Enhancement of Power System Oscillation Damping using Fuzzy Inference System based Coordinated Design of SSSC Controllers

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Abstract

Nowadays, Flexible AC Transmission System (FACTS) devices are widely used in different power systems. As the application of these technologies increases, possible interferences in operational tasks of controllers and inappropriate oscillations in different situations like fault and post-fault conditions make the coordination of their controllers inevitable. In this paper, a Fuzzy Inference System (FIS) based coordinated design of Static Synchronous Series Compensator (SSSC) controllers is presented and discussed. The main advantages of the proposed scheme are good damping and overshoot reduction of oscillations and thereby improving power oscillations damping. The Trajectory Sensitivities (TS) analysis, which is a time domain method to evaluate the stability of a system in the presence of disturbances, is also used to assess the validity of this coordinated controller design method. The comparison of simulation results with the conventional *Proportional-Integral-Derivative* (PID) controller based system validates the effectiveness of this design.

Keywords: Coordinated Design, Fuzzy Inference System, Flexible AC Transmission System, Power System Oscillations, Static Synchronous Series Compensator

1. Introduction

FACTS devices can change power transmission parameters and therefore, can affect the power flow in the power system[1,2]. This effect is not limited to a -pre-specified area and can impress upon the operation of the entire network and devices. The presence of FACTS devices in a power system can also cause interferences in their operation and usually results in undesirable power oscillations[2-4]. Also, these phenomena might occur among FACTS devices and other controllers, resulting in a wide range of oscillations and therefore investigated from voltage stability and small signal stability points of view[5,6]. Many different efforts have been made to coordinate the design of these devices[7-12]. These researches can be divided into three, sensitivity analysis, optimization and artificial intelligence application categories.

There are various sensitivity analysis based methods including modal analysis, eigen value analysis and index based methods. The eigen value sensitivity based analysis approach for design of FACTS controllers in multi-machine power system and a similar approach for coordinated design of multiple stabilizers, has been addressed in[13-15]. A similar method has been proposed in[11] for modeling and simulation of Static VAR Compensator (SVC) and Thyristor-Controlled Series Capacitor (TCSC) to study their load ability limits. Additionally, in[16], a probabilistic theory has been applied to an eigen value sensitivity analysis based PSS design in multi-machine systems. In[17], a small-signal technique has been proposed for the power

grid of China Southern and the optimal control strategies have been investigated for PSS control and High Voltage Direct Current (HVDC) damping controllers. The FACTS controllers have been accepted for power control and enhancing power system dynamic performance and in[18,19], the coordination of the power controller for achieving above objectives has been proposed. Some other researches have concentrated on developing optimization approaches for coordinated design of FACTS devices. An overview of internal and external control schemes has been presented for power system optimization and coordination of series FACTS devices[19]. In[20], Panda and Padhy have used the Particle Swarm Optimization (PSO) technique for the coordinated design of PSS and TCSC for the power system stability enhancement. Coordination of different Voltage Source Converters (VSC) for improving power oscillation damping has been discussed in[21]. Moreover, a coordination algorithm based on both sensitivity analysis and linear optimization technique, has been also utilized for FACTS devices coordinated control and load shedding in[22].

The last category of researches in this field is based on utilizing artificial intelligence methods. A damping controller based on fuzzy logic for Automatic Generation Control (AGC) optimum transient operation has been discussed in[23]. An adaptive coordinated control of PSSs and damping controllers in a power system based on Artificial Neural Network (ANN) theory[24] and a nonlinear programming based algorithm for design of simultaneous coordinated tuning of PSS and FACTS controllers, in order to improve the system oscillations damping[25] are among in this group of researches. Moreover in[26], a cooperative fuzzy-genetic controller has been utilized for Damping Power System Oscillations in multi-machine systems. Finally in[27] and [28], a control system based on ANN and fuzzy techniques has been used respectively to prevent power system instabilities. This paper suggests a fuzzy inference system rule based coordinated design of SSSC controllers in a power system which leads to power system oscillations damping and stability enhancement. The Trajectory Sensitivity (TS) analysis is also utilized for assessment of the dynamic behavior of the control scheme in fault and post-fault conditions. The results verify the validity of the proposed method.

The organization of the paper is as follow: In section 2, modeling of SSSC and its structure is discussed. Section 3 is devoted to the explanation of the fuzzy rule based inference system. Section 4 describes TS method and dynamic stability assessment. In section 5, the proposed coordinated control scheme is described. Section 6 contains the simulation and test results and finally section 7 concludes the paper.

