Power System Disturbance Suppression Using Interval Type-2 Fuzzy Logic Stabilizer

M. A. Hassan, O. M. Salim, G. M. Amer

Elec. Eng. Dep., Benha Faculty of Engineering, Banha University, Egypt.

m_adel25@bhit.bu.edu.eg, omar.salim@bhit.bu.edu.eg, Ghada.amer@bhit.bu.edu.eg

O. E. Gouda

Elec. Power and Machines Dep., Cairo Faculty of Engineering, Cairo University, Egypt.

prof_ossama11@yahoo.com

***Abstract*—Low frequency oscillations (LFOs) have a dramatic effect on small signal stability of a power system. As power system started to operate near its stability limits, LFOs might lead to system instability. Power system stabilizers (PSSs) are provided with automatic voltage regulator to damp such effects. In this paper, an interval type-2 fuzzy logic power system stabilizer (IT2FLPSS) is proposed as a stability enhancements of a single machine power system connected to the infinite bus. In addition, a conventional power system stabilizer (CPSS) has been introduced, both CPSS and IT2FLPSS results' were compared at different disturbance scenarios to show the improvements added to the system when using IT2FLPSS. MATLAB/SIMULINK programs are proposed to illustrate system performance at all proposed scenarios.**

Keywords—Stability, Power System Stabilizer, Single machine System, Conventional Controller, IT2FL.

I. Introduction

Power systems stability studies begun significantly in 1920, while the first small scale test was done in 1924. In 1925, the first stability tests of a real system were done [1]. Back in the 1940s and 1950s; the generators were produced with a large steady state synchronous reactance [2]. In the late 1950s and beginning of 1960s; Most of the new synchronous generators, that have been added to power system, were equipped with automatic voltage regulators (AVRs) [3]. These new generators with AVR increased the generating capacity and enhanced the dynamic stability of power system [3, 4].

Electromechanical oscillation of low frequency is a common problem in large power systems [3, 5, 6, 7]. LFOs, which typically in range of 0.2-3 Hz under different operating conditions, are caused due to disturbances such as sudden change in loads, change in transmission line parameters, fluctuation in the output of the turbine and faults [7]. These oscillations affect the overall stability of the system [3]. In the past five decades the PSS have been used to provide the desired system performance under condition that requires stabilization [3]. PSS can provide a supplementary excitation controller for synchronous generators to be against the effect of high gain AVRs and other sources of negative damping [8]. The main function of this controller is to create a damping electrical torque component in phase with rotor speed deviation in turbine shaft, increasing the generator damping [7].

Most PSSs used in electric power systems depend on the classical linear control theory approach based on a linear model of a fixed configuration of the power system. Such a fixed-parameter PSS, called a CPSS, which is widely used in power systems and has made a great participation in enhancement of power system dynamics. The parameters of CPSS are determined based on a linearized model of the power system around its nominal operating point where they can provide good performance [3, 5]. Due to the high nonlinearities of the power systems, with configurations and parameters that may change with time, CPSS design based on the linearized model of the power systems cannot guarantee its performance in a practical operating environment [3, 5, 7].

To increase the robustness of PSS over a wide range of operating conditions, as well as, increasing its capability of damping oscillations in power system; numerous techniques have been proposed for their design. Such techniques are using intelligent optimization methods (genetic algorithms, neural networks, fuzzy logic and many other nonlinear control techniques) [3, 5, 6, 7]. In this paper; IT2FL controller has been proposed to enhance the performance of PSS, overcome high level of uncertainty, and increase its range of operation. The following sections will present interval type-2 fuzzy logic system, the modeling of a single machine infinite bus (SIMB), and PSS. Finally, enhancements achieved after proposing IT2FLPSS on the system stability.

II. Interval type-2 Fuzzy System

Prior to the 20th century; science was considered to be empty from uncertainty. Scientific progress showed that there are many methods which became able to formulate the real world, and overcome uncertainties [9]. Fuzzy logic controllers (FLCs) have been successfully and widely applied to various fields for decades. Basically, FLC is based on human's experience and knowledge resulting that the precise and accurate description of mathematical model of the controlled plant [10].

