

Fuzzy logic based PSS in Coordination with STATCOM Power Oscillation Damping (POD) controller for Small Signal Stability Enhancement of Multi-machine Power System

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Abstract— this paper presents a coordinated Fuzzy logic based PSS with STATCOM Power Oscillation Damping (POD) Wide Area Damping Controller (WADC) and simultaneous tuning of FACTS based controller and fuzzy logic based global PSS. The disturbance is symbolized as distributed in the network with consideration of momentarily disturbance to the generator in area 1 for few cycles. The tie-line active power flow from among areas, rotor speed deviation and speed, rotor mechanical angle deviation, positive sequence voltage are studied by seeing the test system with conventional PSS (CPSS), fuzzy logic based controller and coordinated fuzzy logic based PSS with shunt connected FACTS controllers specifically STATCOM with Power Oscillation Damping (POD). The simulation results are carried out for validation of the proposed coordinated controller.

Index Terms— Power system stabilizer (PSS), Wide Area Damping Controller (WADC), Small signal Stability, Static Compensator (STATCOM)

I. INTRODUCTION

Power system nowadays is a complex network, sometimes made of thousands of buses and hundreds of generators. available power generation usually does not situated near an uprising of load center. in order to meet the growing power demand, instead of building new transmission lines and expanding substations, utilities have a concern in better utilization of available power system capacities, existing generation and existing power transmission network [2]. on the other hand, power flows in some of the transmission lines are overloaded, which has as an overall effect of deteriorating voltage profiles and decreasing system stability and security. in addition to this, existing traditional transmission facilities, in most cases, are not designed to handle the control requirements of complex and highly interconnected power systems [1]. this situation requires the review of traditional transmission methods and practices, and the creation of new concepts, which would allow the use of existing generation and transmission lines up to their full capabilities without reduction in system stability and security.

The traditional approach to damp out inter-area oscillations is through conventional Power System Stabilizer (CPSS), forming part of the generator excitation system and FACTS controllers, which

employ locally available or measured signal as input [4]. These local signal based controllers lack the global observations.

In this paper, the research on detailed analysis of wide area damping controller considering FACTS based shunt controllers in coordination with fuzzy logic based global power system stabilizer gestated to damp inter-area or low frequency oscillations in large integrated power system. Section II describes the test system taken in the analysis. In section III dynamic equations are linearized about a steady state operating point. Electromechanical oscillations and their frequency range are discussed in section IV. Fuzzy logic based global PSS and shunt connected FACTS controllers for the proposed WADC are discussed in Section V, VI and VII.

In section VIII, the nonlinear simulation on interconnected multi-machine test system has been performed with PSS; fuzzy logic based global PSS and Coordinated Fuzzy with FACTS controllers to evaluate the performance of the system.

II. INTRODUCTION TO TEST SYSTEM

In spite of the high degree of activeness in recent years on wide-area control, there are many aspects remain poorly understood due to the complexity in large power system. Hence, Kundur's benchmark two areas four machine systems has been carried out to analyze the different types of oscillations that occurs in the integrated power system with proposed robust coordinated fuzzy logic based PSS with FACTS wide area damping controller. In the test system all the generators are equipped with governor, AVR, and IEEE ST1A type static exciter.

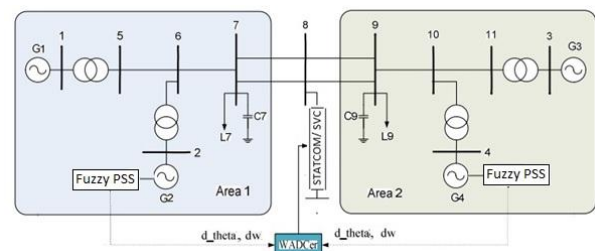


Fig 2.1: Kundur's two area Four Machine system with Coordinated fuzzy and FACTS controllers

The loads taken here are constant impedance type and connected to bus no. 7 and 9. The structure of the

case study power system is given in Fig.2.1. After the calculation of most suitable stabilizing signal and control location [6], a fuzzy logic based global PSS is employed supplement to the input of AVR along with FACTS controllers connected in shunt with the tie line connecting both the areas for the effective damping of inter area oscillations.