2. Modeling of SSSC

The SSSC is among series devices of the FACTS family, which is able to exchange the active and reactive power with the transmission system, control the power flow and improve the system stability and security. The basic model of the series compensator with a voltage source converter is shown in Figure 1.

This model consists of a voltage-sourced converter and a transformer connected in series with a transmission line. By injecting a variable voltage magnitude with a phase angle in quadrature with the line current, an inductive or capacitive reactance can be emulated. This emulated variable reactance in series with the line can impress upon the transmitted electric power[29].

3. Fuzzy Rule based Inference System

3.1 Fuzzification

The fuzzification is a process in which variable crisp real values would be mapped into membership functions of fuzzy sets, representing the degree of the truth of values. All inputs and outputs will be fuzzified by three fuzzy sets as shown in Figure 2.

P, Z and N denote positive, zero and negative sets, respectively. $\mu_p(x_i), \mu_N(x_i)$ and $\mu_Z(x_i)$ also describe the membership function of positive, negative and zero sets, respectively, while represents the crisp input of each one and all are defined in triangular form.
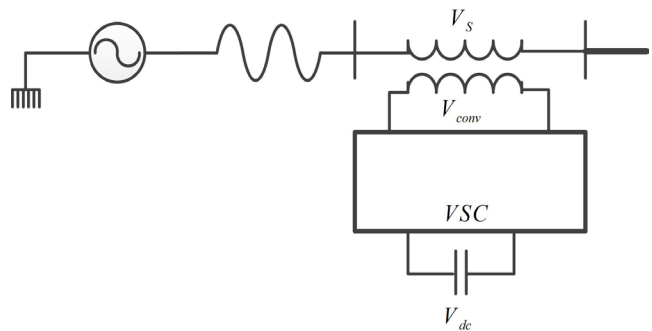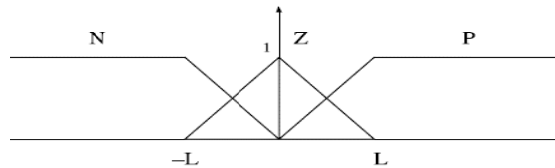

Figure 1. SSSC modeling.

Figure 2. Fuzzy controller membership functions.

3.2 Inference and Defuzzification

These linguistic rules are based on expert knowledge of system and would determine controller behavior. Based on Mamdani's inference method, the fuzzy rule bases of controllers are listed in Tables 1 and 2. For the purpose of converting linguistic output variables of the inference system to numerical values, defuzzification is necessary and centroid defuzzification technique is utilized for both controllers in this design.

4. TS Method and Dynamic Stability Assessment

The stability margin, which is defined for a particular disturbance, can be thought of as the smallest "distance" between the system trajectory and the stability boundary. A large margin demonstrates the system is very stable (for that disturbance), while a margin of zero implies being on the instability borders[30].

The power system dynamic model can be written in the form of differential-algebraic equations, as follows[31]:

$$\dot{x} = \mathcal{F}(x, y; k), x(t_0) = x_0 \qquad (1)$$

$$0 = \mathcal{G}(x, y; k), y(t_0) = y_0 \qquad (2)$$

Where x, y and k are state vectors, algebraic variables vector and system parameters vectors, respectively. The sensitivities of state trajectories with respect to system parameters can be found by perturbing k from its nominal value k_0. The flows of x and y can be respectively defined as follows:

$$\dot{x} = \mathcal{F}_x(t)x_\lambda + \mathcal{F}_y(t)y_\lambda + \mathcal{F}_\lambda(t) \qquad (3)$$

and

$$0 = \mathcal{G}_x(t)x_\lambda + \mathcal{G}_y(t)y_\lambda + \mathcal{G}_\lambda(t) \qquad (4)$$

Where, $f_x = \dfrac{\partial f}{\partial x}$, $f_y = \dfrac{\partial f}{\partial y}$, $f_\lambda = \dfrac{\partial f}{\partial \lambda}$, $g_x = \dfrac{\partial g}{\partial x}$, $g_y = \dfrac{\partial g}{\partial y}$ and $g_\lambda = \dfrac{\partial g}{\partial \lambda}$ are relative derivatives and $x_\lambda = \dfrac{\partial x}{\partial \lambda}$ and $y_\lambda = \dfrac{\partial y}{\partial \lambda}$ are the sensitivities.

