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Placement and operation strategy of FACTS devices using optimal continuous power flow

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Abstract In this paper, an effective method is presented to determine the security margin against voltage collapse, and improve it by means of FACTS devices in the optimal continuous power flow framework. The primary methods for determining the system's critical states of voltage collapse points are based on the convergence of the Newton-Raphson method in various iterations. Unlike these methods, in this investigation, a method based on sequential quadratic programming is proposed to overcome the divergence of the problem near the critical states, and also to incorporate operation and control constraints through optimal continuous power flow. Furthermore, two FACTS devices, the Thyristor-Controlled Series Capacitor (TCSC) and the Static VAR Compensator (SVC), are mathematically represented and employed in the optimization process to improve the security margin. The proposed method is implemented on a practical power network to investigate the efficacy of the method.

1. Introduction

The capacity of power systems can be increased by their performance improvement via optimal use of existing power equipment, rather than by installing new transmission lines. Load growth and the non-optimal use of electric power transmission lines adversely affect the stability of power systems. Although power system control and stability have been studied for several decades, they attract special attention, due to ever-increasing electricity demand and economical considerations. The high cost of transmission line expansion, including equipment, installation and right of way, force transmission lines to operate at their maximum capacity. Therefore, voltage stability, even under normal conditions, becomes more and more difficult to guarantee [1–3].

The role of FACTS devices in power system performance enhancement becomes more important, since the main responsibility of generation units is to produce active, rather than reactive, power compensation. Maximum power transmission (close to lines thermal limit) over a long distance in a power system, without adversely affecting the stability and security margin, can be achieved through a fast power flow control. Voltage stability depends on the ability of the power system to maintain acceptable voltage for the system buses under normal conditions, and, also, in the face of disturbances. In other words, after an incidence of disturbance, i.e. an increase in demand load and/or system characteristic changes, the system may face voltage instability, which may cause an uncontrollable deviation of voltage [4]. The failure of power systems to provide the required reactive power is the main cause of instability. Therefore, considering the reactive power security margin can increase the reliability of the system and prevent any possible blackouts (such as which occurred in Iran on 20th May, 2001).

Flexible AC Transmission Systems (FACTS) obtained a well known reputation for higher controllability in power systems by means of power electronic devices. The first application of FACTS devices is a fast power flow control, which can help to improve the stability and security margin. The influence of these devices is achieved through switched or controlled shunt compensation, series compensation or phase shift control. FACTS devices work as fast current, voltage or impedance controllers. The power electronic allows a very short reaction time, down to far below one second. The Thyristor-Controlled Series Capacitor (TCSC) and the Static Var Compensator (SVC)

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Nomenclature

i, j	Indexes of bus
n	Number of system buses
P_i	Injected active power to the ith bus
Q_i	Injected reactive power to the ith bus
P_{Gi}	Energy output of the unit in the ith bus at the current operating point
$\hat{P}_{Gi,u}$	Energy output of the unit in the ith bus at the security loading point
Y_{ij}	Magnitude of admittance connected between two buses, i and j
P_{0i}	Predetermined active power at the nominal voltage
Q_{0i}	Predetermined reactive power at the nominal voltage
MVA^L	Power system load in terms of MVA at the voltage collapse point
MVA^N	Power system load in terms of MVA at the current operating point
$\lvert V_i \rvert$	Voltage magnitude of the ith bus at the current operating point
$\lvert \hat{V}_i \rvert$	Voltage magnitude of the ith bus at the security loading point
$\lvert V_{\max,i} \rvert$	Upper limit of the voltage magnitude in the ith bus
$\lvert V_{\min,i} \rvert$	Lower limit of the voltage magnitude in the ith bus
Q_{Gi}	Reactive power output of the unit in the ith bus at the current operating point
$\hat{Q}_{G\,i}$	Reactive power output of the unit in the ith bus at the security loading point
$P_{G\max,i}$	Upper limit of the active power of the unit in the ith bus
$P_{G\min,i}$	Lower limit of the active power of the unit in the ith bus
$Q_{G\max,i}$	Upper limit of the reactive power of the unit in the ith bus
$Q_{G\min,i}$	Lower limit of the reactive power of the unit in the ith bus
P_{Di}	Active load of the ith bus at the current operating point
$\hat{P}_{D\,i}$	Active load of the ith bus at the security loading point
Q_{Di}	Reactive load of the ith bus at the current operating point
$\hat{Q}_{D\,i}$	Reactive load of the ith bus at the security loading point
$R + jX$	Impedance of the transmission line
X_C	Magnitude of X_{TCSC}
S_{ij}	Apparent power flow of branch between ith and jth buses at the current operating point
$\hat{S}_{ij}$	Apparent power flow of branch between ith and jth buses at the security loading point
$\bar{S}_{ij}$	Apparent power flow capacity of branch between ith and jth buses
$f(x)$	The objective function
m_e	Number of equality constraints ($G_i(x) = 0$)
m_n	Number of inequality constraints ($G_i(x) \leq 0$)
k_G	Scalar variable relating system losses at the security loading point to that of the current operating point
λ	Voltage security margin (security loading point margin)
θ_{ij}	Angle of element located in the ith row and jth column of the admittance matrix of the power system (Rad)
δ_{ij}	Difference between voltage angles of buses, i and j (Rad).

are two such devices that flexibly control line impedance and susceptance. In most applications, the controllability can help to avoid extreme costs due to power system expansion, such as upgrading or installing substations and power transmission lines. FACTS devices provide a better adaptation to various operational conditions and improve the usage of existing installations.

The effectiveness of FACTS controllers mainly depends on the location of control devices [5]. In order to allocate the FACTS devices according to their characteristics, various objectives have been considered. For instance, static voltage stability enhancement [6–9], violation avoidance of line thermal constraints [10], network load-ability enhancement [11,12], power loss reduction [13], voltage profile improvement [11], fuel cost reduction of power plants using optimal power flow [14], dynamic stability improvement [15], and efficient damping of power swings [16] are the most common objectives reported in the literature for optimal allocation problems. It is worth noting that each of the mentioned objectives improves the performance of the power system network and achieving all objectives simultaneously is desirable for any power system network. In order to improve voltage stability, which is considered in this paper, voltage magnitude alone may not be a reliable indication of how far an operating point is from the collapse point [17]. Hence, satisfying the voltage magnitude constraint does not guarantee the security margin requirements. In order to improve both the voltage magnitude and the Security Margin (SM) of the system, proper TCSC/SVC allocation and setting are suggested. Accordingly, Zarate-Mihano et al. [18] present an optimal allocation method for Flexible Ac Transmission System (FACTS) devices for market-based power systems, considering congestion relief and voltage stability. Also, Wibowo et al. [19] develops a new method for economic dispatch together with nodal price calculations, which includes transient stability constraints and, at the same time, optimizes the reference inputs to the Flexible Ac Transmission System (FACTS) devices for enhancing system stability and reducing nodal prices. Furthermore, in [20], an Optimal Power Flow (OPF)-based security-driven redispatching procedure has been proposed to archive an appropriate security level. In the proposed framework, in [20], a variety of FACTS devices has been incorporated in the redispatching problem to enhance system security.

In this paper, a new formulation to determine a security margin in the presence of TCSC and SVC is presented and solved, using the Sequential Quadratic Problem (SQP) method. To investigate the feasibility of the proposed method, the practical results obtained from its implementation on the Fars power grid are presented, and the influences of TCSC and SVC on the emergency states of the network are also assessed.

The remainder of this paper is organized as follows: in Section 2, the voltage security margin and objective function are presented. The proposed mathematical formulation to calculate the security margin of a power system is presented, considering