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Adaptive Neuro-Fuzzy Inference System (ANFIS) for Stabilizing Power System with Multi-Machine Having Dynamic Loads

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Abstract: *The main objective of this paper is to show, how a PSS (Power System Stabilizer) of a multi machine with dynamic load has been optimized by using an Adaptive Neuro-Fuzzy Inference System (ANFIS) based optimization technique. The designed PSS is to supply an external damping torque to an Automatic Voltage Regulator (AVR) of a synchronous generator without affecting the synchronizing torque. The PSS is designed based on the use of FLC (Fuzzy Logic Controller) by Takagi-Sugeno (T-S) methods for the system. The designed controllers have been tested on a test system having a dynamic load. The simulation results shown using MATLAB/SIMULINK shows that, ANFIS-PSS is effective to control the low frequency electromechanical oscillation of interconnected power systems under severe disturbances with dynamic loads.*

Keywords: *Adaptive Neuro-Fuzzy Inference System (ANFIS), Automatic Voltage Regulator (AVR), Dynamic Load, Power System Stabilizer, Interconnected Power Systems.*

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I. Introduction

Most of the times operating conditions of power systems are not linear [1]. Actually the system goes over a broad range of conditions, causing low frequency oscillations (LFOs) [2]. The LFOs of small magnitudes due to insufficient damping caused by undesirable operating conditions sustain linger and shrink power transfer capability [2]. The generator terminal voltage and reactive power flow is maintained by an excitation system equipped with an automatic voltage regulator (AVR). One of the major objectives of AVR is to maintain the terminal voltage of the generator at certain level. Therefore, AVR enhances a steady-state stability of power systems. But still transient stability remains a challenging issue. In transient stability when a fault happens and continues for a limited period of time, it results in a considerable decrement of terminal voltage and machine power transfer capacity [3]. Latest generators with high gain exciters also create oscillatory instability. Power system stabilizer (PSS) units are often used to improve the damping of local and inter-area modes of electromechanical oscillations. In improving the dynamic stability of the power system, a PSS design is needed [4], [26].The use of a PSS is to extend stability limit via modulation of the generator's excitation [5]. To make satisfactory damping, the stabilizer should generate a stabilizing signal to the high gain excitation system of generators in order to create positive damping torque which is in phase with rotor speed deviation [5]. The large system comprises many interconnected machines. The fine tuning of PSS parameters is a difficult activity. Furthermore, on-going variations in power system operating conditions render this activity more difficult [6].

Conventional PSSs (CPSS) parameters are derived from a linearized model of the power system [7]. In addition to this, CPSSs work better on those specific operating points of the system for which they are modelled. Because of nonlinear behaviour of power systems, configurations and parameters are changed from time to time, so they are not able to give acceptable results over wider ranges of operating circumstances [26]. Now a day, with the advancement of digital computers, it is easy to implement intelligent control approaches. Fuzzy logic PSSs (FLPSSs) have been employed to improve the performance of CPSS. Complex and nonlinear problems are made easier to solve by FLC without knowing the accurate mathematical model of the systems [8]. In view of the fact that the FLPSS shows good performance when compared with CPSS, but there is no orderly design procedure for the fine-tuning of the parameters of it. Additionally during modelling, it is difficult to guess which types of membership functions (MFs) should be employed from analyzing the data [8], [9]. On the other hand, an adaptive neuro fuzzy inference system (ANFIS) based technique is a promising method which adjusts membership functions and rules adaptively to improve a system's performance.

In this paper it is introduces that, a PSS for a multi-machine interconnected power system having a dynamic load using adaptive-neuro fuzzy inference technique. Many literatures discuss on the PSS design considering by static loads in the system [5]-[9]. Loads have an important role in power system stability study [10], [11], because incorporation of load dynamics during a PSS design is important. The main objective of this study is to investigate the performance of ANFIS-PSS in the presence of a dynamic load in the interconnected two area power system.