Table 1. Fuzzy rule base of SSSC 1 controller

SSSC1 load \ SSSC2 load	N	Z	P
N	Z	P	P
Z	Z	Z	Z
P	N	N	Z

Table 2. Fuzzy rule base of SSSC 2 controller

SSSC1 load \ SSSC2 load	N	Z	P
N	Z	P	P
Z	Z	Z	Z
P	N	N	Z

Two values of k are chosen (λ_1 and λ_2) and the corresponding state vectors x_1 and x_2 are respectively computed. Then, the sensitivity is determined, as follows:

$$Sens = \frac{\partial x}{\partial y} \approx \frac{\varDelta x}{\varDelta y}$$

$$\frac{x_2 - x_1}{\lambda_2 - \lambda_1} \qquad (5)$$

In the case of power systems, the sensitivity of state variables, e.g., the generator rotor angle (δ) and speed deviation (Δw_r) are computed by the Eq.(5). These sensitivities obtain information about the result of parameters changes on individual state variables and therefore, on the generators, which the particular state variable is associated to. In order to determine the whole system condition, all these effects of parameter changes on individual generators can be summarized by the norm of sensitivities.

The sensitivity index for the multi-machine test system is given, as follows:

$$S_N(t) = \sqrt[2]{\sum_{i=1}^{m}\left(\left(\frac{\partial \delta_i}{\partial t_{cl}} - \frac{\partial \delta_j}{\partial t_{cl}}\right)^2 + \left(\frac{\partial w_i}{\partial t_{cl}}\right)^2\right)} \qquad (6)$$

that, the jth-machine is chosen as the reference machine.

The new term η has been presented in[32] and define d as $\eta = \dfrac{1}{max(S_N(t))}$. Whenever the system meets instabilities, η will be zero and hence, the amount of η shows the distance from instability[31-34].

5. Control Scheme

5.1 SSSC Power Oscillation Damping Controller

The SSSC injected voltage reference is normally set by a Power Oscillation Damping (POD) controller whose output is connected to the input of the SSSC controller. Generally, the structure of SSSC POD controller, as shown in Figure 3, is similar to a PSS controller. Local signals of SSSC are applied to the damping controller. In the simulation, the active power flow through the SSSC (P_{Line}) is employed. The output is V_{series}, which represents the controlled variable of the SSSC.

The POD controller consists of active power measurement system, general gain, low-pass filter, washout high-pass filter, lead compensator and output limiter. The input to the POD controller is the active power.

5.2 Coordinated Controller

As mentioned, there are different methods for the coordinated control of FACTS controllers in multi-machine power systems. In this paper, the coordinated control of SSSC controllers based on fuzzy logic is used to coordinate the parameters of the multi-machine power system as shown in the Figures 4 and 5.

6. Simulation Results

6.1 Test System

The 6-bus test system, used to validate the proposed model and control algorithm, is shown in Figure 6. The system's data is based on MATLAB software related models. The transmission system operates at 500kV/60Hz, and has not any SSSC. The power grid formed of two power generation buses (M1 and M2) and one major load center at bus B3. The power generation bus M1 has a rating of 2100 MVA and M2 has a rating of 1400 MVA.
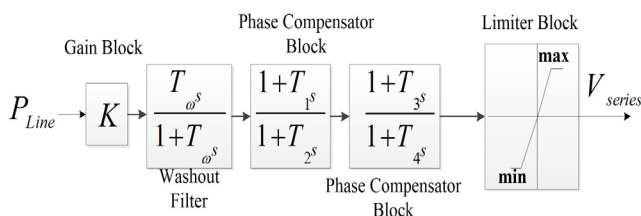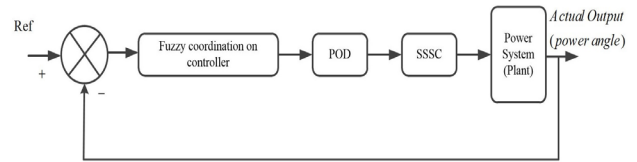

Figure 3. SSSC POD controller.

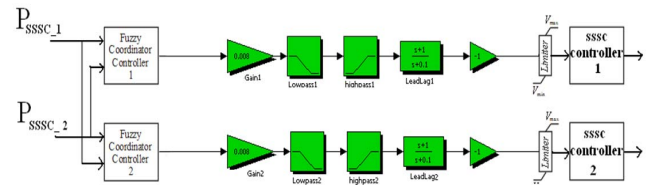**Figure 4.** Closed loop fuzzy controller used for POD-SSSC.

