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Optimal location of PWM based series compensator in a power system

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ABSTRACT

This paper proposes a new approach for optimal placement of PWM based Series Compensator (PWMSC) in large power systems. The proposed approach is based on the Selective Modal Analysis (SMA) and dynamics index to damp out the inter-area oscillation modes. For this reason, first, SMA is used to calculate the low frequency modes of oscillation, and then Most Dominant Line (MDL) Table based on the dynamic index is proposed which shows the influence of active power flows of the transmission lines on inter-area modes of the power system. The parameters of the PWMSC damping controller are designed by optimization based approach for the purpose of damping inter-area oscillations in practical system. Optimal PWMSC placement is validated by comparing different candidate placements based on the total damping that they provide for system. The effectiveness of the proposed method is demonstrated on the 16-machine five-area power system for various network conditions.

1. Introduction

Series compensation was added to the power systems to cancel a portion of the reactive line reactance for improving the stability as well as increasing effectively the power transfer capability. Development of power electronics introduces the use of flexible AC transmission systems (FACTS) technologies in power networks [1]. Subsequently, it has been presented that variable series compensation is highly effective in both controlling power flow in the transmission lines and in improving dynamic stability [2]. Because different FACTS placements can cause important differences in the dynamic behavior of the system, placements should be chosen with care. It should be noted that not only can a good placement improve the stability of the system, a poor placement can provide undesirable performance.

The PWM based Series Compensator (PWMSC), a new series-FACTS controller, provides the virtual compensation of transmission line impedance by injecting the controllable reactance in series with the line. The ability of PWMSC to operate in capacitive as well as inductive mode makes it very effective in controlling the power flow of the network. Such compensators [3,4] have the advantage of being simpler in both power circuit structure and more importantly control. It is known that transmission lines loading may be restricted by system dynamics stability. The PWMSC is a powerful new tool to help relieve these constraints. Furthermore, its controller can be designed to modify the line reactance and provide enough damping to system oscillation modes.

In recent years, several papers have been published to discuss ways to answer the question of which optimal location and appropriate stabilizing signals could result in the FACTS devices having the maximum effect on the network. Majority studies considered only static criterion like improving power transfer, available transfer capability and loss minimization [5–7] and did not consider any dynamic criteria for the optimal placement of the FACTS technologies. Gupta et al. [8] introduced a hybrid participation factor for appropriate placement of Static VAR Compensator (SVC), using both dynamic and static criteria to improve the voltage stability. Okamoto et al. [9] proposed effective modal controllability index to find optimal location for damping inter-area mode of oscillations. However, this method needs to calculate the sensitivity function of the real power output of the generator participating in the inter-area mode of oscillations with respect to each line, thus, if the number of lines increases, then the computational burden increases. In Ref. [10], a fast algorithm based on controllability indices has been proposed for optimal placement of FACTS controllers. In this algorithm, it is assumed that FACTS devices can be located simultaneously on all lines of the case study. Based on this assumption, additional terms augment the original state space system and are used to determine the optimal placements. Eigenvalue sensitivity based approach has also been used in [11]. The small eigenvalue sensitivity for a given mode generally means that there is little leverage over that oscillation mode. The main drawback of this technique is that the suitable feedback signals are not chosen according to the optimal location.

In this paper, a Selective Modal Analysis (SMA) has been used for calculating the power system oscillation modes of interest and dynamic placement. The SMA algorithm [12,13], for reduced order eigenanalysis, assumes a separation of the state variables

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into relevant and less relevant for the modes of interest. The modes of interest in power system small-signal stability analysis are the electromechanical ones whereas the relevant variables are the state variables that describe the rotor dynamics (the rotor angle and speed of each generator). This algorithm guarantees not only the accuracy of the results but also that the order of all matrices involved in the calculation is not higher than the number of machines in the large power system. Thus, the numerical difficulty in the eigen-solution of high dimensional matrices is successfully avoided and the computational burden is greatly reduced. In the following, after obtaining the critical eigenvalues by SMA algorithm, a new dynamic performance index is proposed that provides a method to compare different candidate placements in terms of the damping oscillations.

The main motivation of this paper is:

- Find the optimal location and damp out the inter-area oscillations using the PWMSC in a large scale power system.
- Introducing a dynamic performance index to optimal location of PWMSC.
- Optimization of the PWMSC damping controller parameters to improve dynamic stability.