1. Adaptive-Neuro Fuzzy Controller

An ANFIS editor GUI is available in Fuzzy Logic Toolbox in MATLAB. This toolbar receives input-output data set as input. Thus, it creates a fuzzy inference system (FIS). FIS's MF parameters tend to be adjusted with the use of either only a back propagation algorithm, or in a permutation with a least squares method [14]-[19]. The process agrees to the fuzzy systems towards learning from the data they model. At this point of the system, the input-output data pair is generated using the FLPSS structure. Afterwards, a fuzzy inference system is created by using the ANFIS model in MATLAB. Inputs are used, namely wr and wr-r´, and output is VPSS [13], [20]. In this study, a Takagi-Sugeno (T-S) type FIS model is used. The inputs are Gaussian membership type. Seven MFs are required to cover the full range of respective inputs. In this way, 49 rules appear for the output function which demonstrates a linear relation to the inputs [26]. Analysis using ANFIS controller has good performance of getting short period of settling time when compared with CPSS and FLPSS.

1.1. Fuzzy PSS Design

FLPSS controller design input signals which characterize the dynamic performance of the system are selected. In this paper, a Takagi-Sugeno (T-S) form of FLC is used which has two inputs and one output component. Inputs to the FLC are the generator rotor angular speed deviation (wr) and change of speed deviation (wr-r) and the output is voltage (VPSS) [21]-[26]. Seven linguistic fuzzy subset for each of the inputoutput variables are used [12], [13]. The linguistic variables are given in Table 1. Two inputs, wr and wr-r, generate 49 rules that define the relation between input and output of FLC. Thus, the stabilizing signals have been computed [13], [17]. The linguistic variables for writing the rule are shown in Table 1 and the rule table of FLC is shown in Table 2. Given that the exciter needed a non-fuzzy signal, the centroid defuzzification approach is used to obtain output [17]. The MFs for inputs and output are shown in Figures 2 to 4. 3D view of the anfis rule is shown in Figure 5.

Table 1: Linguistic Variables

NB	Negative Big
NM	Negative Medium
NS	Negative Small
ZE	Zero
PS	Positive Small
PM	Positive Medium
PB	Positive Big

Table 2: Rule Table of FLC

wr	wr-r						
	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NM	PS
NM	NB	NM	NM	NM	NS	NS	ZE
NS	NM	NM	NS	NS	ZE	ZE	PS
ZE	NM	NS	NS	ZE	PS	PS	PM
PS	NS	ZE	ZE	PS	PS	PM	PM
PM	ZE	PS	PS	PM	PM	PM	PB
PB	PS	PM	PM	PB	PB	PB	PB

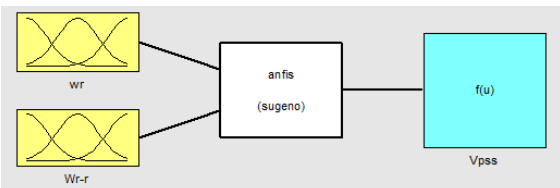

Figure 1: Input Output Member ship functions

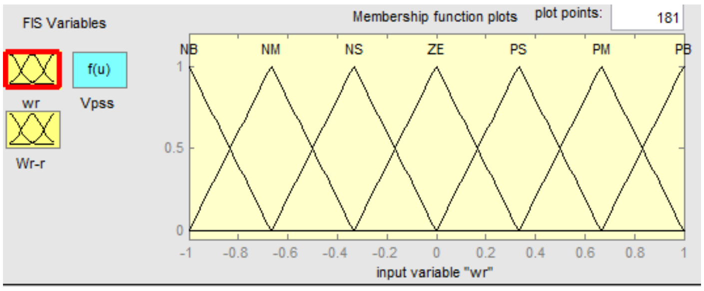

Figure 2: MF for Rotor Angular Speed Deviation (wr)

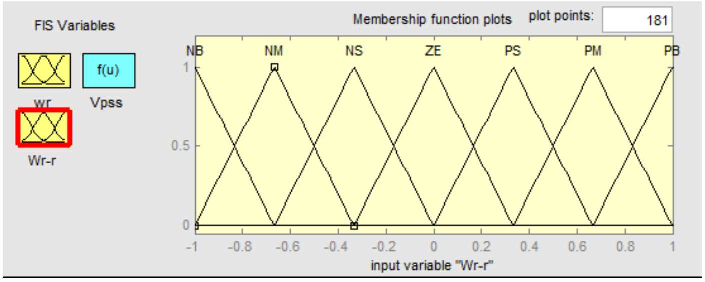

Figure 3: MF for Change of Speed Deviation (wr-r)

