Fuzzy Coordination of FACTS Controllers for Damping Power System Oscillations

Lijun Cai
Electrical Engineering Department
University of Duisburg
47057 Duisburg Germany
cailijun@uni-duisburg.de

István Erlich
Electrical Engineering Department
University of Duisburg
47057 Duisburg Germany
erlich@uni-duisburg.de

Abstract — **This paper concerns the optimization and coordination of the conventional FACTS (Flexible AC Transmission Systems) damping controllers in multi-machine power system. Firstly, the parameters of FACTS controller are optimized. Then, a hybrid fuzzy logic controller for the coordination of FACTS controllers is presented. This coordination method is well suitable to series connected FACTS devices like UPFC, TCSC etc. in damping multi-modal oscillations in multi-machine power systems. Digital simulations of a multi-machine power system subjected to a wide variety of disturbances and different structures validate the efficiency of the new approach.**

Keywords: **FACTS, Fuzzy Logic, Coordination, Fuzzy-Coordination Controller, Damping, Stability**

1. INTRODUCTION

Nowadays, FACTS devices can be used to control the power flow and enhance system stability. They are playing an increasing and major role in the operation and control of power systems. The UPFC (Unified Power Flow Controller) is the most versatile and powerful FACTS device [1]. The parameters in the transmission line, i.e. line impedance, terminal voltages, and voltage angle can be controlled by UPFC. It is used for independent control of real and reactive power in transmission lines. Moreover, the UPFC can be used for voltage support and damping of electromechanical oscillations [2~4]. In this paper, a multi-machine system with UPFC is simulated.

Damping of electromechanical oscillations between interconnected synchronous generators is necessary for secure system operation [5]. A well-designed FACTS controller can not only increase the transmission capability but also improve the power system stability. A series of approaches have been made in developing damping control strategy for FACTS devices. The researches are mostly based on single machine system. However, FACTS devices are always installed in multi-machine systems. The coordination between FACTS controllers and other power system controllers is very important.

Fuzzy-coordination controller is presented in this paper for the coordinated of traditional FACTS controllers. The fuzzy logic controllers are rule-based controllers in which a set of rules represents a control decision mechanism to adjust the effect of certain cases coming from power system. Furthermore, fuzzy logic controllers do not require a mathematical model of the system. They can cover a wider range of operating conditions and they are robust [6].

This paper focuses on the optimization of conventional power oscillation damping (POD) controllers and fuzzy logic coordination of them. By using fuzzy-coordination controller, the coordination objectives of the FACTS devices are quite well achieved.

The paper is organized as follows. Following the introduction, in section 2, three-machine system model and a UPFC model are introduced. Then in section 3 the control schemes for UPFC are discussed. In section 4 the parameters optimization and fuzzy-coordination controller design are proposed. The simulation results are given in section 5. Finally, brief conclusions are deduced.

2. SYSTEM MODEL

2.1. Power System Model

A three machine nine bus interconnected power system is simulated in this paper. There are two UPFCs in the power system: between Bus2 Bus3 and, Bus6 Bus7. The diagram of the power system model is shown in Fig. 1. The system parameters are given in Appendix 1.

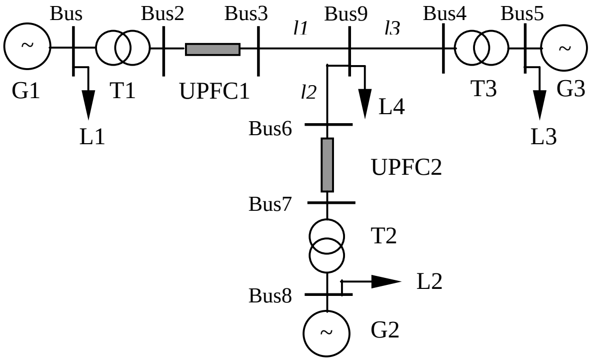

Fig. 1. Power system model

2.2. UPFC Model (UPFC Theory)

Basically, the UPFC have two voltage source inverters (VSI) sharing a common dc storage capacitor. It is connected to the system through two coupling transformers. One VSI is connected in shunt to the system via a shunt transformer. The other one is connected in series through a series transformer. The UPFC scheme is shown in Fig. 2.

