An Adaptive Controller for Power System Stability Improvement and Power Flow Control by Means of a Thyristor Switched Series Capacitor (TSSC)

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***Abstract*—In this paper, a controller for a thyristor switched series capacitor (TSSC) is presented. The controller aims to stabilize the power system by damping interarea power oscillations and by improving the transient stability of the system. In addition to this, a power flow control feature is included in the controller. The power oscillation damping controller is designed based on a nonlinear control law, while the transient stability improvement feature works in open loop. The damping controller is adaptive and estimates the power system parameters according to a simplified generic model of a two-area power system. It is designed for systems where one poorly damped dominant mode of power oscillation exists. In the paper, a verification of the controller by means of digital simulations of one two-area, four-machine power system, and one 23-machine power system is presented. The results show that the controller improves the stability of both test systems significantly in a number of fault cases at different levels of interarea power flow.**

***Index Terms*—Power flow control, power oscillation damping (POD), thyristor controlled series capacitor (TCSC), thyristor switched series capacitor (TSSC), transient stability.**

I. INTRODUCTION

Flexible ac transmission systems (FACTS) devices have, during the last decades, arisen as an option to improve the stability and to resolve congestions in today's power systems, which are often loaded to levels close to their security limits. These devices, which are based on power electronics, operate by controlling reactive and active power injections in the power system, or by altering the grid characteristics by controlling line reactances or voltage angles at critical nodes. In this paper, a controller for a thyristor switched series capacitor (TSSC) is presented. This is a device capable of changing the apparent reactance of a line in a number of discrete steps. The controller is developed using a continuous approach, making it suitable for use also with devices like the thyristor controlled series capacitor (TCSC) having continuous reactance control. The proposed controller is a power-oscillation-damping (POD) controller, which includes features for transient stability improvement and power flow control. The main focus of this work is on POD, which is a challenging task due to the changing nature of the structure of the power system and the operating conditions.

POD is traditionally performed by power system stabilizers (PSS) connected to the automatic voltage regulators (AVR) of the generators in the power system. Properly tuned, these can effectively damp both local and inter-area modes of power oscillation. However, in many power systems, supplementary damping of the power oscillations may improve the system stability further which can increase the transfer capability of critical lines in the system. Many POD controllers have been presented during the years. Most approaches are based on a power system model with full or reduced complexity, which is linearized. In such a system, linear control theory can be applied and the poles of the closed-loop system can be placed such that the damping of the critical oscillation modes is improved [1]. The downside of linearized approaches is that they are based on a specific operating point of the power system and a specific system topology. Operation far from the point of linearization or with a changed system topology, which is often the case after large disturbances, may lead to insufficient damping of the power oscillations. To address these issues, other approaches for control design have been investigated. One approach is robust control, where H_∞-controllers in particular are popular [2]–[4]. Here, the possible changes to the system and the operating point are classified as uncertainties of the transfer function. Another approach is adaptive control, where gain-scheduling [5], multiple-model [6], and fuzzy-logic [7] approaches have been proposed. In this paper, an adaptive controller based on a simple generic system model is proposed. The controller is based on a nonlinear control law that combines the demand of POD with the demand of power flow control. The advantage of using a generic system model is that it requires only limited knowledge of the system data and that it can be used in many different systems as long as the basic assumptions hold. In this paper, the main assumption is that the system exhibits electromechanical interarea oscillations with one dominating mode of oscillation.

This paper is organized as follows. Section II describes the generic system model, which is used for the control design, Section III introduces the four-machine and 23-machine test systems, and Section IV introduces the principles for the design of the damping controller. In Section V, the estimation process of the system parameters is described, and Section VI introduces the transient stability improvement approach. Section VII then describes the complete proposed controller, and the simulation results are discussed in Section VIII. Finally, the conclusion is drawn in Section IX.

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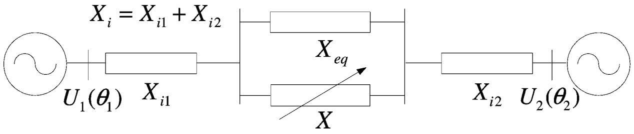

Fig. 1. Generic system model used for control of the TSSC.

II. Generic System Model

In order to design a POD controller, a system model is required. The nature of interarea oscillations is often such that there is a dominant mode of oscillation, which is significantly less damped than all other modes. With this in mind, a simple way to reduce the total power grid is to view it as a system split into two grid areas and the reactances of the lines interconnecting the areas [8], as seen in Fig. 1. Here, each area is represented by a single synchronous machine with a lumped moment of inertia. In this study, the model parameters are estimated continuously by the controller as the controlled series compensator (CSC) reactance changes, using the locally measured responses in the active power (P_X) of the CSC line. This line is represented by a variable, known reactance X, which is the sum of the uncompensated line reactance X_0 and the controlled CSC reactance X_{CSC}. The model is characterized by four additional parameters: one series reactance X_i, one parallel reactance X_{eq}, the frequency of the interarea oscillation f_{osc}, and its damping exponent σ assuming the oscillation to be of the form $P(t) = e^{\sigma t}\sin(2\pi f_{\text{osc}} t)$. The inner voltages of the machines are described by voltage phasors of magnitudes $E_{1,2}$ and phase angles $\delta_{1,2}$ while the terminal voltages of the machines are assumed to be well controlled by AVR and described by voltage phasors of constant magnitudes $U_{1,2}$ and variable phase angles $\theta_{1,2}$. The transient reactances of the machines are denoted X'_{d1} and X'_{d2}.