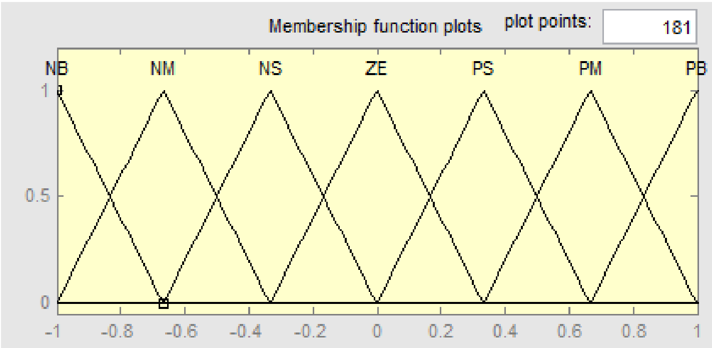

Figure 4: MF for Output is Voltage (VPSS)

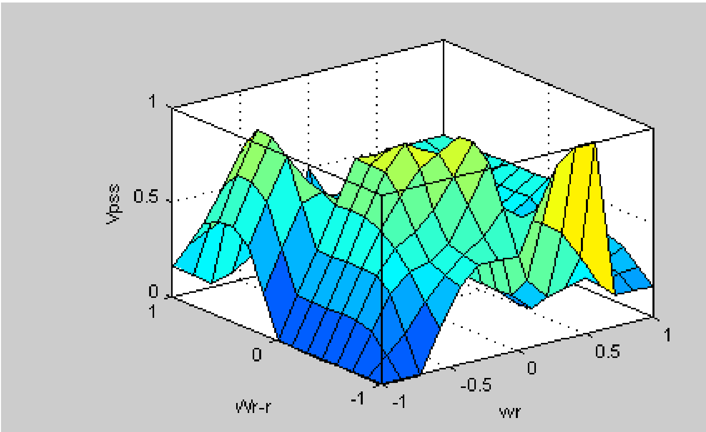

Figure 5: Surface View of ANFIS

The ANFIS-PSS design follows the steps below.

- Generate input-output data of the system using FLPSS.
- Then create a suitable ANFIS structure for a given challenge.
- Select number of training epoch.
- Using the test patterns train ANFIS until it performs in the expected level.
- Then check the model validation.

Figures 6 shows the Architecture of T-S type ANFIS controller used in this study. As we can see from the figure the system has two input variables and one out put variable. 49 rules are built from the seven membership functions.

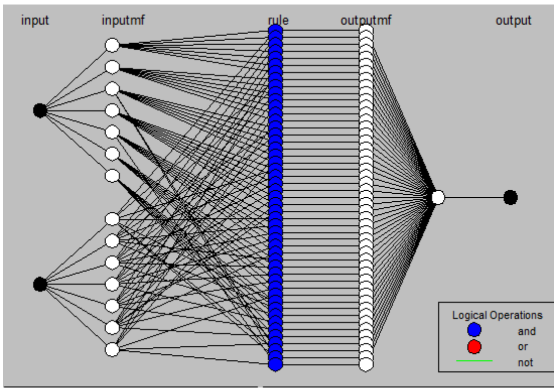

Figure 6: Architecture of T-S type ANFIS controller

II. Problem Description and Analysis

Two area multi-machine power system used in this paper is shown in Figure 7 [15]. The test system is modified by connecting a dynamic load at middle bus. Two symmetrical areas are connected through two 230 kV lines of 220 km long transmission lines. Each area has two similar round rotor generators rated at 20kV/900MVA. The inertia constants of generators in area 1 (A-1) and area 2 (A-2) are 6.5s and 6.17s, respectively. A dynamic load rated at 967 MW and 100MVAR is connected in A-1. Similarly, another static load rated at 1767MW, 100MVAR and -187MVAR is connected in A-2. Load voltage is improved by inserting a capacitor of 200MVAR and 350MVAR in A-1 and A-2, respectively.