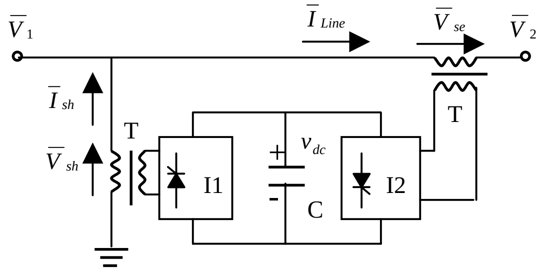

Fig. 2 UPFC scheme

The UPFC has several operating modes. Two control modes are possible for the shunt control: [2,7,8]

1) VAR control mode: the reference input is an inductive or capacitive Var request;
2) Automatic voltage control mode: the goal is to maintain the transmission line voltage at the connection point to a reference value.

By the control of series voltage, UPFC can be operated in four different ways [2,7,8]:

1) Direct voltage injection mode: the reference inputs are directly the magnitude and phase angle of the series voltage;
2) Phase angle shifter emulation mode: the reference input is phase displacement between the sending end voltage and the receiving end voltage;
3) Line impedance emulation mode: the reference input is an impedance value to insert in series with the line impedance;
4) Automatic power flow control mode: the reference inputs are values of P and Q to maintain on the transmission line despite system changes.

Generally, for damping of power system oscillations, UPFC will be operated in the direct voltage injection mode. The mathematic model of UPFC for the dynamic simulation is shown in Fig. 3.

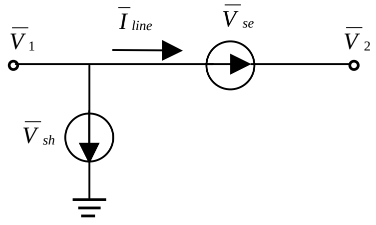

Fig 3. UPFC model

3. CONTROL SCHEME

3.1. Traditional FACTS Damping Control Scheme

Under a large disturbance, line impedance emulation mode will be used to improve first swing stability. For damping of the subsequent swings, as suggested before, UPFC will be operated in the direct voltage injection mode. In this mode, the UPFC output is the series compensation voltage $\overline{V}_{se}$. This voltage is perpendicular to the line current $\overline{I}_{line}$ and the phase angle of $\overline{I}_{line}$ is ahead of $\overline{V}_{se}$ [9]. Thus, as shown in Fig.4, the damping control of the UPFC is the same as a TCSC POD control scheme [10]. By the control of the magnitude of $\overline{V}_{se}$, the series compensation damping control can be achieved.

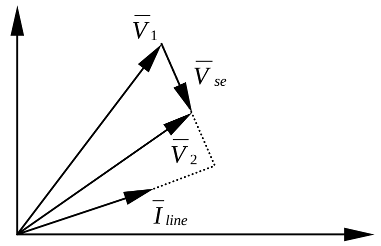

Fig. 4. Series compensation mode

3.2. POD Controller

Commonly the POD controllers involve a transfer function consisting of an amplification link, a washout link and two lead-lag links [10]. A block diagram of the conventional POD controller is illustrated in Fig. 5. In this paper the active power of the transmission line is used as input signal.

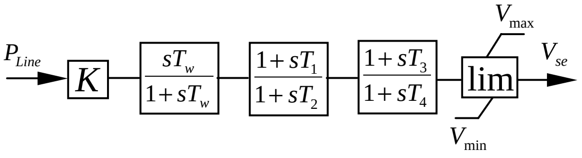

Fig. 5. UPFC POD controller

The UPFC POD controller works effectively in single machine system. In order to improve the dynamic performance of a multi-machine system, the behavior of the controllers must be coordinated. Otherwise the power system will be deteriorated.

3.3. Fuzzy Logic Control

In order to keep the advantage of the existing POD controller and to improve its control performance in multi-machine systems, the hybrid fuzzy coordinated controller is suggested in this paper.

Fuzzy logic controller is one of the most practically successful approaches for utilizing the qualitative knowledge of a system to design a controller [6]. In this paper the main function of the fuzzy logic control is to coordinate the operation of FACTS controllers. In section 4 the design of the fuzzy logic coordinated controller is presented in detail.