III. Test Systems

Two different test systems are used to study the performance of the proposed controller. A four-machine system, as shown in Fig. 2, and a 23-machine system, as shown in Fig. 3. The four-machine system is based on a commonly used 230 kV/60 Hz system for studies of interarea oscillations [9]. Some changes are made from the original system: one tie line is added and the length of the lines interconnecting the two grid areas is stretched to 300 km. Shunt compensation in node 8 is also inserted to maintain a good voltage profile. The generators are equipped with fast exciters and PSS units with an intentionally selected low gain in order to give a system with a small positive damping ratio. The test system has two local power oscillation modes with a frequency in the range of 1 Hz with a reasonable damping and one interarea mode of oscillation with a frequency in the range of 0.6 Hz, which is poorly damped. One important goal for the TSSC in this system is to improve the damping of the interarea mode. The 23-machine system is the Nordic 32 system built to model the dynamics of the Nordic power system [10]. This system is in its original form well damped, mainly because of well-tuned PSS units connected to the system generators. A discussion of the original system characteristics is found in [11]. The loads in the original system are modeled using voltage- and frequency-dependent load models. To challenge the damping controller, all of the PSS units used in the system were disconnected and the load characteristics were changed to voltage-independent loads at nodes 2031 and 2032, and voltage- and frequency-independent loads at nodes 41, 42, 43, 46, and 51. The system was studied in the normal load case (lf029) and the peak load case (lf028) described in [10]. In the peak load case, the system has the least damped modes: $\sigma_1 = -0.016, f_1 = 0.50$ Hz; $\sigma_2 = -0.21, f_2 = 0.74$ Hz; $\sigma_3 = -0.24, f_3 = 0.88$ Hz; whereas in the normal load case, the least damped modes are $\sigma_1 = -0.09, f_1 = 0.54$ Hz; $\sigma_2 = -0.21, f_2 = 0.73$ Hz; and $\sigma_3 = -0.27, f_3 = 0.89$ Hz. The least damped, critical mode, corresponds to the generators in Finland (4071, 4072) and the northern part of Sweden (4011, 4012, 1012, 1013, 1014, 1021, and 1022) swinging toward the rest of the system. To improve the damping of this mode, to improve the transient stability in the system, and to control the power flows in the system, a TSSC device is placed in series with the line 4011–4021, where the observability and controllability of the critical mode is good.

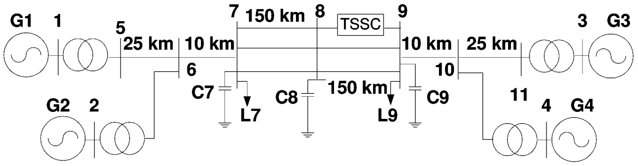

Fig. 2. Four-machine test system.

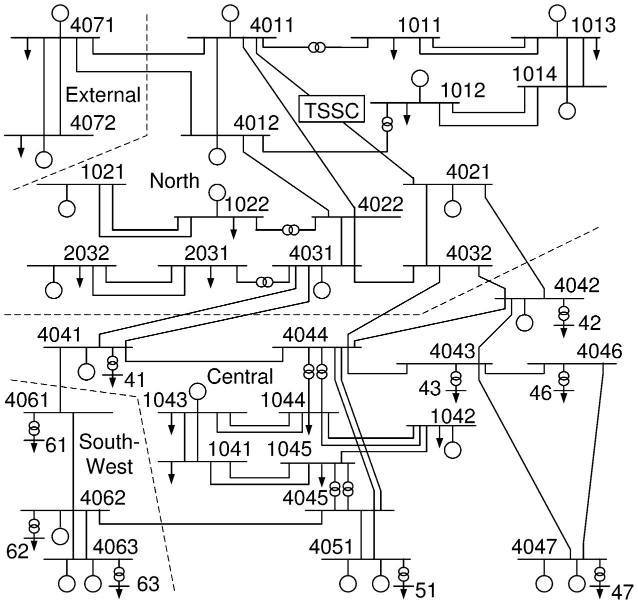

Fig. 3. Twenty-three-machine test system—Nordic 32.

IV. Principles of POD

Consider an ideal CSC located on one of the tie-lines N8–N9 in the four-machine test system. Fig. 4 shows the result of a time-domain simulation of a step change in the CSC reactance when the system is initially in steady state. It can be seen that an interarea oscillation is generated as a result of the action of the CSC. If a three-phase to ground fault at node 8 is simulated at $t = 1.0$ s and cleared after 100 ms with no line disconnection