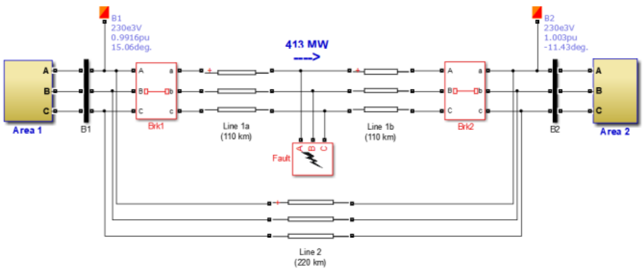

Figure 7: Two Area Multi-Machine Power System

The multi-machine two area complex power system's dynamic performance has been analyzed with ANFIS-based PSS. The generators are modelled by a sixth order state-space model and the dynamic load is presented by an exponential model [16] with time constants for controlling the dynamics of active and reactive power. For induction motor loads, the time constants are in the range up to one second [16].

III. Simulation Results and Discussion

A symmetrical three phase to ground fault is applied at the middle of the transmission line, which is cleared by tripping the fault line to test the robustness ANFIS-PSS. The simulation results can be summarized as follows:

As shown in Figure 8 and Figure 9 in the next section, dynamic performance of the two area power systems connected with dynamic load is observed. Figure 10 shows the machine one with fuzzy logic controller. Figure 11 shows the 12- cycle over shoot and settling time when three phase fault happens on two area test system with ANFIS-PSS for speed deviation and voltage as input to PSS. Figure 12 shows the voltage reference and positive sequence voltage and power of two area test system with ANFIS-PSS for speed deviation and voltage as input to PSS. As we can see from the figure the settling time for stability is short and become stable in short period of time. Figure 13 shows that the settling and overshoot characteristics on two area test system with ANFIS-PSS for speed deviation and voltage as input to PSS. Figure 14 shows the comparative of settling time with 12-cycle in the same case. As we can see from Figure 11 and Figure 14 the 8-cycle has maximum overshoot when fault happens than 12- cycle. From Figure 15 to Figure 19 the machines and systems characteristics is shown when two area test system with ANFIS-PSS for speed deviation and angular acceleration as input to PSS. As we can see from the two cases, settling and overshoot characteristics of two area test system with ANFIS-PSS for speed deviation and voltage as input to PSS shown in Figure 13 has shorter settling time than with ANFIS-PSS for speed deviation and angular acceleration as input to PSS shown in Figure 18. The third case is two area test system with ANFIS-PSS for speed deviation and accelerating power as input to PSS, and the overshoot and settling time characteristics of the system when fault happens at this conditions is summarized in Figure 20 to Figure 23. As we can see in Figure 23 the overshoot and settling time is better than second case shown in Figure 18 and it is poor when we compare with the first case shown in Figure 13. Therefore, settling and overshoot characteristics of two area test system with ANFIS-PSS for speed deviation and voltage as input to PSS has better stability performance than the other two cases. Figure 16 shows the 12- cycle over shoot and settling time when three phase fault happens of two area test system with ANFIS-PSS for speed deviation and angular acceleration as input to PSS. Figure 21 shows the 12- cycle over shoot and settling time when three phase fault happens of two area test system with ANFIS-PSS for speed deviation and accelerating power as input to PSS. Similarly Figure 14, Figure 19 and Figure 24 shows 8- cycle over shoot and settling time when three phase fault happens on two area test system with ANFIS-PSS for speed deviation and voltage as input to PSS, speed deviation and angular acceleration as input to PSS and speed deviation and accelerating power as input to PSS respectively.