4. PARAMETER OPTIMIZATION AND CONTROLLER DESIGN

4.1. Parameter Optimization for a Single Machine POD Controller

In order to work effectively under different operating conditions, many researches are made on the controller parameter optimization [11]. Parameters of the POD controller can be adjusted either by trial and error or by optimization technique. In this paper the parameters of the POD controller are optimized using a nonlinear programming algorithm.

Originally, the aim of the parameter optimization is to damp oscillations of power systems where the UPFCs are installed. This objective can be formulated as the minimization of a nonlinear programming problem expressed as follows:

$$\begin{aligned} &\min. && f(\mathbf{x}) \\ &s.t. && A(\mathbf{x}) = 0 \\ & && \mathrm{B}(\mathbf{x}) \geq 0 \end{aligned} \tag{1}$$

where $f(\mathbf{x})$ is the objective function, $\mathbf{x}$ are the parameters of the POD controller. $A(\mathbf{x})$ are the equality functions and $B(\mathbf{x})$ are the inequality functions respectively. Particularly $B(\mathbf{x})$ indicate the restrictions of the POD parameter. (i.e. the restrictions of lead-lag links and wash-out links). In this simulation, only the inequality functions $B(\mathbf{x})$ are necessary.

The objective function is extremely important for the parameter optimization. In this paper the objective function is defined as follows:

$$f(\mathbf{x}) = \int_0^{t1} \delta(t, \mathbf{x})\, dt \tag{2}$$

where $\delta(t, \mathbf{x})$ is the power angle curve of the generator and $t1$ is the time range of the simulation. With the variation of the controller parameters $\mathbf{x}$, the $\delta(t, \mathbf{x})$ will also be changed. The power system simulation program PSD (Power System Dynamic) [15] is employed in this simulation to evaluate the performance of the POD controller.

Equation (1) is a general parameter-constrained nonlinear optimization problem and can be solved successfully. In this paper the Matlab Optimization Toolbox is applied [12].

The optimization starts with the pre-selected initial values of the POD controller. Then the nonlinear algorithm is used to iteratively adjust the parameters, until the objective function (2) is minimized. These so determined parameters are the optimal settings of the POD controller.

The flow chat of the parameter optimization is shown in Fig. 6

The proposed optimization algorithm was realized in a single machine power system. In this optimization the pre-fault state and post-fault state are the same, where $\delta(0) = \delta(\infty)$. The optimized parameters are given in Appendix 2.

4.2. *Fuzzy Logic Coordinated Controller Design*

Most of the FACTS POD controllers belong to the PI (proportional integral) type and work effectively in single machine system [13]. Especially, after the parameter optimization, the damping of power system oscillations is perfectly achieved. However the performance of the above mentioned POD controllers deteriorates in multi-machine system. Therefore the coordination between POD controllers must be taken into account.

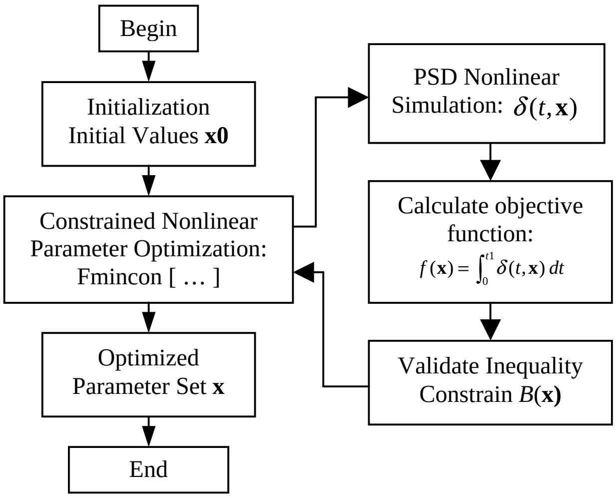

Fig. 6. Flow chart of the parameter optimization

To cope with the coordination problem, the optimization based coordination [11] and the feedback signal based coordination [14] have been developed. Also fuzzy logic has successfully been applied to coordination [13]. The method used in [13] is using the fuzzy logic controller to coordinate the input signal of the FACTS controller.

