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# Voltage stability boundary and margin enhancement with FACTS and HVDC

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ABSTRACT

Voltage stability is a major concern of today's power system, especially under heavily loaded conditions because of reactive power limits. FACTs devices are very effective solution to prevent voltage instability and voltage collapse due to fast and very flexible control. In this paper, the impacts of SVC, STATCOM, TCSC and HVDC on voltage stability boundary (VSB) in $P$–$Q$ plane have been studied. The bus impedance matrix and load flow results are used to find the voltage stability boundary. The $Z_{bus}$ is modified to take into account the effect of FACTS on VSB. The variable susceptance model for SVC and variable series impedance power flow model for TCSC are used in Newton Raphson's method. The STATCOM is modelled as variable voltage source connected in series with an equivalent impedance of the shunt connected transformer. Similarly HVDC is also modelled as two STATCOMs connected at each end of the line one as rectifier and another as inverter. Some important bus and line stability indices are evaluated to determine the most effective location for SVC/STATCOM and TCSC/HVDC respectively in order to achieve the maximum enhancement of voltage stability margin. The study has been carried out on IEEE-14 bus and IEEE-30 bus test systems using MATLAB programming. A comprehensive study is done to compare the effectiveness of FACTS devices and HVDC on voltage stability margins.



## Introduction

The continuing interconnection, manifold increase in demand, restructuring, economic and environmental pressures led to a more complex and sensitive power system operating very close to its stability limits. The mainstream philosophy of restructured sector is to minimize investments and maximize the equipment utilization. This evolution of deregulated power system has increased the possible sources of system disturbances leading to a less robust, more unpredictable system as far as operation is concerned. In fact, what may seem stable in long term may not be stable in short term. As a result, in recent years since last three decades, several incidents of blackouts have been reported due to voltage instability [1,2]. Uncontrollable decay of the system voltage at one or more load buses or even over a sufficient portion of the network as a response to load variation and generation or structure disturbances has been termed as voltage instability (VI). VI stems from the attempt of load dynamics to restore power beyond the capability of transmission and generation system [3]. Voltage collapse (VC) is the process of successive voltage decrease leading to blackout in significant parts of the system. The initial event may be due to a variety of causes – small gradual system changes, or large sudden disturbances such as loss of generating unit or heavily loaded line. Immediately following the loss of line there would be a considerable reduction of voltage at adjacent load centres due to extra reactive power demand. This would cause a load reduction and stabilizing effect. The actions of generator exciters and underload tap changer (ULTC) transformer to quickly restore voltages and hence loads worsen the situation. With each tap change operation, the resulting increment in load would increase line losses, which in turn cause a greater drop in load levels. As a result, the reactive power output of generators would increase and hit maximum excitation limit. The share of reactive loading would be transferred to nearby generators and thus leading to overloading of more and more generators. This cascade tripping of lines and generators would lead to major blackouts [2,3]. Several controls usually employed to mitigate VI and VC are proper adjustments of transformer tap settings, reactive power compensations (generators, synchronous condensers, shunt capacitors, FACTs devices, etc.), active power transfer and load shedding.

Voltage stability assessment and its enhancement have become the important aspects for power system operators and researchers. Many performance indices have been developed that can predict

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how close the system is to the voltage collapse point. The main aim of these indices is to define a scalar magnitude that can accurately reflect the system state as parameters changes. Venikov et al. [4] first gave the index to predict VI and showed that it is the Jacobian of the load flow equation that characterizes the classical steady state limits. Therefore, eigen values of the linearized system matrix have a direct relation with any bifurcation of the equilibrium state. Many static voltage stability assessment methods have been developed so far, such as eigen and singular values, modal analysis and sensitivity methods [5,6]. In [7] a new *V–Q* sensitivity based index is proposed to predict instability for system with static as well as dynamic loads. The sensitivity matrix of the generated reactive powers w.r.t. to loading parameters is relatively easy to calculate. Large sensitivity factors reveal both critical generators and critical loads. The methods to assess dynamic voltage stability proposed are bifurcation analysis, energy functions, and direct methods. The drawback of these Jacobian based indices is that these are not suitable for online applications due to their inaccuracy of collapse predictions or the high computational requirements. Loading margin is the most basic and widely accepted index of voltage collapse that can be calculated using continuation power flow or direct methods. It can be used with dynamic system models and takes full account of the power system nonlinearly and limits. Some indices based on system parameters (bus admittance/impedance) and variables (voltages, currents and line power flows) have also been developed. These can be further divided into bus and line voltage stability indices [8–14]. Mohamed and Jasmon suggested several advantages of identifying critical lines over the methods of identifying the critical buses [9]. Many voltage stability indices (VSIs) based on Thevenin's equivalent impedance matching scheme have also been proposed to assess stability margin in real time from local and wide area measurements [15–20]. These indices can be determined and monitored with synchronized phasor measurement technology and utilized to take the control action in time with early anticipation of impending voltage instability. A simple and fast method based on Thevenin's equivalent model of power system is to obtain stability margin from voltage stability boundary (VSB) of critical bus in *P–Q* plane [21,22].