III. LINEARIZED MODEL

The stability of the operating point of a dynamic system to small disturbances is termed small signal stability. To test for small signal stability the system's dynamic equations are linearized about a steady state operating point to get a linear set of state equations.

$$\begin{aligned}\dot{x} &= Ax + Bu \\ y &= Cx + D\end{aligned}$$

The theory of linear system provides very useful information about the operating behavior and dynamic behavior of the interconnected power system. In fact low frequency oscillations are linear when small disturbance. An interconnected power system network can be represented by the following set of non-linear differential and algebraic equations

$$\begin{aligned}\dot{x} &= f(x, z, u) \\ 0 &= g(x, z, u) \\ y &= h(x, z, u)\end{aligned}$$

Where f and g are vectors of differential and algebraic equations respectively and h is vector of output equations. The notation $x \in R^n, z \in R^m, u \in R^p$ and $y \in R^q$ are the state, algebraic, input, output vectors respectively n is the dimension of system, p is the no. of inputs, q is the no. of outputs. A linear model of the network is used for selection of control signal. After linearizing the system around an operating point the state space model of the system can be represented

$$\begin{aligned}\dot{x} &= Ax + Bu \\ y &= Cx\end{aligned} \quad (2)$$

Where $x \in R^n, u \in R^p$ and $y \in R^q$ are state, input and output vector respectively. Where as $A \in R^{n \times n}, B \in R^{n \times p}, C \in R^{q \times n}$ are state, input and output matrix respectively.

In addition to the critical mode identification, modal analysis was also performed for coherent machine identification where the one group of generators forms one area and oscillating with another group of generators. Following each rate of change of state calculation, the perturbed state is returned to its equilibrium value and the intermediate variable values are reset to their initial values. Each step in this process is similar to a single step in a simulation program.

IV. ELECTROMECHANICAL MODES

Interconnected power systems exhibit several kinds of oscillations when subjected to a perturbation. These oscillations are also named as power swings and to maintain the system stability these oscillations must be effectively damped. Oscillations in power systems are separated by the system factors. Some of the major oscillations [2] attributed to system collapse are as follows:

- 1) *Intraplant mode*: Generator units at the same power plant oscillate with each other at 2.0 to 3.0 Hz conditional on the generator capacities and connecting impedances [2].
- 2) *Local plant mode*: One generator unit swings against the rest of the generators at 1.0 to 2.0 Hz. The influence of the oscillation is confined to the generator and grid connection [2].
- 3) *Inter-area mode oscillations*: This occurrence is noticed over a great part of the power system. It includes two coherent groups of generators swinging in contradiction of for each other at 1 Hz or less. The oscillation frequency is roughly 0.3 Hz [2].
- 4) *Control mode oscillations*: They are related with generators and badly regulated exciting system, turbine-governors, power controllers. Active and reactive power controllers can interact with each other [2].
- 5) *Torsional mode oscillations*: They are related with a turbine shaft in the frequency range of 10-46 Hz. Generally they are created when a multi-stage turbine is integrated to the grid via a series compensated link. [2].

V. OPTIMAL SIGNAL SELECTION AND CONTROL SITE LOCATION

The tie-line active power flow at various lines of the system has been taken for signal selection. The signal selection is carried out by residue approach and geometric measure of controllability/observability approach. Table-II and Table-III shows results obtained from Residue approach and Geometric approach respectively.

Table II: Normalized values of the Residue approach for the 4 machine two area system

Signals	Generators			
	G-1	G-2	G-3	G-4
P6-7	0.5298	0.6849	0.5206	0.6686
P7-8	0.3545	0.4584	0.3484	0.4475
P8-9	0.3224	0.4169	0.3168	0.4070
P9-10	0.7735	1	0.7601	0.9763

Table III: Normalized values of the geometric measure of controllability/observability approach for 4 machine 11 bus system.

Generators	Signals			
	P_{6-7}	P_{7-8}	P_{8-9}	P_{9-10}
G-1	0.3528	0.7735	0.7655	0.4179
G-2	0.4560	1	0.9897	0.5402
G-3	0.3466	0.7601	0.7522	0.4106
G-4	0.4452	0.9763	0.9662	0.5274

The most important task to design the wide area damping control is to select the most effective wide

area signals. The basic criteria for selection of the signal are to have good observability and controllability of the signal for the systems inter area mode. So the signal which allows maximum observability and controllability of system's mode has to be selected as the most effective stabilizing signal for the controllers.

VI. FUZZY LOGIC BASED GLOBAL PSS

The fuzzy control system block diagram is shown in Figure 5.1. Here, a fuzzy controller embedded in a closed-loop control system. The plant outputs are denoted by $y(t)$, its inputs are denoted by $u(t)$, and the reference input to the fuzzy controller is denoted by $r(t)$.