In this paper the fuzzy logic controller is to coordinate the parameters of FACTS controllers. The structure of the proposed fuzzy-coordination controller is shown in Fig. 7.

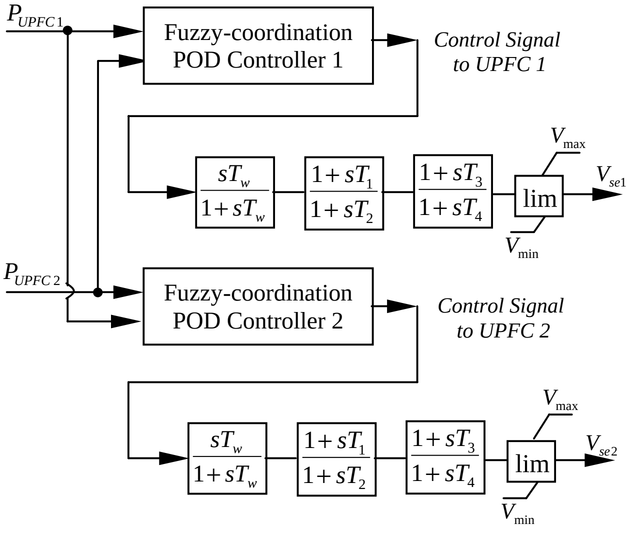

Fig. 7. UPFC fuzzy-coordination controller

where the inputs P_{UPFC1} and P_{UPFC2} are the active power flow through the UPFC1 and UPFC2. The output signals are command signals adjusted to the UPFC controllers 1 and 2. In this way, the conventional POD controllers are tuned by using fuzzy-coordination controllers. The fuzzy-coordination controller involves Fuzzification, Inference and Defuzzification unit.

4.2.1 Fuzzification

Fuzzification is a process whereby the input variables are mapped onto fuzzy variables (linguistic variables). Each fuzzified variable has a certain membership function. The inputs are fuzzified using three fuzzy sets: B (big), M (medium) and S (small), as shown in Fig. 8.

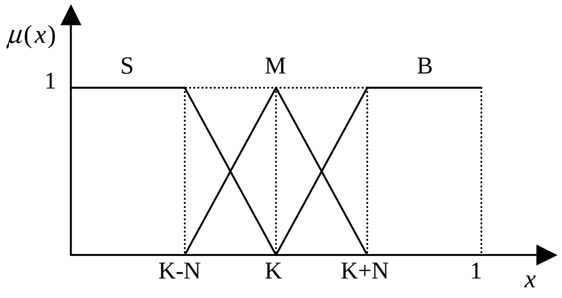

Fig. 8. Membership function

The membership function of the small set is:

$$\mu_S(x) = \begin{cases} 1 & x < K - N \\ \dfrac{-x+K}{N} & K - N \le x \le K \\ 0 & x > K \end{cases} \tag{3}$$

where x, namely P_{UPFC1} or P_{UPFC2}, is the input to the fuzzy controller. Similarly the big set membership function is:

$$\mu_B(x) = \begin{cases} 0 & x < K \\ \dfrac{x-K}{N} & K \le x \le K + N \\ 1 & x > K + N \end{cases} \tag{4}$$

And the medium set membership function is:

$$\mu_M(x) = \begin{cases} 0 & x < K - N \\ \dfrac{x+N-K}{N} & K - N \le x \le K \\ \dfrac{-x+N+K}{N} & K \le x \le K + N \\ 1 & x > K + N \end{cases} \tag{5}$$

The parameters *L* and *K*, as shown in Appendix 3, are determined basing upon the rated values of UPFCs. These parameters can also be optimized by using the simulation results.

4.2.2 Inference

Control decisions are made based on the fuzzified variables. Inference involves rules for determining output decisions. Due to the input variables having three fuzzified variables, the fuzzy-coordination controller has nine rules for each UPFC controller. The rules can be obtained from the system operation and the knowledge of the operator. Table 1 shows the inference system.

To determine the degree of memberships for output variables, the Min-Max inference is applied.

