Voltage Stability Assessment in the Presence of Optimally Placed D-FACTS Devices

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***Abstract*—Distributed Flexible AC Transmission System (D-FACTS) devices offer many potential benefits to power system operations. This paper presents a novel strategy for the application of D-FACTS devices in controlling system voltage. The impact of installing D-FACTS devices is examined by studying the sensitivities of voltage magnitude with respect to line impedance. Sensitivities enable us to determine the potential benefits of the D-FACTS Devices offered to the system. Most appropriate locations to install D-FACTS devices for controlling system voltages are also determined. In this paper, steady state model of recently introduced D-FACTS device DSSC is incorporated in voltage stability assessment of an interconnected power system in terms of its reduced equivalent two-bus integrated system. The participation of a particular bus in global voltage instability is assessed in terms of global voltage stability index (GVSI). It has also been used to assess the global voltage stable state of the network. The proposed methodology has been applied under simulated condition on IEEE 30-bus test system.**

Keywords—Distributed FACTS; Voltage control; Reactive power control; Line impedance sensitivity

I. INTRODUCTION

Due to increase in power demand, modern power system networks are being operated under highly stressed conditions. This has resulted into the difficulty in meeting reactive power requirement, especially under contingencies and hence maintaining the bus voltage within acceptable limits. Voltage instability is one of the major problems associated with modern power systems [1]. Reports of the occurrence of voltage collapse are becoming more frequent and this problem has been an area of great interest to power system researchers [2-4].

Voltage collapse is a local phenomenon and occurs at a bus within an area of high loads and low voltage profile. The voltage problem of the affected bus may cause a series of line outages and resulting in system blackout. It is well recognized that voltage collapse normally occurs when there exists a large demand of reactive power [5] but at exactly what load level the failure will occur, is not easily predicted.

Flexible AC Transmission System (FACTS) was launched to solve the emerging power system problems [6,7]. It identifies alternating current transmission systems incorporating power electronic based controllers to enhance the controllability to increase power transfer capability. These controllers are used to regulate power flow, transmission voltage and can mitigate dynamic disturbances through rapid control action. Thyristor Controlled Series capacitor (TCSC) and Static Synchronous Series Capacitor (SSSC) are used to control the power flow through transmission lines. Other devices such as Static Var compensators (SVC) and static synchronous compensator (STATCOM) are widely used for shunt reactive compensation in order to maintain a flat voltage profile. To analyze the effect of these controllers, steady state models have been developed over the decade [7-9]. Power flow analysis of systems using such models would provide data necessary to calculate voltage collapse indicators in order to evaluate the response of the system.

Although FACTS devices are well-understood from a technical perspective but they have not experienced the massive deployment that their theory may warrant because of the huge investment costs, poor return on investment as well as reliability concerns. Improvements in available electrical technology allow us to revisit FACTS concepts from a fresh perspective and recently introduced distributed flexible AC transmission system (D-FACTS) devices offer such an opportunity.

More recently, Distributed Flexible AC Transmission System (D-FACTS) device, Distributed Static Series Compensator (DSSC) has been designed to address power control types of problems [10-12]. From power system perspective, D-FACTS devices have many potential benefits. D-FACTS devices can be attached directly to transmission lines and can be used to dynamically control effective line impedance. D-FACTS devices are smaller and less expensive than traditional FACTS devices which make them better candidates for wide scale deployment. D-FACTS devices can act inductive as well as capacitive, so both raising and lowering system voltage are important potential applications. In particular, this paper analyzes effects of changing transmission line impedances and the use of D-FACTS devices for voltage control.

Several incidences of voltage collapse have been observed in past few decades. With the concept of network equivalence [13-16], an attempt is made in this paper to describe a method of equivalence a multi-bus power network to an equivalent two-bus system [15] developed from the Newton-Raphson power flow considering D-FACTS controllers and thereby

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voltage stable states of the entire system following the load changes in 'weak' load buses investigated for a typical power system network. Here we examine the use of D-FACTS devices as a means to improve voltages in the IEEE 30-bus test system. Voltage stability enhancement using these D-FACTS controllers is compared in the test system considered. The simulation also includes the detection of the 'weak' load bus/buses [17,18] and identification of the global voltage stable states of the system following the derived two-bus equivalent system simulation.

II. ANALYSIS OF LINE IMPEDANCE SENSITIVITIES

Sensitivities are linearized relationships between variables and are often used in power systems analysis. Linearized relationships can reveal the impact of a small change in a particular variable on the rest of the system. Linear approximations in nonlinear systems are useful because they can provide insight into how variables depend on other variables when such relationships may otherwise be difficult to characterize. Since D-FACTS devices change effective line impedance, line impedance sensitivities [19] are useful to determine potential benefits of D-FACTS devices.