A. Type-2 Fuzzy Set And Membership Function

Type-2 fuzzy sets (T2FSs) were introduced by Zadeh in 1975 [9, 10]. The concept of T2FS was initially proposed as an extension of classical type-1 fuzzy logic systems (T1FLS) [11]. In figure 1, the same input p is applied to the three different types of fuzzy sets, resulting in a degree of membership which is specific to the type of fuzzy set. The amount of uncertainty that is associated with the degree is shown in color in Fig. 1 and is explained in Fig. 2 which illustrates secondary membership functions (third dimension) for the same types of fuzzy sets in Fig. 1. A T2FS, denoted Ã, is characterized by a type-2 membership function $\mu_{\tilde{A}}(x,y)$, where $x \in X$, and $u \in J_x \subseteq [0,1]$, that is,

$$\tilde{A} = \{((x,u), \mu_{\tilde{A}}(x,u)) \mid \forall x \in X, \forall u \in J_x \subseteq [0,1]\} \tag{1}$$

in which $0 \leq \mu_{\tilde{A}}(x,y) \leq 1$. Ã can also be expressed as [10, 12];

$$\tilde{A} = \int_{x \in X} \int_{u \in J_x} \frac{\mu_{\tilde{A}}(x,u)}{(x,u)} J_x \subseteq [0,1] \tag{2}$$

At each value of x, say $x = x_1$, the 2D plane whose axes are u and $\mu_{\tilde{A}}(x_1,u)$ is called a vertical slice of $\mu_{\tilde{A}}(x,u)$. It is $\mu_{\tilde{A}}(x=x_1,u)$ for $x_1 \in X$ and $\forall u \in J_x \subseteq [0,1]$, that is,

$$\mu_{\tilde{A}}(x = x_1, u) = \mu_{\tilde{A}}(x_1) = \int_{u \in J_{x1}} \frac{f_{x1}(u)}{u} J_x \subseteq [0,1] \tag{3}$$

in which $0 \leq f_{x1}(u) \leq 1$, and $f_{x1}(v)$ is a T1FS,which is referred to as a secondary set of IT2FS. When the secondary set is set to unity, i.e. $f_{x1}(u)=1$, an interval type-2 membership function reflects a uniform uncertainty at the primary memberships of *x* [10, 12].

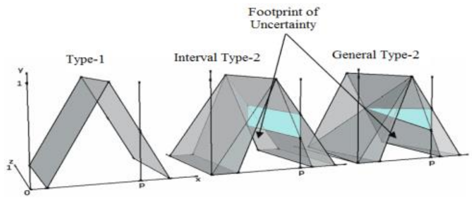

Fig. 1. Three types of fuzzy sets with the same input p [9]

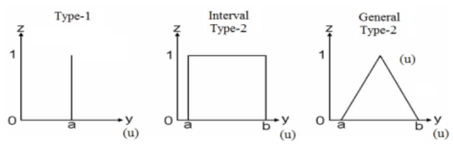

Fig. 2. The third dimension induced by an input p [9]

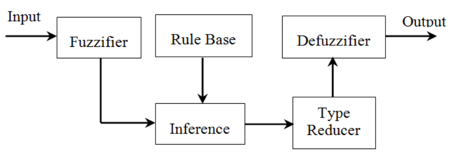

Fig. 3. The IT2FLC block diagram [9,10]

B. *Structure of A Type-2 Fuzzy Logic System*

Very similar to a type 1 fuzzy logic system (TIFLS) structurally, a type-2 fuzzy logic system (T2FLS) also contains the components as: fuzzifier, rule base, fuzzy inference engine, and output processor as shown in Fig. 3 [10].

Unlike T1FLS; T2FLS output processor has additional part called type reducer which represents a mapping of a T2FS into a T1FS [10].

III. SYSTEM MATHEMATICAL MODEL

A. *Modeling of synchronous machine*

Due to small disturbances or step changes the equilibrium between the two opposing forces is affected. So, there is an unbalance between mechanical torque and electrical torque of the individual machines [13, 14].

$$T_a = T_m - T_e \tag{4}$$

Where T_a is an acceleration torque, T_m is a mechanical torque, and T_e is an electrical torque.