Both of the two UPFC controllers use the same inference system. Only the input of them are exchanged. (as shown in Fig. 7)

Table 1 Inference system

P_{UPFC1} P_{UPFC2}	**S**	**M**	**B**
S	B	M	S
M	B	M	S
B	M	S	S

4.2.3 Defuzzification

The output variables of the inference system are linguistic variables. They must be converted to numerical output. The fuzzy-coordination controller uses centroid method. The output of the fuzzy-coordination controller is

$$u = \frac{\sum_{i=1}^{9} \mu_c(u_i) \cdot u_i}{\sum_{i=1}^{9} \mu_c(u_i)} \tag{6}$$

where u_i corresponds to the value of control output for which the membership values in the output sets are equal to unity.

5. SIMULATION RESULTS

5.1. Parameter optimization

The parameter optimization is made in single machine system. Fig. 9 demonstrates the improvement in damping of power system oscillation. The initial and optimized values of the POD controller are given in Appendix 2.

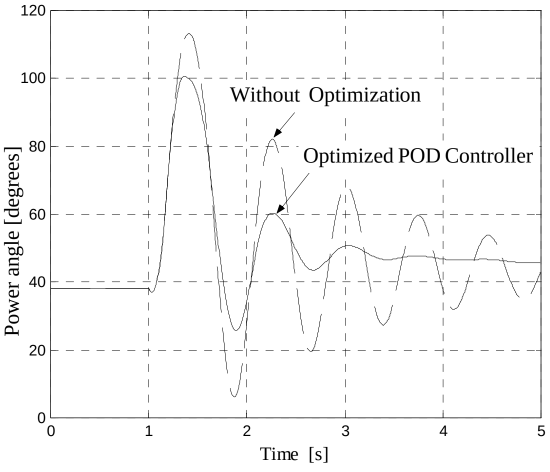

Fig. 9. Parameter optimisation in a single machine infinite bus system

5.2. Simulation in multi-machine system

Using the multi-machine power system shown in Fig. 1, different disturbances and different network parameters are simulated. The performance of the fuzzy-coordination controller for UPFC in damping power system oscillations is examined. The following simulations are made for evaluating the performance of the proposed controller. In this paper machine G3 is taken as the reference.

Case 1: Three-phase fault at Bus 2

A three-phase fault of 100 ms duration is simulated at Bus 2. Fig. 10 presents the results of the examined power system with fuzzy-coordination controller. From Fig. 10 it can be seen that with the proposed controller, the dynamic performance of the power system is quite improved.

The pre-fault operating condition (in p.u.) is: P1=0.105, P2=0.185.

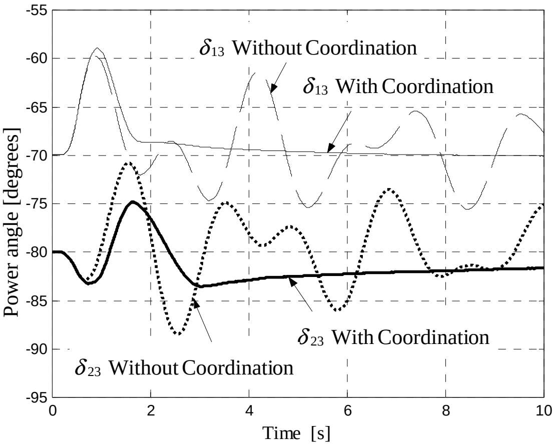

Fig. 10. Fuzzy-coordination controller simulation case 1

Case 2: Changing of operation conditions (Three-phase fault at Bus 3)

To validate the robustness of fuzzy-coordination controller the pre-fault operating conditions of the power network is changed to P1=0.195, P2=0.28. Moreover the fault type is also different: a three-phase fault of 110 ms duration is simulated at Bus 3. Fig. 11 shows the results of the simulation. The proposed controller acts pretty well with the variation of operation condition.