A. Equations and Notation

The AC power injection equations for real power P and reactive power Q at a bus i are stated in (1a) and (1b),

$$P_{i,calc} = V_i \sum_{j=1}^{n} V_j \left[G_{ij}\cos(\theta_i - \theta_j) + B_{ij}\sin(\theta_i - \theta_j) \right] \tag{1a}$$

$$Q_{i,calc} = V_i \sum_{j=1}^{n} V_j \left[G_{ij}\sin(\theta_i - \theta_j) - B_{ij}\cos(\theta_i - \theta_j) \right] \tag{1b}$$

Where n is the number of buses.

Real and reactive power balance is expressed by the concatenated vector $f_{(p,q)}(s_{(\theta,V)})$ of Δp and Δq which must equal to zero,

$$\Delta p_i = P_{i,calc} - (P_{i,gen} - P_{i,load}) \tag{2a}$$

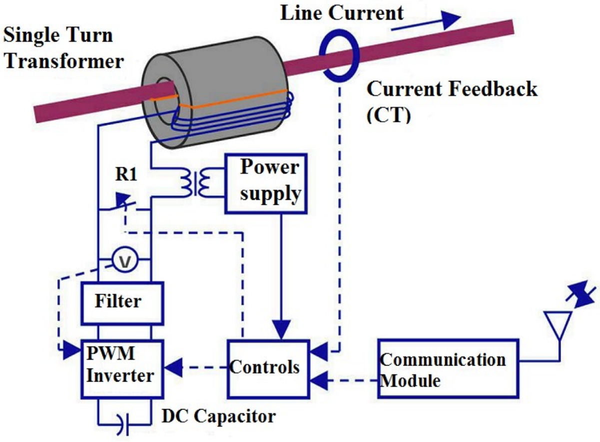

Fig. 1. Schematic Diagram of DSSC

$$\Delta q_i = Q_{i,calc} - (Q_{i,gen} - Q_{i,load}) \tag{2b}$$

$$f_{(p,q)}(s_{(\theta,V)}) = \left[\Delta p, \Delta q \right]^T \tag{3}$$

Where $s_{(\theta,V)}$ is a vector of bus voltage states represented in polar coordinates by magnitudes V and angles θ,

$$(s_{(\theta,V)}) = \left[\theta, V \right]^T \tag{4}$$

$G+jB$ is the system admittance matrix. Admittance matrix elements depend explicitly on reactive line impedances x as well as resistances r.

$$G_{ij} = -\frac{r_{ij}}{r_{ij}^2 + x_{ij}^2} i \neq j \tag{5a}$$

$$B_{ij} = -\frac{x_{ij}}{r_{ij}^2 + x_{ij}^2} i \neq j \tag{5b}$$

The above equations are used to analyze the impact of D-FACTS devices in power system.

B. Admittance Matrix Sensitivities

Since D-FACTS devices change the effective reactive impedance x of a line, it is useful to consider the power flow equations in terms of x (and r) instead of G and B. Expressing individual elements of G and B in terms of impedances as in (5a) and (5b) and taking the derivative of each term with respect to its reactive line impedance yields the following:

$$\frac{\partial G_{ij}}{\partial x_{ij}} = \frac{2 r_{ij} . x_{ij}}{(r_{ij}^2 + x_{ij}^2)^2} \tag{6a}$$

$$\frac{\partial B_{ij}}{\partial x_{ij}} = -\frac{2 x_{ij}^2}{(r_{ij}^2 + x_{ij}^2)^2} + \frac{1}{r_{ij}^2 + x_{ij}^2} \tag{6b}$$

C. Power Injection and State Variable Sensitivities

The relationships between the power injection equations $f_{(p,q)}$ and state variables $s_{(\theta,V)}$ are given by the power flow Jacobian J.

Where J is formed as follows:

$$J = \begin{matrix} nq+nv\{ \\ nq\{ \end{matrix} \begin{pmatrix} \frac{\partial \Delta p}{\partial \theta} & \frac{\partial \Delta p}{\partial V} \\ \frac{\partial \Delta q}{\partial \theta} & \frac{\partial \Delta q}{\partial V} \end{pmatrix} \tag{7}$$

nq is the number of PQ buses and nv is the number of PV buses.

The negative inverse of the power flow Jacobian describes the way the state variables change in a solution of the power flow due to real and reactive bus power injection mismatch.

$$\Delta s_{(\theta,V)} = \left[-J \right]^{-1} . f_{(p,q)} \tag{8}$$