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Fuzzy based damping controller for TCSC using local measurements to enhance transient stability of power systems

Mohsen Bakhshi, Mohammad Hosein Holakooie, Abbas Rabiee *

Department of Electrical Engineering, University of Zanjan, Zanjan, Iran

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A B S T R A C T

This paper proposes a local fuzzy based damping controller (LFDC) for thyristor controlled series capacitor (TCSC) to improve transient stability of power systems. In order to implement the proposed scheme, detailed model of TCSC, based on actual behavior of thyristor valves, is adopted. The LFDC uses the frequency at the TCSC bus as a local feedback signal, to control the firing angle. The parameters of fuzzy controller are tuned using an off-line method through chaotic optimization algorithm (COA). To verify the proposed LFDC, numerical simulations are carried out in Matlab/Simpower toolbox for the following case studies: two-area two-machine (TATM), WSCC three-machine nine-bus and Kundur's two-area four-machine (TAFM) systems under various faults types. In this regard, to more evaluate the effectiveness of the proposed method, the simulation results are compared with the wide-area fuzzy based damping controller (WFDC). Moreover, the transient behavior of the detailed and phasor models of the TCSC is discussed in the TATM power system. The simulation results confirm that the proposed LFDC is an efficient tool for transient stability improvement since it utilizes only local signals, which are easily available.

1. Introduction

Flexible AC transmission systems (FACTS) devices are effective tools to enhance power transmission capability, stability margin and voltage profile. Among various types of FACTS devices, thyristor controlled series capacitor (TCSC) is an economical and efficient choice to improve dynamic behavior of interconnected power systems via fast and smooth variation of the transmission line reactance [1–4].

Different applications of TCSC have been widely addressed in technical literature, which confirm capability of TCSC in the face of detrimental phenomena such as transient instability and subsynchronous resonance (SSR). The series capacitor inherently raises the probability of SSR problem. In this regard, a number of articles have developed the structure of TCSC controller to eliminate the SSR problem [5–7]. In order to improve small signal stability and damping of both local and inter-area electromechanical oscillations, power system stabilizer (PSS) is vastly used as the first choice [8]. On the other hand, in the recent years coordination between PSS and various types of FACTS devices has been examined as an alternative methodology instead of conventional PSS-based damping controllers. To address the mentioned subject, supplementary damping controllers (SDCs) are presented in [9–11]. Moreover, the robust H_∞ damping controller is developed in [12]. A TCSC fuzzy damping controller based on transient energy function is discussed in [13]. Ref. [14] proposes the self-tuning fuzzy PI controller for enhancement of power system stability. Improvement of power system transient stability is another advantage of the TCSC. In Ref. [15], the authors studied transient stability by using trajectory sensitivity analysis in multi-machine power systems. In addition, transient stability has been improved using an artificial neural network and T-S model based fuzzy controller for TCSC in [16,17] respectively. It should be noted that the majority of researches in association with the TCSC have utilized simplified equivalent models such as linear and phasor models for TCSC, while the actual impacts of thyristor switches on the TCSC behavior have been neglected.

The TCSC input signals are usually divided into two main categories, local and remote signals. The remote signals require fast and safe communication infrastructure, which regardless of employing the modern communication systems, the communication failure is an inseparable feature of these systems [18]. Wide area measurement system (WAMS) is an interesting technology, which is based on synchronous phasor measurements and communication channels for implementation of wide area controllers (WACs). However, this technology is inherently suffered from time

* Corresponding author.
E-mail addresses: m.bakhshi@znu.ac.ir (M. Bakhshi), hosein.holakooie@znu.ac.ir (M.H. Holakooie), rabiee@znu.ac.ir (A. Rabiee).

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delay, which impresses the stability and reliability of the system. Moreover, determination of the maximum allowable time delay is another challenge for the WAC-based power systems [19].

This paper proposes a local fuzzy based damping controller (LFDC) for TCSC to enhance the transient stability of multi-machine power systems. The employed local control signal is the frequency of the voltage at the TCSC installed bus, which is dependably available. In order to verify the performance of proposed LFDC scheme, it is compared with wide-area fuzzy based damping controller (WFDC). Since, wide-area measurements are available after a certain time delay, and due to the failure of communication infrastructures, the performance of WFDC scheme is analyzed and compared with the proposed LFDC in the presence of such practical limitations. The comparative results of the LFDC and WFDC in different test systems substantiate that the proposed LFDC can satisfy the desired performance under different types of faults. Furthermore, the detailed model of TCSC is implemented, which gives more realistic results than its conventional phasor model. Briefly, the main contributions of this paper are:

- Utilization of local signal (frequency at the TCSC bus) instead of wide-area signal (rotor-speed) to design TCSC damping controller.
- Implementation of detailed model of TCSC and surveying the effect of this model on the behavior of power system low frequency oscillations.
- Developing a fuzzy controller with optimized coefficients using COA algorithm.
- Presenting a complete comparative study to examine the performance of the proposed LFDC scheme in different case studies for normal condition and different communication links delays and failures.