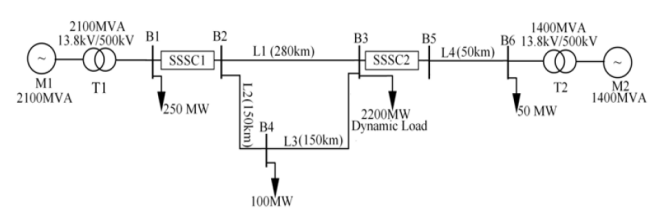**Figure 5.** Fuzzy-POD SSSC coordinated controller.

Figure 6. Test system model.

The load of 2200 MW is modeled using a dynamic load model, where the active and reactive powers absorbed by the load are functions of the system voltage.

The generation bus M1 is connected to this load through two paths. The generation bus M2 is also connected to the load by L4. Also, three loads are located at B1, B4 and B6 buses.

SSSC1 is located between B1 and B2 buses and SSSC2 is also placed between B3 and B5, both with the rating of 100MVA and are capable of injecting up to 10% of the nominal system voltage.

A three-phase fault with two different fault clearing times (10 and 20 cycles) is modeled in the B4, which does not have any SSSC. In following sections, the effectiveness of the proposed model for damping of oscillations caused by fault and fault clearing will be discussed.

In Table 3, lines length, resistance, inductance and capacitance per unit length is demonstrated.

6.2 Results

In this section, the performance of the proposed coordinated control scheme is evaluated using simulations by

Table 3. Lines details

Line segments	Length (km)	Resistance per unit length (Ohms/km)		Inductance per unit length (mH/km)		Capacitance per unit length (nF/km)	
		R1	R0	L1	L0	C1	C0
L1	280	0.02546	0.3864	0.9337	4.1264	12.74	7.751
L2	150	0.02546	0.3864	0.9337	4.1264	12.74	12.74
L3	150	0.02546	0.3864	0.9337	4.1264	12.74	12.74
L4	50	0.02546	0.3864	0.9337	4.1264	12.74	12.74

MATLAB software and its related toolboxes. The operation comparison and TS method based evaluation of coordinated and a non-coordinated system is also presented. The variation of η in the presence of a three-phase fault with two different fault clearing times (10 and 20 cycles) in the middle of line L2 is presented in Table 4. According to this table, as the clearing time increases, the value of η decreases. This implies that the stability condition of the system would deteriorate as the fault duration is increased.

As the system becomes more instable, the state trajectory shows more sensitivity to parameters variations[35]. Based on the equation 6, the sensitivity indices are depicted versus time in figures 7 and 8, for the cases with 10 and 20 cycles fault clearing time respectively. In order to have better realization, all the values of sensitivity indices are normalized by the maximum value of sensitivity index, which occurs in the case with 20 cycles clearing time. As it is demonstrated, coordinating the SSSCs will effectively reduce the state trajectory sensitivities. Moreover, in the case with more clearing time, the variation of sensitivity indices will be more which implies more system instability.

As mentioned before, the maximum amount of trajectory sensitivities are inversely related to the stability margin and η would approach zero at critical parameter values. Hence, the value of η gives an indication of distance from instability and so, this index can be used, to evaluate the stability of the system. With 20 cycles fault clearing time, the value of η for coordinated SSSC is more than 2 times greater than non-coordinated and in 10 cycles one, this value is also considerable. These values of η imply the enhanced stability of the system. The rotor angle of generators in both conditions (with and without coordination) with both 10 and 20 fault clearing times is shown in Figures 9 and 10. Finally, Figure 11 depicts the transmitted power from bus No.2 for a 10 cycle fault. The oscillation damping and overshoot reduction are clearly advantages of the proposed control scheme.