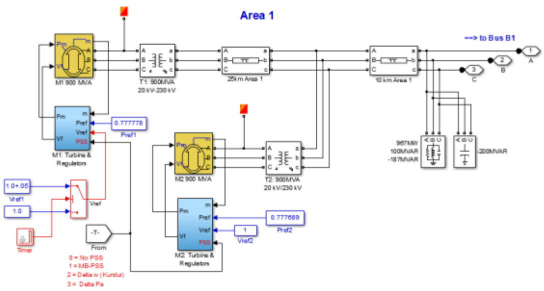

Figure 8: Area One with Dynamic Load

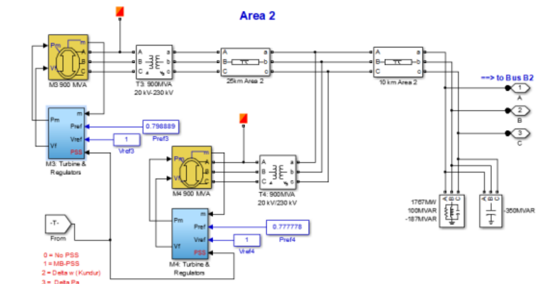

Figure 9: Area Two with Dynamic Load

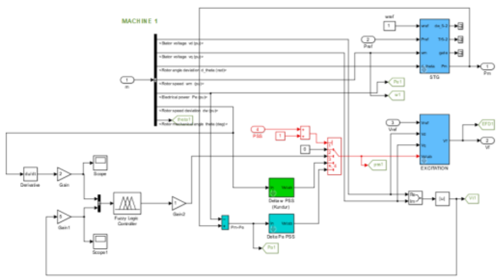

Figure 10: Simulink Model of Two Area Test System with ANFIS-PSS for Speed Deviation and Voltage as Input to PSS

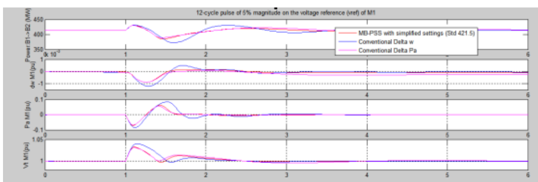

Figure 11: 12-Cycle Three Phase Fault with the Outage of One 230 KV Line for Two Area Test System with ANFIS-PSS when Speed Deviation and Voltage as Input to PSS

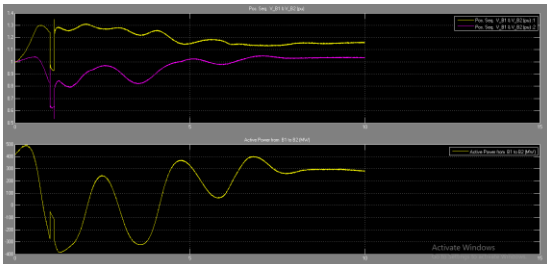

Figure 12: Positive Sequence of voltage and power of Machine one for Two Area Test System with ANFIS-PSS when Speed Deviation and Voltage as Input to PSS

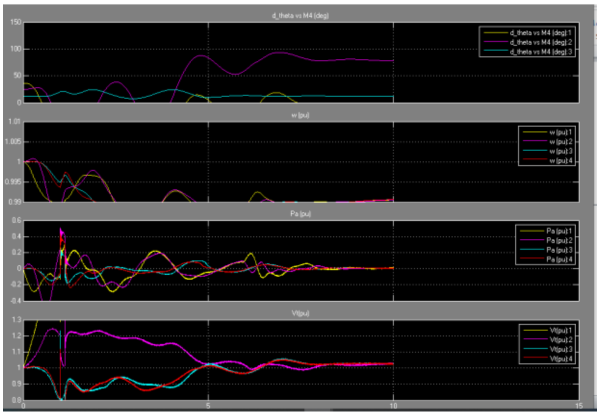

Figure 13: Settling and Overshoot characteristics for Two Area Test System with ANFIS-PSS when Speed Deviation and Voltage as Input to PSS.

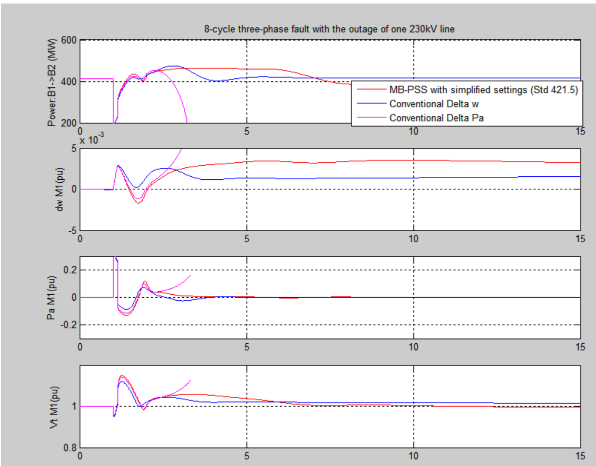

Figure 14: 8-Cycle Three Phase Fault with the Outage of One 230 KV Line for Two Area Test System with ANFIS-PSS when Speed Deviation and Voltage as Input to PSS

