume of injected active and reactive powers, or by controlling voltage angle at the specific buses of the system in order to improve the quality of the power and stability of the system (Hanzelka and Milanović, 2008; Bayod-Rújula, 2009). The Thyristor Switched Series Capacitor (TSSC) or Thyristor Controlled Series Capacitor (TCSC) devices can also be used to change the apparent reactance of the line in discrete or continuous mode (Edris, 1997; Zhang and Ding, 1997). Furthermore, excitation control is known as an effective controller to improve dynamic and transient stability in power systems (Mathur and Varma, 2002).

Voltage stability which is one of the contexts of power system stability can be defined as the ability of a power system to preserve steady-state bus voltages, before and after being subjected to a disturbance (Van Cutsem, 2000). When the system operates close to critical conditions, voltage stability analysis is an important and promising approach to estimate the response of the system to typical disturbances such as line tripping or step load increasing (Borghetti et al., 1997; Van Cutsem, 2000; Zima et al., 2005). Therefore, power system is voltage stable when voltages at all buses in the system after a disturbance are close to voltages at normal operating condition (Kundur et al., 2004). It should be noted that voltage control and instability are local problems, but it may have a widespread impact on the system (Van Cutsem, 2000; Zima et al., 2005).

This study concentrates on an overview of definitions and research studies related to the context of voltage
steady state voltage stability in power systems. The operating issues and the current methods to enhance stability of the power system are also discussed.

**STEADY STATE VOLTAGE STABILITY**

Steady state voltage instability and its occurrence are considered as a serious problem in a large power system (Garng and Zhang, 2001). To maintain system voltage at a stable point has become a major crisis due to the thermal capability or steady state voltage stability limits (Lof et al., 1992; Young-Huei et al., 1997). Voltage instability is known as a continuous voltage collapse, when the network loadings and the reactive power demand increase at the specific areas or entire system (Zima, 2002; Vargončík and Kolcun, 2007). One of the most important factors causing voltage instability is the incapability of the power system to provide the reactive power in the presence of reactive loads or high reactive power losses to keep desired voltages (Ajjarapu and Christy, 1992).

Considering the equivalent circuit of a transmission system and its phasor diagram, as shown in Fig. 1, the real and reactive power absorbed by the load, $P_n$ and $Q_n$, can be expressed as (Machowski et al., 1997):

$$P_n = V I \cos \phi = V \frac{I X \cos \phi}{X} = \frac{E V}{X} \sin \delta$$

(1)

$$Q_n = V I \sin \phi = V \frac{I X \sin \phi}{X} = \frac{E V}{X} \cos \delta - \frac{V^2}{X}$$

(2)

where $\phi$ and $\delta$ are the phase angle between $V$ and $I$; and $E$ and $V$, respectively.

Equation (1) and (2) can be simplified and written as:

$$\frac{P_n}{E} = \frac{X}{T} \sin \phi \cos \phi + \frac{X}{T} \cos \phi$$

$$\frac{Q_n}{E} = \frac{X}{T} \cos^2 \phi$$

(3)

Figure 2 shows the graphical illustration of Eq. (3) in terms of the P-V curve or Nose curve with respect to $\phi$ as a parameter. From the Figure, it is clear that the voltage decreases at a lagging power factor as the real load increases, and the voltage initially increases and decreases (Wijekoon et al., 2003) through a low lagging power factor. Equation (3) and Fig. 2 show the effect of power demand on voltage stability which should be strongly considered in stability analysis.

**EXCITATION CONTROL IN GENERATORS**

The main factors in long term voltage stability are the field current and frequency control at generators (Johansson, 1998). The frequency regulation problems have forced engineers to develop the turbine speed governors and excitation controllers to rapid control of frequency and voltage output of the synchronous generators within the specified limits in case of changes in real and reactive power demands (Patel et al., 2004). So as to carry out excitation control to enhance stability control, rapid and accurate measurement of various types of prime data, such as the real power, system frequency, and rotational speed is necessary. The major task of the excitation system is to control and adjust the field current, which can regulate the terminal voltage of the synchronous machine (Bevrani, 2009). Due to the high time constant of field circuit, exciter should have a high ceiling voltage which enables the exciter to operate transiently with the voltage levels up to 3 to 4 times of the normal level (Stewart, 1947). In addition, because of the high reliability required, the rate of change of voltage should be as fast as possible and...
each generating unit should be supplied by its individual exciter (Bayne et al., 1975; Kirby and Hirst, 1997).