Table 4. TS analysis

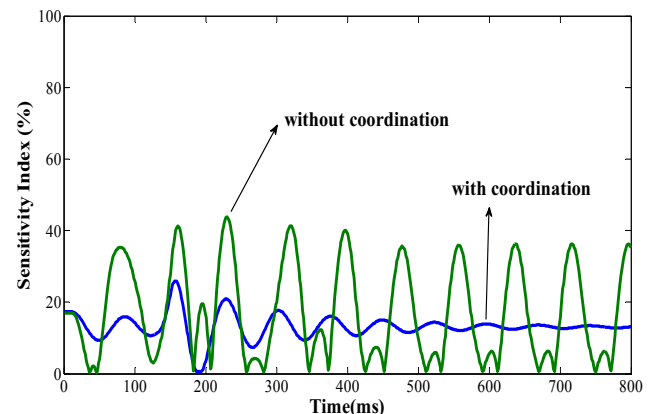| state	Variation of normalized Fault clearing time (cycle)	
	10	20
Without Coordination	0.32	0.14
With coordination	0.54	0.3

Figure 7. Sensitivity index for 10 cycle fault at bus 4.
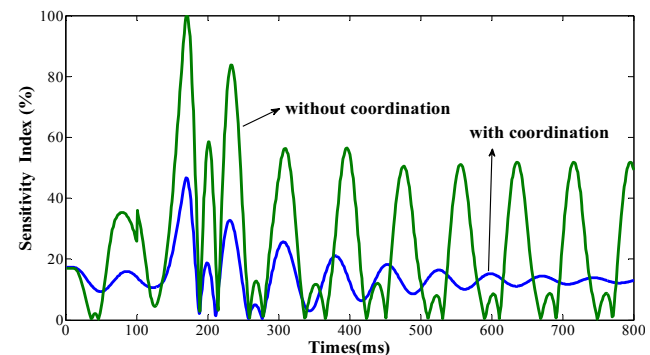

Figure 8. Sensitivity index for 20 cycle fault at bus 4.
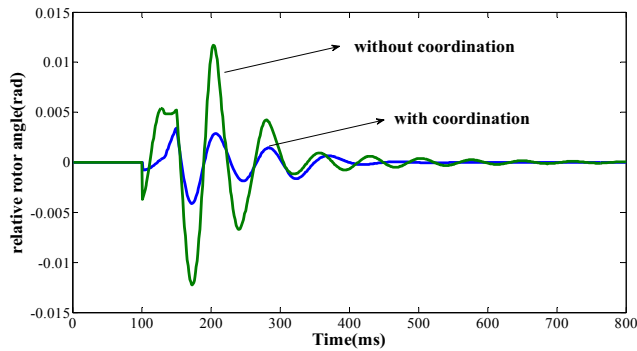
Figure 9. Comparison of relative rotor angles for 10 cycle fault at bus 4.
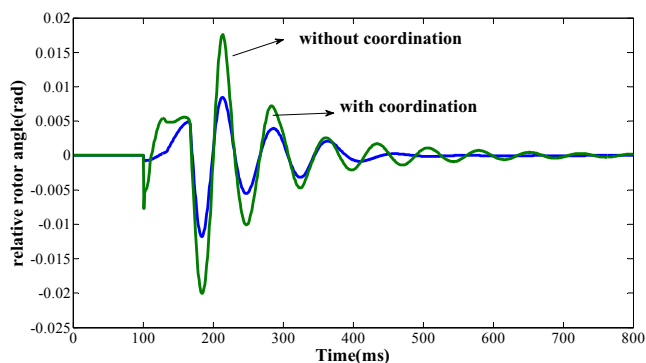

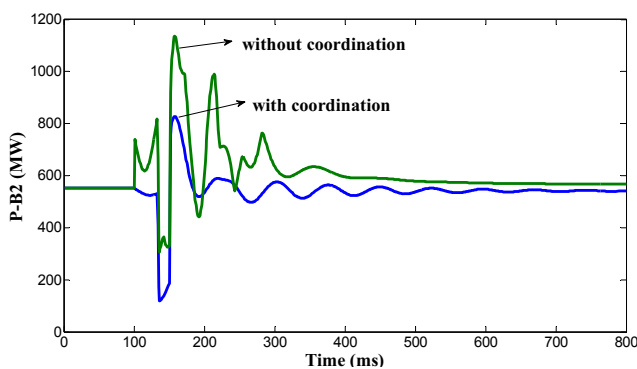**Figure 10.** Comparison of relative rotor angles for 20 cycle fault at bus 4.

Figure 11. Transmitted power from bus 2 for 10 cycles fault at bus 4.

7. Conclusion

This paper has presented a fuzzy rule based controller coordination for a multi-SSSC system. The trajectory sensitivity analysis has been used to assess the dynamic

stability of the proposed scheme. The main advantage of the proposed design is the power oscillations overshoot reduction and their damping and thereby enhancing the power system stability. TS analysis of state variables, like generator rotor angle and rotor speed deviation, introduces the proposed scheme as a suitable method for SSSC equipped power system stability enhancement.

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