The proposed approach is introduced in detail in the rest of the article as follows: Section 2 presents the operation and model of the PWM based series compensator. Section 3 describes the selective modal analysis algorithm for calculating the oscillation modes of interest. Section 4 presents the dynamic index to select the most effective location of series compensation. An optimization based approach has been used for designing the damping controller in Section 5. Section 6 points out the simulation results. Lastly, discussion and conclusions follows.

2. Mathematical model of PWMSC

A newly developed AC link converter based series compensation, a new series-FACTS controller, is presented here. The PWM based series compensators exploit the concept of the variable series reactance compensation. It is known that transmission lines loading may be restricted by power system dynamics stability. The power circuit of the proposed compensator inserted in series with a transmission line is shown in Fig. 1 [14].

The PWMSC consists of: (a) series injection transformers (b) compensation capacitors and (c) PWM controlled switches S_a, S_b, S_c, S'_a, S'_b and S'_c. In Fig. 1, the three switches S_a, S_b, S_c are with the same switching function in a complementary way to those in S'_a, S'_b and S'_c switches. The switching period divides the circuit in two switching states. When S'_a , S'_b and S'_c are *on*, the capacitors are inserted to the system through a series injection transformer. When S'_a, S'_b and S'_c are *on* the series injection transformer is shorted, thereby isolating the capacitors from the system. Switches S'_a, S'_b and S'_c are controlled with the complementary signal so as to provide a freewheeling path for the currents at the secondary of the coupling transformer when the main switches are *off*. The compensator operates as a means for controlling continuously the degree of series compensation through the variation of the duty cycle of a single asynchronous train of pulses with fixed frequency. The duty cycle (D) of the AC link converter is defined as the ratio of the on-period of switches S'_a, S'_b and S'_c with respect to the total switching period.

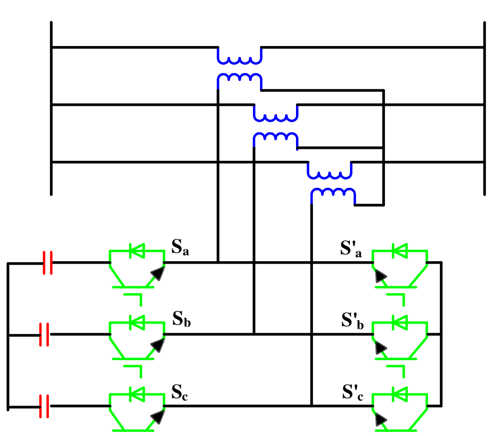

Fig. 1. Block diagram of the PWMSC structure.

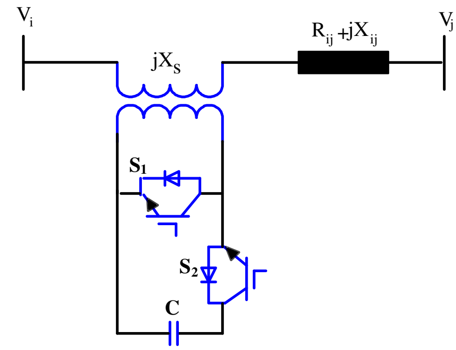

Fig. 2. Single line diagram of PWMSC.

Consider a line l, having reactance X_{ij}, connected between buses i and j (Fig. 2). If the reactance of injected series compensator placed in the line l is X_s. The primary series transformer is represented by a leakage reactance (X_T) in series with an ideal transformer at transmission line side. In the secondary, there is the AC link converter and a bank of capacitors with reactance X_C that is switched PWM technique. The equivalent and injected impedances at transmission line may be calculated with state space averaging techniques as follows [13]:

$$X_{eq} = X_{ij} + X_T + X_S \tag{1}$$

$$X_S = -n^2(1 - D)^2 X_C \tag{2}$$

where n is the turns ratio of the transformer. Eqs. (1 and 2) show that the effective impedance depends on the duty cycle of the AC link switches; hence, this duty cycle provides a means of realizing the desired controllable impedance, power flow at line and power oscillations control. Also, it can be seen that the injected reactance using PWMSC can be varied continuously between two extreme values. The leakage reactance of the series transformer in *pu* and the rated capacitive reactance of the compensator. The data of the PWMSC is presented in Appendix A.

3. Proposed dynamic index

3.1. SMA algorithm

The SMA algorithm is a comprehensive framework for accurate, efficient and physically based modeling and analysis of selected portions of the structure and behavior of LTI dynamic systems [12]. With SMA the part of the model that is relevant to the dynamics of interest is singled out in a direct manner and the remainder of the model is collapsed in a way that leaves the selected structure. In general, the power system model for the small signal