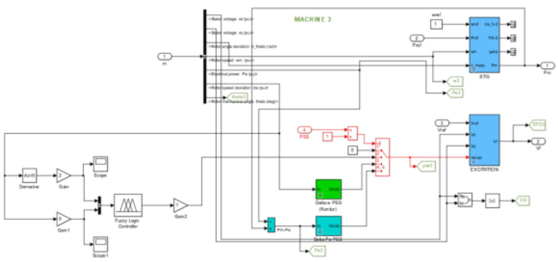

Figure 15: Simulink Model of Two Area Test System with ANFIS-PSS when Speed Deviation and Angular Acceleration as Input to PSS

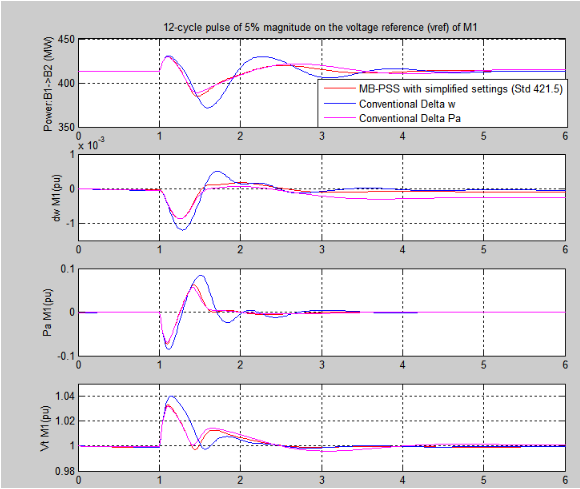

Figure 16: 12-Cycle Three Phase Fault with the Outage of One 230 KV Line for Two Area Test System with ANFIS-PSS when Speed Deviation and Angular Acceleration as Input to PSS

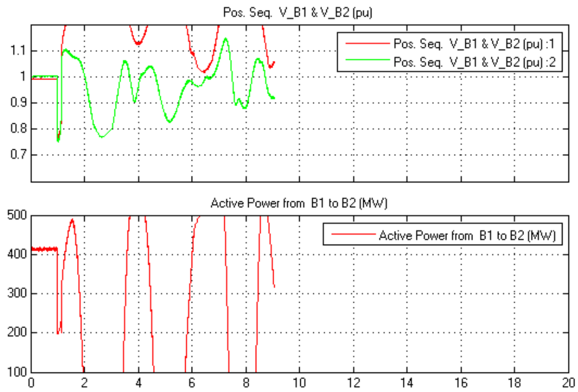

Figure 17: Positive Sequence Voltage and Active Power Transferred From Area One to Area Two for Two Area Test System with ANFIS-PSS when Speed Deviation and Angular Acceleration as Input to PSS

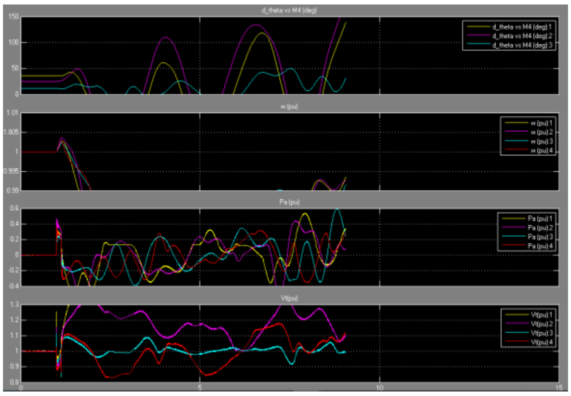

Figure 18: Settling and Overshoot characteristics for Two Area Test System with ANFIS-PSS when Speed Deviation and Angular Acceleration as Input to PSS