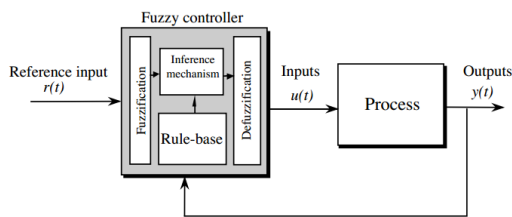


Figure 6.1: Block Diagram of Fuzzy Control System

The fuzzy controller has four main components:

- a) The fuzzification interface simply modifies the inputs and converts controller inputs into information that can be easily utilized by the inference mechanism to apply rules so that they can be interpreted and compared to the rules in the rule-base.
- b) The rule-base is a set of If-Then rules that contains a fuzzy logic quantification of the expert's linguistic description. Rule-base holds the knowledge in the form of a set of rules to achieve good control over the system.
- c) An inference engine or inference mechanism emulates the expert's decision making and evaluates which control rules are relevant at the current time and then decides what the input to the plant should be.
- d) The defuzzification interface converts the conclusions reached by the inference mechanism into the actual inputs to the plant for the process.

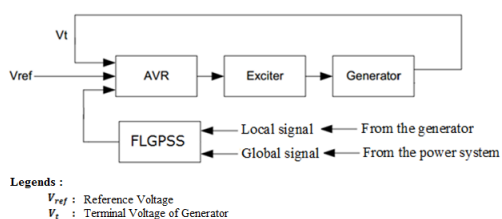


Figure 6.2: General Structure of the Proposed Control Scheme

The proposed control scheme employs additional stabilizing control signal applied to the input of exciter through AVR, as a result an enhanced stabilizing signal through excitation systems is fed to selected individual

generators involved in the controlling areas. The rule base for the fuzzy logic controller is designed. In this research, the two inputs i.e. speed deviation and tie line active power deviation [19], result in 49 rules for each machine. The rule base employing the rules for two inputs i.e. speed deviation and tie line active power deviation is given in Table 5.1

Table 5.1 Rule base for the Fuzzy logic based PSS

Speed Deviation	Tie Line Power						
	LN	MN	SN	ZE	SP	MP	LP
LN	LP	LP	LP	MP	MP	SP	ZE
MN	LP	MP	MP	MP	SP	ZE	SN
SN	LP	MP	SP	SP	ZE	SN	MN
ZE	MP	MP	SP	ZE	SN	MN	MN
SP	MP	SP	ZE	SN	SN	MN	LN
MP	SP	ZE	SN	MN	MN	MN	LN
LP	ZE	SN	MN	MN	LN	LN	LN

The fuzzy logic based global PSS implemented for each area in two area four machine system is employing a global signal from power system as input to the stabilizer. The first input to the fuzzy logic controller incorporated in this research is speed deviation of respective generator and the second input is extracted from the active power transfer across the tie-line connecting both coherent areas [17]. The output of fuzzy logic based global PSS provides the global stabilizing voltage signal for generator through its excitation system.

VII. INTRODUCTION TO FACTS

The process to permit, site, and construct new transmission lines has become extremely difficult, expensive, time-consuming, and controversial. FACTS technologies allow for improved transmission system operation with minimal infrastructure investment, environmental impact, and implementation time compared to the construction of new transmission lines. FACTS controllers control the interrelated parameters that govern the operation of transmission system like series impedance, shunt impedance, current, voltage and phase angle. So FACTS controllers can be utilized to control power flow and enhance system stability [8]. A better utilization of the existing transmission systems by increasing their capacities close to the thermal ratings and enhancing controllability by installing FACTS controllers becomes imperative in today's competitive power market. There are two main aspects that should be considered in using FACTS controllers: The first aspect is the flexible power system operation according to the power flow control capability of FACTS controllers. The other aspect is the improvement of stability of power systems.

The shunt-type FACTS controllers are always used to compensate the reactive power and stabilize the bus voltage, and the relatively mature shunt-type FACTS devices are SVC (Static Var Compensator) and STATCOM (Static Synchronous Compensator).

A. Static Compensator (STATCOM)

The STATCOM is made up of a coupling transformer, a VSC, and a dc energy storage device. The energy storage device is a relatively small dc capacitor, and hence the STATCOM is capable of only reactive power exchange with the transmission system [10]. If a dc storage battery or other dc voltage source were used to replace the dc capacitor, the controller can exchange real and reactive power with the transmission system, extending its region of operation from two to four quadrants.