The dynamic equation of the machine rotor corresponds to the acceleration law of the rotating bodies and can be expressed as [15]:

$$\frac{d\Delta\omega}{dt} = \frac{1}{2H}(\Delta T_m - K_1\Delta\delta - K_d\Delta\omega) \tag{5}$$

$$S\Delta\delta = \omega_0 \Delta\omega(s) \tag{6}$$

Where Δω, H, Δδ, K_1, and K_d are the speed deviation, per unit inertia constant, electrical rotor angle perturbation, damping coefficient, and ratio of the change in the electrical torque over the change in the rotor angle when the flux linkages in the d axis are constant, respectively.

B. *Generator Modeling*

For small variations of the three variables terminal voltage Δe_t, Internal transient voltage of generator $\Delta E`_q$, and power angle Δδ, the following relations can be derived [15]:

$$\Delta e_t = K_5\Delta\delta + K_6\Delta E_q^` \tag{7}$$

$$\Delta E_q^` = \frac{K_3\Delta E_{fd}}{1 + SK_3T_{d0}^`} - \frac{K_3K_4\Delta\delta}{1 + SK_3T_{d0}^`} \tag{8}$$

$$\Delta T_e = K_1\Delta\delta + K_2\Delta E_q^` \tag{9}$$

Where K_2, K_3, K_4, K_5, K_6, ΔE_{fd}, and $T`_{do}$ are the Ratio of the change in the electrical torque over the change in the flux linkages in the d axis when the rotor angle is constant, impedance factor, demagnetizing effect of a change in rotor angle, ratio of the change in terminal voltage over the change in rotor angle with constant $E`_q$, ratio of change in terminal voltage over the change in $E`_q$ for constant rotor angle, change in DC exciter voltage, generator field open circuit time constant, respectively.

C. *Excitation System Modeling*

Excitation current is provided by the excitation system, which usually consists of:

1) Amplifier

$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{K_A}{1+\tau_A S} \tag{10}$$

Where K_A is the gain of amplifier which will be in the range of 10 to 400 τ_A is the amplifier time constant which has a very small value in the range of 0.02 to 0.1 second, and often is neglected [14]. In this paper; a value of K_A= 200 is selected, since at this value there are four oscillatory modes , unlike values less than 200 which contain no more than two oscillatory modes , and at values more than 200 may lead to unstable condition [13].

2) Exciter

The value of the change in the exciter output, including the effect of change in power angle, is [15]:

$$\Delta E_q^{`} = \frac{K_E(\Delta E_{fd} - K_4 \Delta\delta)}{1+S\,\tau_E} \tag{11}$$

Where K_E, and τ_E are exciter model gain, and time constant, respectively.

3) Sensor

$$\frac{E_s(s)}{E_t(s)} = \frac{K_R}{1+\tau_R S} \tag{12}$$

Where K_R, and τ_R are sensor model gain, and time constant, respectively [14].

4) *Voltage Regulator*

The voltage regulator is the device that senses changes in the terminal voltage or current and cause corrective action to take place. In other hand, it derives the exciter to change its output [16].

IV. POWER SYSTEM STABILIZER

PSSs were developed to aid in damping of oscillations by making modulations of excitation system of generators. The action of a PSS is to extend the angular stability limits of a power system by providing supplemental damping to the oscillation of synchronous machine rotors through the generator excitation. To provide damping; stabilizers must produce a component of electrical torque on the rotor which is in phase with speed variations [3, 7]. This supplementary control is very beneficial during line outages and large power transfers. However, power system instabilities can arise in certain circumstances due to negative damping effects of the PSS on the rotor. The reason for this; is that PSSs are tuned around a steady-state operating point; their damping effect is only valid for small disturbances around this operating point. During severe disturbances, a PSS may actually cause the generator under its control to lose synchronism in an attempt to control its excitation field [3, 8].