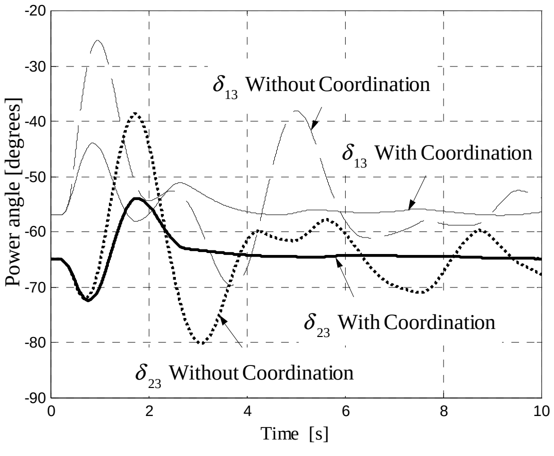

Fig. 11. Fuzzy-coordination controller simulation case2

Case 3: Changing of network parameters (Three-phase fault at Bus 9)

In order to verify the performance of the fuzzy-coordination controller for the changing of system parameters, the reactance of transformers T1 and T2 are increased by 20%. A three-phase fault of 100 ms is simulated at Bus 9. The simulation results, as shown in Fig. 12, illustrate that the proposed controller is robust in parametric change.

The pre-fault operating condition (in p.u.) is: P1=0.10, P2=0.120.

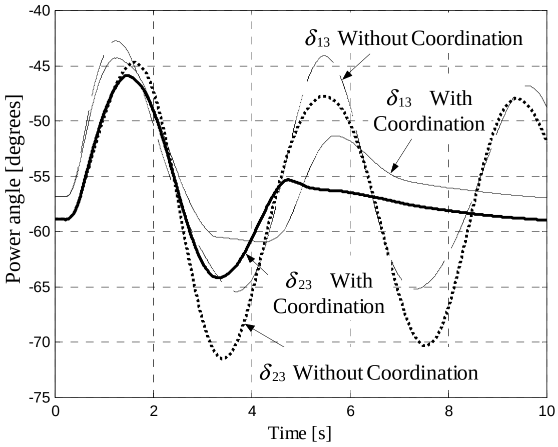

Fig. 12. Fuzzy-coordination controller simulation case 3

6. CONCLUSIONS

The paper presents a new fuzzy-coordination controller for the FACTS devices in a multi-machine power system to damp the electromechanical oscillations. The fuzzy-coordination controller is designed based on the conventional POD controllers. The amplification part of the conventional controller is modified by the fuzzy-coordination controller. The performance of the proposed method is simulated over a wide range of operating conditions and disturbances and its robustness is proved. Both inter-area and local modes oscillations are quite damped using this new controller. The proposed control scheme adopts the advantages of the conventional POD controller and it is not only robust but also simple and being easy to be realized in power system.

APPENDIX

Appendix 1: power system model

Base Value:

$V_B = 220KV$; $S_B = 100MVA$;

Generators:

$2H_1 = 2H_2 = 8s$; $2H_3 = 10$;

$D_1 = D_2 = D_2 = 0.0$;

$T_{d01} = T_{d02} = 4.49s$; $T_{d03} = 6s$;

$$X_{d1} = X_{d2} = 1.56(p.u.);\ X_{d3} = 2(p.u.);$$

$$X_{q1} = X_{q2} = 1.06(p.u.);\ X_{q3} = 1.9;$$

$$X_{d1}^{'} = X_{d2}^{'} = 0.17(p.u.);\ X_{d3}^{'} = 0.25(p.u.);$$

Transformers:

$$X_{T1} = X_{T2} = X_{T3} = j0.305\ (p.u.)$$

Transmission lines:

$$Z_{l1} = Z_{l2} = Z_{l3} = 0.0 + j0.25\ (p.u.)$$

UPFCs:

$$V_{Oper} = 220KV;\ V_{se\max} = 0.1V_{Oper};\ V_{se\min} = -0.1V_{Oper};$$

Loads:

$$L_1 = L_2 = L_3 = 0.05\ (p.u.);\ L_4 = 0.65\ (p.u.)$$

Appendix 2: parameter optimization

Parameter Value	K	T_w	$T_1 = T_3$	$T_2 = T_4$	$V_{\max}$	$V_{\min}$
Initial	0.5	3.0	0.05	0.05	0.1	-0.1
Optimized	1.82	3.0	0.02	0.15	0.1	-0.1

Appendix 3: Fuzzy-coordination controller

K=0.7, N=0.2

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