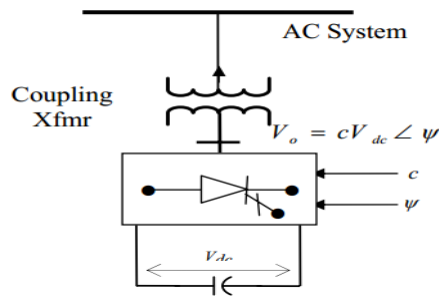


Fig 7.1 STATCOM Configuration.

The STATCOM's output voltage magnitude and phase angle can be varied. By changing the phase angle ψ of the operation of the converter switches relative to the phase of the ac system bus voltage, the voltage across the dc capacitor can be controlled [11], thus controlling the magnitude of the fundamental component of the converter ac output voltage, as $V_o = c V_{dc}$.

VIII. STATCOM with POD based WADC

There are various techniques proposed for WADC synthesis including time delay effects such as multi-agent H_{∞} , predictor-based H_{∞} , and mixed H_2/H_{∞} controllers for time-delayed systems, where 'H' referred to as Henkel Norm [6-8]. Communication delay in remote signal transmission can be subdivided into two parts; time taken from measurement site of PMU to the phasor data concentrator and then to the control site or the location of the local PSS where the compensating output signal of the WADC is added in supplement to the output of the local PSS and exciter voltage reference

The purpose of FACTS wide area damping control is to shift all the system eigenvalues into the left hand side of the S-plane, so that the needed minimum damping ratio can be satisfied and the system damping can be increased into the acceptable level. As the power oscillation is a prolonged dynamic event, it is essential to vary the applied shunt compensation, and thereby the (midpoint) voltage of the transmission line, to antagonize the accelerating and decelerating swings of the disturbed machine(s). That is, when the rotationally oscillating generator accelerates and angle δ increases ($d\delta/dt > 0$), the electric power transmitted must be increased to compensate for the excess mechanical input power. Conversely, when the generator decelerates and angle δ decreases ($d\delta/dt < 0$), the electric power must be decreased to balance

the insufficient mechanical input power [9]. (The mechanical input power is assumed to be essentially constant in the time frame of an oscillation cycle.)

The requirements of Var output control, and the process of power oscillation damping, is illustrated by the waveforms in Figure 8.1. Waveforms in Figure 8.1 (a) shows the undamped and damped oscillations of angle δ around the steady-state value δ_0 . Waveforms in Figure 8.1 (b) shows the undamped and damped oscillations of the Electric power P around the steady-state value P_0 . (The momentary drop in power shown at the beginning of the waveform represents an assumed disturbance that initiated the oscillation) Waveform 8.1 (c) shows the reactive power output on of the shunt-connected Var compensator. The capacitive (positive) output of the compensator increases the mid-point voltage and hence the transmitted power when $d\delta/dt > 0$, and it decreases those when $d\delta/dt < 0$

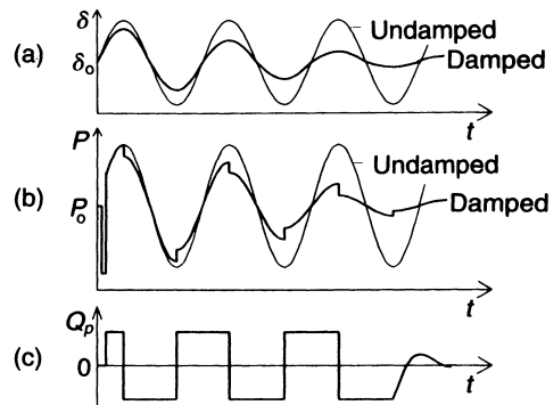


Fig. 8.1: Waveforms illustrating power oscillation damping by reactive shunt compensation: a) generator angle, (b) transmitted power, and (c) Var output of the shunt compensator.

IX. CLOSED LOOP VERIFICATION AND NON-LINEAR TIME DOMAIN SIMULATION

The performance of the proposed power system stabilizer is first verified by small signal analysis. A small disturbance (1+0.05) to the voltage reference input of exciter of generator 1 is applied. Time response analysis of the proposed close loop control system is performed for the verification of the expected outcomes. The loads in the system are assumed to be constant impedance type. To damp out local modes of oscillations and inter-area modes of oscillations the tie line is left connected with shunt type FACTS based Wide Area Damping Controller.

In order to validate the result, the of signal selection is performed in the case of STATCOM which serves as wide area damping controller to the Kundur's two area four machine system used for the case study example. A design of lead-lag compensator based POD (Power Oscillation Damper) is discussed and results of various stability assessment of the designed controller are given in this section.