A. *Conventional Power System Stabilizer*

PSS plays against the oscillations by forcing the change in excitation level appropriately. Without PSS, the reduced damping in power system is due to phase lags resulted by the field time constants and the phase lags in the normal voltage regulation loop. The PSS uses phase compensation by adjusting the timing of correction signal opposing the rotor oscillations. A power system stabilizer can therefore increase the generator's damping coefficient. The PSS as shown in Fig. 4 has three components; the phase compensation block, the signal washout block and gain block. The phase compensation block provides the appropriate phase lead characteristics to compensate for the phase lag between exciter input and generator electrical torque. The signal washout block serves as high pass filter with time constant T_W high enough to allow signals associated with oscillations in ω to pass unchanged. The stabilizer gain K_{stab} determines the amount of damping introduced by PSS [3, 8, 17].

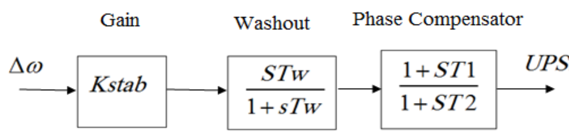

Fig. 4. Conventional lead-lag PSS [17]

From [18]; Parameters of CPSS are tuned to be K_{stab}= 9.5, T_W= 1.4 sec, T_1= 0.154 sec, and T_2= 0.033 sec.

B. *Interval Type-2 Fuzzy Logic Power System Stabilizer*

IT2FS has improved performance for many applications which require handling high levels of uncertainty [9, 11]. This paper will introduce IT2FLC to increase the performance of PSS and decrease the effect of high level of noise. The initial step in designing the IT2FLPSS is the determination of the state variables which represent the performance of the system. The input signals to the IT2FLPSS are to be chosen from these variables. The input values are normalized and converted into fuzzy variables. Rules are executed to produce a consequent fuzzy region for each variable. The expected value for each variable is found by type reducer plus defuzzifying the fuzzy regions. The speed deviation (Δω) of the synchronous machine and its derivative ($\Delta\omega^{\bullet}$) are chosen as inputs to the IT2FLPSS and the output is the stabilizing signal UPSS. The proposed controller also uses five linguistic variables. Rules that are presented in Table I have been deduced from [3, 5]. The block diagram presented in Fig. 5 shows an IT2FLC controller in MATLAB simulation, and in Fig. 6 the simulation of the surface control is presented.

TABLE I. PROPOSED CONTROL OUTPUT OF IT2FLC

Acc. \ Speed	***NB***	***NM***	***Z***	***PM***	***PB***
NB	NB	NB	NM	Z	Z
NM	NB	NM	NM	Z	Z
Z	NB	NM	Z	PM	PB
PM	Z	Z	PM	PM	PB
PB	Z	Z	PM	PB	PB

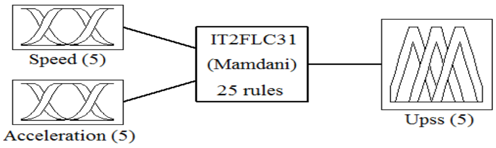

Fig. 5. Block diagram of proposed IT2FLC

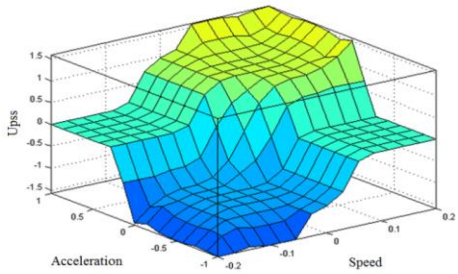

Fig. 6. Surface view of proposed IT2FLC

V. SIMULATION AND RESULTS

Simulation is carried out on SMIB system with automatic voltage regulator (AVR), thyristor high gain exciter, synchronous generator, and PSS are shown in Fig. 7. The model, in Fig. 8, is created using MATLAB/SIMULINK. The followings are the parameters of the machine, the exciter and the stabilizer. CPSS and IT2FLPSS are used interchangeably to evaluate the performance of the proposed IT2FLPSS; system response is compared in both cases. From [18]; parameters are K_1= 0.6821, K_2= 0.8649, K_4= 1.97, K_5=-0.1102, K_6= 0.5467, K_R= 1, T_R=0.02, K_E=0.323, T_E=1.806, H=7, and K_d=10.

When a load perturbation (ΔT_m= 0.4 pu) was applied at the instant of 2 sec, kept applied, and there is no PSS. The system became unstable as shown in Fig. 9 due to oscillation increase with the time.