The rest of this paper is organized as follows. Section 2 introduces the detailed model of TCSC. Section 3 describes the proposed LFDC which includes the preliminary remarks, the fuzzy controller and the chaotic optimization algorithm (COA). Case studies and simulation results are presented in Sections 4 and 5, respectively. Finally, Section 6 summarizes the findings and concludes the paper.

2. Detailed model of TCSC

The TCSC is usually composed of a fixed capacitor (FC) in parallel with a thyristor controlled reactor (TCR). The TCR consists of bi-directional and anti-parallel thyristor valves in series with a reactor. In power system stability studies, the TCSC increases the stability margin by manipulating the equivalent series reactance of transmission line. The fundamental frequency reactance of the TCSC is calculated as follows [2]:

$$X_{TCSC} = X_C - \frac{X_C^2}{X_C - X_L}\cdot\frac{2\beta + sin(2\beta)}{\pi} + \frac{4X_C^2}{X_C - X_L}\cdot\frac{cos^2(\beta)}{k^2-1}\cdot\frac{k.tan(k\beta) - tan(\beta)}{\pi} \quad (1)$$

with:

$$\alpha + \beta = \pi \quad (2)$$

where $k = \sqrt{X_C/X_L}, X_C, X_L, \alpha$ and β are the reactance of the FC, reactance of the TCR reactor, delay firing angle and conduction angle, respectively. The mentioned equation has been achieved with the assumption that the voltage across the TCSC is non sinusoidal. The TCSC is operated in inductive mode when delay firing angle is the interval $[\pi/2, \alpha_{cri}]$, whereas the capacitive mode is obtained for $[\alpha_{cri}, \pi]$. α_{cri} is called critical firing angle and can be obtained as follows [2]:

$$\alpha_{cri} = \pi\left(1 - \frac{1}{2k}\right) \quad (3)$$

At the above firing angle, the reactance of TCSC is tended to infinite. Therefore, it is necessary to define an unavailable bound.

3. Proposed local fuzzy based damping controller

3.1. Preliminary remarks

Conventionally, FACTS controllers utilize generators mechanical speed deviations as remote feedback signals to damp the electromechanical oscillations, since such oscillations directly observable from mechanical speed [20]. Remote signals which are available via WAMS, can be used for effectively damping of electromechanical oscillations through WACs. Unavailability of communication infrastructures is the main problem of such method. Moreover, the communication channel inherently causes a time delay. As a result, a robust damping controller design based on local signals is an interesting work from the practical point of view.

Structure of the proposed LFDC is shown in Fig. 1(a). This controller utilizes a local signal, which can be easily provided from the TCSC installation bus. According to the proposed method, a specific local parameter as a feedback signal is measured from the TCSC bus. This signal is compared with the reference value and the resultant error is applied to the fuzzy controller. Subsequently, the output of the fuzzy controller is the reference value of TCSC reactance. Then, the acquired signal is passed through a lookup table to obtain the delay firing angle. By substituting (2) in (1), X_{TCSC} is expressed as $X_{TCSC} = f(\alpha)$. Then, the lookup table is constructed using this expression. However, (1) is mathematically nonlinear and analytical calculation of $\alpha = f^{-1}(X_{TCSC})$ is impossible. In this study, curve fitting technique is used to overcome the problem. The inductive and capacitive areas are fitted by one and three third-order polynomial curves (totaly four curves), respectively as follows:

$$X_{TCSC}(\alpha) = a_1\alpha^3 + a_2\alpha^2 + a_3\alpha + a_4 \quad (4)$$

The coefficients $a_k, (k = 1, \ldots, 4)$ are given in Appendix. It should be noted that all of the above equations are strictly ascending/descending and their inverse can be easily calculated.

Various signals such as active power flowing through the line, frequency and voltage at the TCSC installed bus can be used as an input for the fuzzy controller. The electromechanical oscillations are observable through the electrical frequency and hence this paper proposes the local electrical frequency as the input signal for the LFDC.

To verify the performance of the proposed LFDC, the WFDC is also employed which is based on wide-area measurements. In this sense, the generator speed is measured and transmitted to the TCSC bus by a communication channel. The diagram of the WFDC scheme is shown in Fig. 1(b).

In order to design the fuzzy controller in such a nonlinear system consists of TCSC, generators and transformers, the trial-and-error method is conventionally adopted [21]. However, optimum design of the controller may not be obtained by this method. Heuristic techniques provide intelligent trial-and-error procedures, and hence, in this paper the chaotic optimization algorithm (COA) is adopted in order to optimal design of the fuzzy controller.