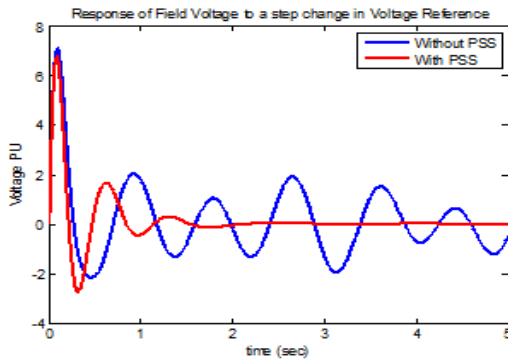


Fig. 9.1 Response of voltage with conventional PSS for Two Area Four Machine System

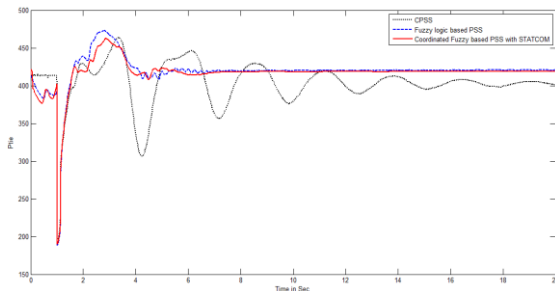


Fig 9.2: Response of tie-line active power flow deviation with STATCOM

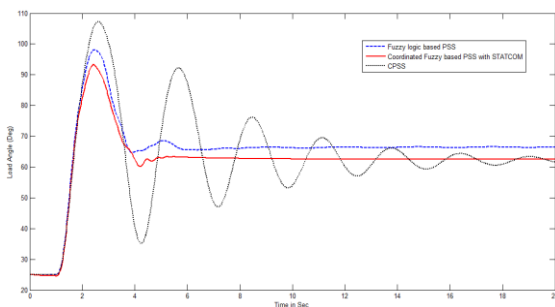


Fig. 9.3: The response of change in rotor angle of generator 1 w.r.t. generator 4

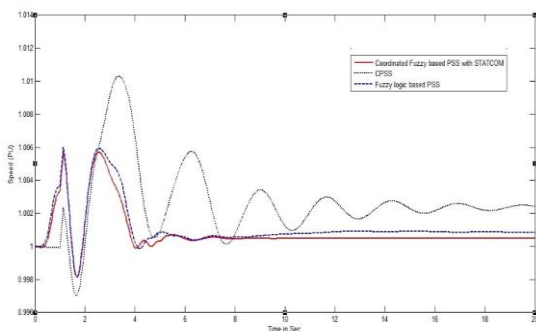


Fig 9.4: The response of rotor speed deviation of Generator1

The responses of the tie-line active power flow deviation, change in rotor angle of generator 1 with respect to the variation of the rotor angle of generator 4 and rotor speed deviation of Generator1 with Conventional Power System stabilizer, fuzzy logic based PSS and coordinated fuzzy logic based PSS with STATCOM Power Oscillation Damping (POD) controller are shown in figure 9.1, 9.2 and 8.3 respectively. The

response of terminal voltage of bus no. 9 where the coordinated fuzzy with STATCOM Power Oscillation Damping (POD) controller has been used as the wide area damping controller is shown in fig. 8.4

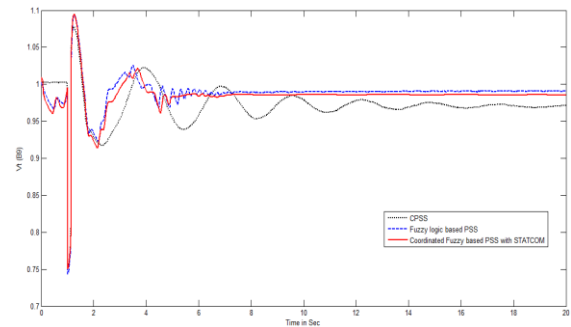


Fig. 9.5: The response of terminal voltage of bus no. 9

The performance responses of coordinated fuzzy logic based PSS with STATCOM based wide area damping controllers has been studied and it can be concluded from the responses that the coordinated STATCOM based WADC provides a better stability response as compared to conventional controller.

X. CONCLUSION

In this paper, the present work contributes in the area of power system stability and its improvement using coordinated design of fuzzy logic based damping controllers along with shunt connected FACTS devices. Design the FACTS based controllers and simultaneous tuning of FACTS based controller and fuzzy logic based global PSS has been undertaken. A lead-lag based POD has been designed in the case of power system using STATCOM based Wide Area Damping Controller. In order to test the performance of the designed STATCOM based wide-area controller a small signal stability assessment has been performed and the results have been validated.

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