Generally, there are three types of excitation systems including dc excitation systems, ac excitation Systems, and static excitation systems (Friedman and Corporation, 2002).

The Proportional Integral Derivative (PID) controller is one of the most common controllers with simple structure and strong adaptability for excitation control (Kiam Heong et al., 2005; Tan et al., 2007). Recent studies on PID parameters tuning led to develop efficient complex control techniques based on artificial neural networks and genetic algorithms (Berenji, 1992; Rahimi and Ardehali, 2011). Other studies have combined the intelligent algorithm with the fuzzy PID control to improve the PID controller by presenting PSO searching method. To enhance the local optimization problem of the PSO algorithm, the rebound strategy to optimize the boundary restricts of PSO has been used, which can achieve the rapid and steady control of the excitation of the synchronous generator (Junfeng et al., 2006; Pan et al., 2011). Figure 3 shows the structure diagram of a sample fuzzy-PID controller (Hui et al., 2009). In Fig. 3, first the fuzzy-PID controller formulates fuzzy computation based on the terminal voltage error $e(t)$ and error variation rate $e_c(t)$, then logical reasoning and judgment is created according to the fuzzy rules. Finally, by combing with the initial values of the parameters, the output values $u(t)$ of the PID controller can be generated.

Fuzzy neural networks controller based methods are also wildly proposed in the previous studies. In these methods, the artificial neural networks have been used to build a network holding fuzzy information and study the rules of convention fuzzy controller. Also, the fuzzy relational matrix, which is the core of fuzzy reasoning, has been replaced the trained neural networks. Then the controller that is based on the fuzzy neural networks can make control response quickly when the controlled object has the difference between the actual output value and the given input value (Lin and Lee, 1991; Godjevac, 1995; Ching-Hung and Ching-Cheng, 2000). Figure 4 shows the block diagram of a fuzzy neural networks controller (Wei et al., 2009).

**FACTS AND MODERN STABILITY CONTROL**

Reactive power compensation is often known as an effective method to improve voltage stability of power systems. Due to the effective role of the power system components and controller, it is important to determine voltage stability in case of occurrence of disturbance and static/dynamic voltage instability, which is a difficult task in complex power system. Hence, how to achieve a simple, suitable and realistic principle for static voltage stability is still an important task in field of voltage stability problems. The rapid improvement and utilization of FACTS in the power transmission system has led to many applications to improve static/dynamic voltage and angle stability of the system. Due to the effects of reactive power on voltage reduction and voltage instability, the FACTS devices can be effectively used for decreasing the effects of reactive load and increasing the reactive power. It should be noted that the injection of reactive power have to be local and adequate (Zhang and Ding, 1997).

The FACTS devices, including Static Synchronous Compensator (STATCOM), Static Var Compensators (SVC), Thyristor Controlled Series Compensator (TCSC), and Static Synchronous Series Compensator (SSSC), have their own characteristic and limitations (Gyugyi et al., 1997; Sode-Yone et al., 2005). Therefore, they may the issue under consideration and the time frame involved. represent by different mathematical models depending on Generally, the FACTS devices can be divided into three categories including series connected, shunt connected and combination of series and shunt connected controllers. In theory, the series controllers are used to inject voltage in series with the line to alleviate line overloads and increase transfer capability, where the shunt controllers are able to inject current at the point of connection to compensate voltages by injecting reactive power at the low voltage buses. Also, the combined controllers such as Unified Power Flow Controller (UPFC) are used to inject current into the system with the shunt part and voltage in series with the series part of the controllers to control both the active and reactive power flow (Song et al., 2004).
The main difficulty in FACTS installation is to determine the possible locations of each FACTS device. Due to this problem, several methods have been proposed based on the sensitivity analysis on series controllers, such as TCSC. In addition, several methods have been proposed based on system load ability and contingency analysis to determine optimal location of shunt controllers, such as SVC. It should be noted that the calculation of the sensitivity to determine the suitable location of shunt and series controllers must be determined at the specific buses where the problems are occurred, which is quite time consuming approach to analyse for every bus and its respective line (Jurado and Rodriguez, 1999).