The power flow through ac transmission system can be controlled by controlling the parameters phase, magnitude of bus voltages and line impedances. This novel transmission system concept called Flexible AC Transmission System (FACTS) was proposed by Electrical Power Research Institute (EPRI) of U.S in 1998 [23]. Since then, to transfer more power and improve system stability, allocation of FACTS has become an area of wide interest for the power system operators and researchers. Modal analysis near the point of collapse, sensitivity based approaches, index 'L', heuristic methods like particle swarm optimization, GA, mixed integer dynamic optimization are widely used methods for allocation of FACTS [24–30]. In Ref. [30], visualization of the area of voltage stability region (AVSR) [31] has been presented. The three dimensional surface with the impact of FACTS and HVDC are plotted from the concept of Thevenin's equivalent at a load bus.

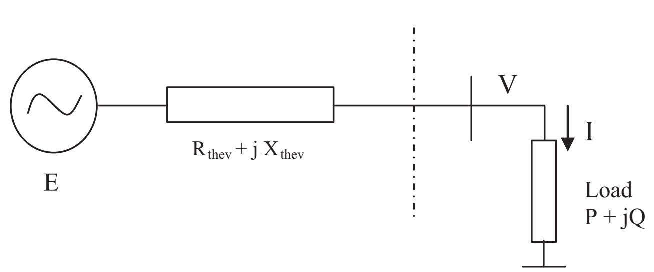


**Fig. 1.** Two bus equivalent of a power system.

This paper presents the effects of FACTS controllers on voltage stability boundary, a simple method of assessing voltage stability of load buses of power system. The voltage stability boundary is generated from load flow solution and bus impedance matrix ($Z_{bus}$). The present work is mainly concerned with the inclusion of FACT controllers (SVC, TCSC, and STATCOM) and HVDC in load flow studies to study and compare their effects on voltage stability boundary. Three important indices, eigenvector, VQ sensitivity factor, and minimum distance to voltage collapse are used to find the critical bus for placing shunt controller. The series controller is placed in the weakest line identified by recently developed line stability indices.

The main highlights of the proposed work are:

(i) Inclusion of FACTS and HVDC in load flow studies and Thevenin's equivalent to plot voltage stability boundary of a load bus.
(ii) Determination of location of shunt and series controller using important and recently developed bus and line voltage stability indices.
(iii) Enhancement in voltage stability margins with FACTS and HVDC and their comparison.

## Voltage stability boundary (VSB)

### *Determination of VSB*

A simple method of assessing voltage stability of a power system is given by Haque. The VSB in *P–Q* plane represents the active power and reactive power of the load at the point of voltage collapse [21]. The VSB can be determined very easily from a two bus equivalent of the original system as shown in Fig. 1. It involves the solution of a simple polynomial. The active, reactive and apparent power margins of the any load bus can then be directly determined from its VSB.

For a given load $P + jQ$ at the bus, the load current $I$ and voltage $V$ can be written as

$$I = (P - jQ)/V^{*} \tag{1}$$

$$V = E - Z_{thev} I \tag{2}$$

After simple calculations using the above two equations, the voltage magnitude $V$ of the load bus can be obtained from the solution of the following equation:

$$V^4 + 2(R_{thev}P + X_{thev}Q)V^2 - E^2V^2 + \left(R_{thev}^2 + X_{thev}^2\right)(P^2 + Q^2) = 0 \tag{3}$$

This equation has only two feasible (real and positive) solutions under normal load conditions. The higher voltage ($V^H$) is called the stable solution and the lower voltage ($V^L$) is called the unstable solution. At the point of voltage collapse the two solutions become equal. This condition for VC can be obtained from Eq. (3) and rewritten as:

$$V^H = V^L \tag{4}$$

Using Eqs. (3) and (4) can be rewritten as:

$$f(P, Q, E, R_{thev}, X_{thev}) = 0 \tag{5}$$

The set of loads that satisfies the above equation are critical values of reactive and active powers ($P_{cr}$ and $Q_{cr}$). Thus VSB at a load bus can easily be generated from the solution of the above equation. A typical VSB is shown in Fig. 2.