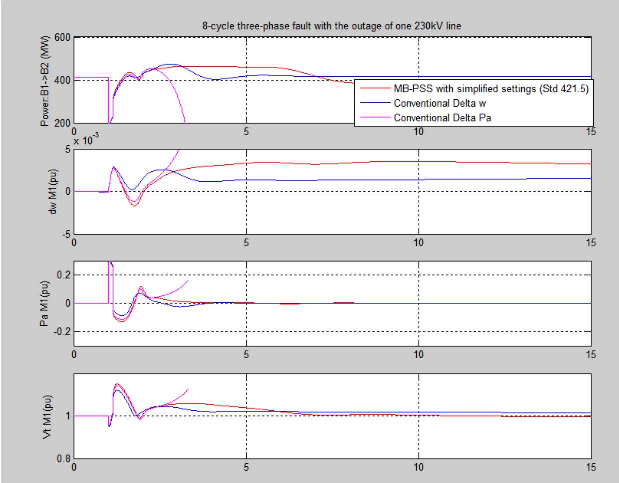

Figure 19: 8-Cycle Three Phase Fault with the Outage of One 230 KV Line for Two Area Test System with ANFIS-PSS when Speed Deviation and Angular Acceleration as Input to PSS

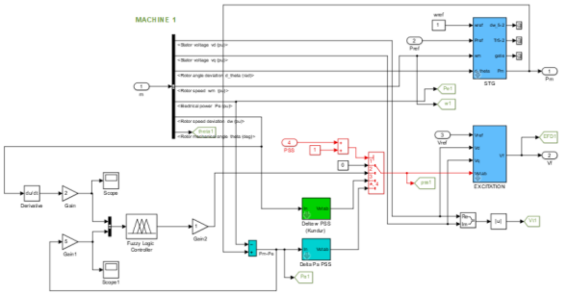

Figure 20: Simulink Model of Two Area Test System with ANFIS-PSS when Speed Deviation and Accelerating Power as Input to PSS

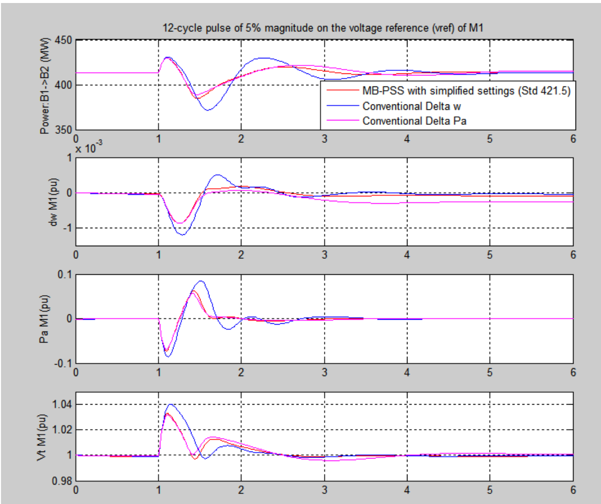

Figure 21: 12-Cycle Three Phase Fault with the Outage of One 230 KV Line for Two Area Test System with ANFIS-PSS when Speed Deviation and Accelerating Power as Input to PSS

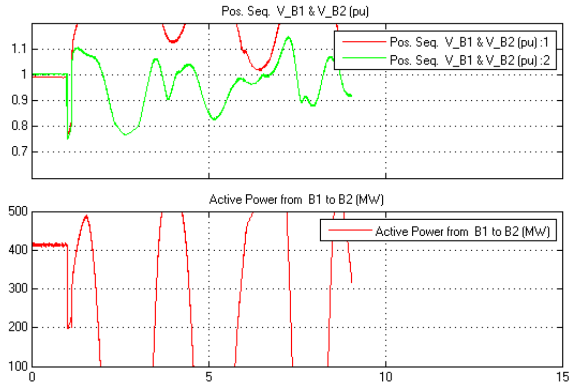

Figure 22: Positive Sequence Voltage and Active Power Transferred From Area One to Area Two for Two Area Test System with ANFIS-PSS when Speed Deviation and Accelerating Power as Input to PSS