**Static Var Compensators (SVC):** One type of FACTS devices is SVC, which is a shunt connected static Var controller with an adjustable output according the required capacitive or inductive current. In other words, SVC operates as a shunt compensator to control and maintain the magnitude of voltage at a desired level by the change of parallel susceptance from sensing the change of bus voltage. Furthermore, SVC, which mainly operated at load side bus as a replacement for existing voltage control devices, can control transient stability, power fluctuation, and low frequency oscillations in the system (Song and Johns, 1999).

The equivalent circuit of SVC is shown in Fig. 5. As shown in the figure, SVC is modelled by a variable reactor and a fixed capacitor. Using the optimal parameters for capacitors and variable reactor, the amount of injected reactive power by the SVC can be continually determined in order to control the voltage or to maintain the desirable power flow in the system. Usually to control the SVC parameters, some search algorithms such as GA and SA are used in order to find the optimal parameters of SVC to achieve the optimal coordinated control of the compensator. It should be noted that SVC has its own upper and lower susceptance limits, which determine the capability of supplying adjustable reactive power within these limits. When a SVC reaches to its limit, it cannot supply the needed additional reactive power support. Hence the system may lose its stability at this situation (Khaki et al., 2008).

**Static synchronous compensator (STATCOM):** The STATCOM (also known as the static VAR generator (SVG)) is a voltage converter device which uses in order to generate the active and reactive power needed by the system. The STATCOM has several advantages including fast response, continuous and quick control of reactive power, and smaller storage capacitance (Zhang and Ding, 1997). In addition, the ability of the reactive power compensation in STATCOM is better than SVC. Therefore, STATCOM may consider as an effective
solution to the problem of voltage stability. Figure 6 shows the basic structure of STATCOM. Figure 6 shows that STATCOM is a shunt connected device which is connected to the grid through a series reactance.

On the DC side of the converter device, which is equipped with a Pulse-Width Modulation (PWM) controller, there is only a capacitor and there is no source or demand of real power. Dynamic reactive compensation can be achieved by adjusting voltage and angle of internal voltage source (Arnold, 2001; El-Moursi and Sharaf, 2006; Ghafouri et al., 2007; Ben-Sheng and Yuan-Yih, 2008).

Thyristor Controlled Series Compensator (TCSC): The TCSCs are a type of FACTS devices which are an effective and economical means to provide fast active power flow regulation and control of series compensation such as sub-synchronous resonance. This device consists of a set of capacitor bank and a parallel thyristor controlled inductor. By controlling active power through TCSC using the firing angle of the thyristors, this device is able to indirectly control the power angle of remote generator and enhancing the transient stability problems (Stromberg, 1998; Mahajan, 2006; Wagh et al., 2009; Meikandasivam et al., 2011). Figure 7 shows the basic configuration of TCSC.

Static Synchronous Series Compensator (SSSC): The SSSC is a series connected, Voltage Source Convertor (VSC) based device which is able to compensate reactive power and increase the critical clearing time of fault and damps out the post-fault rotor angle oscillations (Sen, 1998; Poshtan et al., 2006). The SSSC is able to directly control the current, and indirectly the power of the system by controlling the reactive power exchange between the SSSC and the AC system (Kamarposhti and Lesani, 2011). The SSSC has numerous advantages over the TCSC including omission of large passive components such as capacitors and operational ability for both inductive and capacitive modes (Padiyar, 2007). Figure 8 shows the basic configuration of SSSC.

CONCLUSION

Due to the increased reactive power consumption, power systems have been operated under more stressed conditions. Under this situations, a number of unstable behaviour such as voltage drops have been experienced in power systems. In this paper, a basic definition about context of voltage stability has been addressed using power-voltage relationships and P-V curve. Furthermore, the effects of field current and frequency control at generators on voltage stability and control has been discussed. Also a brief explanation about fuzzy-PID and Fuzzy neural networks controllers has been given. In section 4, the effects of FACTS devices on modern voltage stability control has been discussed and two common types of FACTS devices including SVC, STATCOM, TCSC and SSSC has been introduced.

REFERENCES


