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Optimal siting of TCSC for reducing congestion cost by using shadow prices

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Abstract

As competition is introduced in the electricity supply industry, congestion becomes a more important issue. Congestion in a transmission network occurs due to an operating condition that causes limit violations on the transmission capacities. Congestion leads to inefficient use of the system or causes additional costs (congestion cost). One way to reduce this inefficiency or congestion cost (CC) is to control the transmission flow through the installation of thyristor controlled series capacitor (TCSC). This paper also deals with an optimal siting of the TCSC for reducing CC by using shadow prices. A performance index for an optimal siting is defined as a combination of line flow sensitivities and shadow prices. The proposed algorithm is applied to the sample system with two conditions: one is concerning the quadratic cost functions, and the other is concerning the bidding functions. Test results show that the siting of the TCSC is optimal to minimize the CC by the proposed algorithm.

Keywords: Congestion cost; Thyristor controlled series capacitor; Optimal power flow; Shadow price

1. Introduction

Electric power utilities in many countries have focused considerable interest on the institutional structure of open transmission access (OTA). Competition in OTA allows the market participants easy access to the transmission system in a non-discriminatory and equitable manner.

Transmission congestion occurs when transmission line power flows reach the finite network capacities, and precludes the simultaneous delivery of power from an associated set of power transactions [1–3]. Congestion can result in an overall increase in the cost of power delivery. Such a congestion cost (CC) can cause large differences in spot prices in a system that is under severe stress and possibly in need of transmission expansion [4]. Also, the CC can be much greater than the cost of transmission losses. Therefore, congestion is quite an important factor in the total cost of operating the power system, and has been at the center of the extensive debate on OTA.

Flexible AC transmission system (FACTS) devices, which were first defined by Hingorani [5] in 1988, have a large potential ability to make power systems operate in a flexible, secure and economic way. At present, the studies on FACTS are concerned with FACTS device developments and their impacts on the power systems. It is also significant to study the impact of the FACTS devices on improving the performance of power systems such as optimization, optimal power flow (OPF) [6–8].

An OPF is a procedure to determine the optimal steady state operation of a power system so as to minimize a given objective function while satisfying a set of physical and operating constraints [9]. OPF plays a key role in the pricing mechanism that is important for providing services based on the standards of quality, reliability, and security in the OTA environment. The need for OPF has been increased to solve the problems of today's power system of OTA such as calculating spot prices and performing the necessary decomposition of power prices into components reflecting the generation, losses and congestion [10].

This paper presents a method of utilizing thyristor controlled series compensators (TCSC) by adjusting the power flows on the congested lines to reduce the CC. TCSC is one of the main types of FACTS, that is adequate for controlling line power flows. Some previous papers [6,7] presented methods to incorporate the power flow control needs of FACTS in studying the optimal active power flow. However, those considered only the FACTS that are installed at a pre-defined position. This paper focuses on the optimal siting for TCSC to be installed to reduce the CC.

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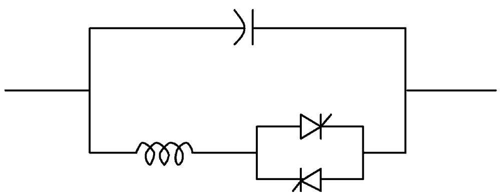

Fig. 1. Common structure for TCSC.

In order to determine the optimal siting, not only are the sensitivities of TCSC parameters to the power flows on the congested lines, but also shadow prices on the congested lines are introduced in the new performance index in this paper. The shadow price is a dual variable represented as a Lagrange multiplier corresponding to a constraint, and indicates a sensitivity that means a marginal change in the cost function due to a change in the finite transmission capacity [11,12]. The new performance index is proposed to each candidate siting where a TCSC is to be installed in the form of a combination of power flow sensitivity and shadow price to the congested lines. Therefore the index gives a measure of the optimal siting of a TCSC to minimize the CC. The simulation studies on a simple 5-bus system are presented and discussed to show the effectiveness of the proposed method.