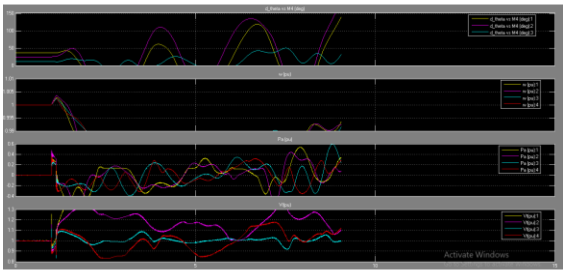

Figure 23: Settling and Overshoot characteristics of Two Area Test System with ANFIS-PSS when Speed Deviation and Accelerating Power as Input to PSS.

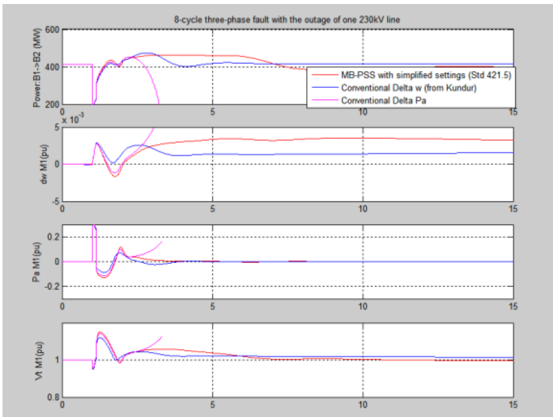

Figure 24: 8-Cycle Three Phase Fault with the Outage of One 230 KV Line for Two Area Test System with ANFIS-PSS when Speed Deviation and Accelerating Power as Input to PSS

IV. Conclusion

In this paper, adaptive-neuro fuzzy technique for the design of PSS is performed. The ANFIS-PSS type of stabilizer has been tested on a two area complex multi machine system having a dynamic load under fault conditions. Simulation results illustrate the effectiveness of the proposed adaptive neuro-fuzzy based PSS especially for dynamic loads. The settling time and overshoot is minimum as compared to the CPSS and FLPSS. Because of nonlinear behaviour of power systems, configurations and parameters are changed from time to time, so CPSS is not able to give acceptable results over wider ranges of operating circumstances. Now a day, with the advancement of digital technology, it is easy to implement intelligent control approaches. FLPSS has been employed to improve the performance of CPSS. Complex and nonlinear problems are made easier to solve by FLC without knowing the accurate mathematical model of the systems. Even if the FLPSS shows good performance when compared with CPSS, but there is no orderly design procedure for the fine-tuning of the parameters of it. Additionally during modelling, it is difficult to guess which types of membership functions (MFs) should be employed from analyzing the data. On the other hand, an adaptive neuro fuzzy inference system (ANFIS) based technique is a promising method which adjusts membership functions and rules adaptively to improve a system's performance. The system is tested on a sample standardized test system. As it can be seen from the result analysis, ANFIS-PSS has excellent damping of low frequency electro mechanical oscillation under disturbances.

Appendix

- **Synchronous generator parameters: G1 to G4:**

Nominal power=900e6VA, line-to-line voltage=20e3V, frequency =60Hz, Xd =1.8pu, Xd'=0.3pu, Xd"=0.25pu, Xq =1.7pu, Xq'=0.55pu, Xq"=0.25pu, Xl=0.2pu, Tdo'=8s, Tdo"=0.03s, Tqo'=0.4s, Tqo"=0.05s, Stator resistance (Rs) =0.0025pu, Inertia coefficient, H(s) =6.5s for G1 & G2, H(s) =6.175s for G3 & G4, friction factor (F) =0, pole pairs=4.

- **Dynamic load parameters:**

Nominal L-L voltage, Vn(Vrms)=230e3, frequency, fn(Hz)=60Hz, Active power, (Po)=967We6, Reactive power(Qo)=100e6Var, Initial positivesequence voltage (Vo)=0.994pu, exponents,np=1.3, nq=2, time constants, Tp1=0.1, Tp2=0.1, Tq1=0.1, Tq2=0.1, Vmin=0.7pu.

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