2. Modeling of TCSC

The configuration of a typical TCSC from a steady-state perspective is the fixed capacitor (FC) with a thyristor-controlled reactor (TCR). The FC–TCR structure depicted in Fig. 1 [13] is the one used in this paper to develop the desired model. The TCR consists of a fixed reactor of inductance L and a bi-directional thyristor valve.

The TCR at fundamental frequency can be readily demonstrated to be equivalent to a variable inductance X_V as Eq. (1)

$$X_V = X_L \frac{\pi}{2(\pi - \alpha) + \sin 2\alpha} \tag{1}$$

where X_L is the fundamental frequency reactance of the inductor without a thyristor control, and α is the firing angle of the valves with respect to the zero crossing of the controller voltage. Hence, the total equivalent impedance X_{TCSC} of the controller can be represented by:

$$X_{TCSC} = \frac{X_C X_V}{X_C - X_V} = \frac{X_C X_L}{X_C/(\pi[2(\pi - \alpha) + \sin 2\alpha]) - X_L} \tag{2}$$

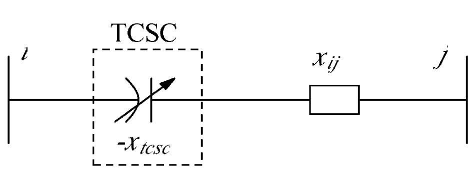

Fig. 2. Steady-state equivalent circuit of TCSC.

Fig. 2 shows a TCSC compensated transmission line represented by parameter $X_{ij} - X_{TCSC}$ between bus i and bus j. Since the TCSC operation in the inductive region reduces the transmission capability of the line, it is assumed in the capacitive region. The TCSC control limits on the firing angle α, i.e. $\alpha \in [\alpha_m, \alpha_M]$ are converted in this paper to the limits on the variable reactance X_{TCSC}. In the case studies, the most compensated reactance of the line is assumed to be 75% of its original uncompensated reactance.

3. Optimal power flow

3.1. Formulation of OPF

The objective of active power optimization is to minimize production cost while observing the transmission line and the generation active power limits. The problem can be stated as follows:

$$\text{minimize } F_T = \sum_{i=1}^{m} C_i(P_{Gi}) \tag{3}$$

$$\text{subject to } \sum_{i=1}^{m} P_{Gi} - \sum_{k=1}^{n} P_{Dk} - P_L = 0 \tag{4}$$

$$P_l \le P_l^{\max} \tag{5}$$

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max} \tag{6}$$

where n and m are the number of system buses and number of generating units, respectively, and $C_i(P_{Gi})$ is the production cost of the unit at bus i, F_T the total production cost of m generators, $P_{Gi}^{\min}$, $P_{Gi}^{\max}$ the active power limits of the unit at bus i, P_{Dk} the active power load at bus k, P_L the network active power loss, and P_l, $P_l^{\max}$ is the active power flow and its limit on line l.

The augmented Lagrangian is

$$\begin{aligned} L(P_{Gi}) = {} & F_T(P_{Gi}) + \lambda\left(\sum_{k=1}^{n} P_{Dk} + P_L - \sum_{i=1}^{m} P_{Gi}\right) \\ & + \sum_{l=1}^{N_l} \mu_l (P_l - P_l^{\max}) \\ & + \sum_{i=1}^{m} \left[\mu_i^{\min}\left(P_{Gi}^{\min} - P_{Gi}\right) + \mu_i^{\max}(P_{Gi} - P_{Gi}^{\max})\right] \end{aligned} \tag{7}$$

where the Lagrangian multipliers are as follows: λ is for the power balance equation, referred to system λ, $\mu_i^{\min}(\mu_i^{\max})$ is for lower(upper) active power limits of the unit at bus i, μ_l is for active power flow limit on line l, and N_l is the number of transmission line flow violations.

In this paper, the main objective is to determine the optimal siting of TCSC for reducing the CC. This problem is not solved simultaneously with the OPF problem, but solved by