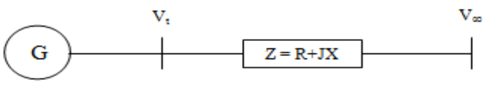

Fig. 7. Single machine connected to infinite bus [18]

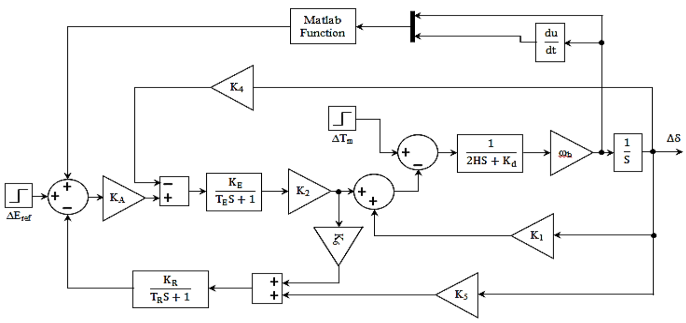

Fig. 8. A proposed linearized model of Synchronous Generator with IT2FL Controller

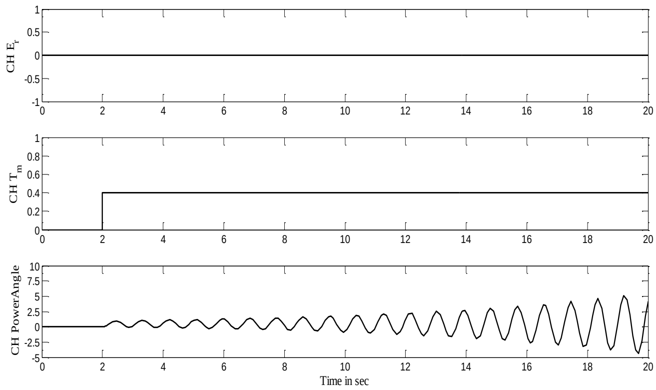

Fig. 9. Effect of ΔTm and ΔEref on power angle without PSS

Different scenarios are studied and applied to the system to subject it to different operating conditions, and show the effects of adding IT2FLPSS and CPSS on the system. Case 1 and 2 show how IT2FLPSS and CPSS damp the effect of ideal pulse noise that may come due to change in either load or excitation source, while Case 3 and 4; show how IT2FLPSS and CPSS reduce the effect of low and high level of continuous noise that occur in practical life.

Case 1: When a load perturbation (ΔT_m = 0.6 pu) was applied at the instant of 3 sec, and continues for 7 seconds. Simulation variations and responses are shown in Fig. 10. The simulation results clearly show that the IT2FLPSS damps out system oscillations faster compared to CPSS.

Case 2: When a load perturbation (ΔT_m=0.6 pu), and excitation reference voltage change (ΔE_{ref}= 0.6 pu) were applied at the instant of 2 sec and 3 sec respectively, ΔE_{ref} continues for 8 seconds, and ΔT_m continues for 7 seconds. Simulation variations and responses are shown in Fig. 11. The simulation results clearly show that the IT2FLPSS damps out system oscillations faster compared to CPSS.

Case 3: When a low continuous change in ΔE_{ref}, and ΔT_m were appeared in the system; a PSS work to reduce its effect on power angle. Simulation variations and responses are shown in Fig. 12. The simulation results clearly show that the IT2FLPSS damps out system oscillations faster compared to CPSS.

Case 4: When a high continuous change in ΔE_{ref}, and ΔT_m were appeared in the system; a PSS work to reduce its effect on power angle. Simulation variations and responses are shown in Fig. 13. The simulation results clearly show that the IT2FLPSS damps out system oscillations faster compared to CPSS.

VI. CONCLUSION

In this paper; a comparative study between CPSS and IT2FLPSS has been carried out on a single machine infinite bus. The study could observe, from the MATLAB/SIMULINK simulation, that the IT2FLPSS can provide better damping performance over a wide range of operating conditions. Such a nonlinear fuzzy based PSS will yield better and faster damping under small and large disturbances even with changes in system operating conditions.

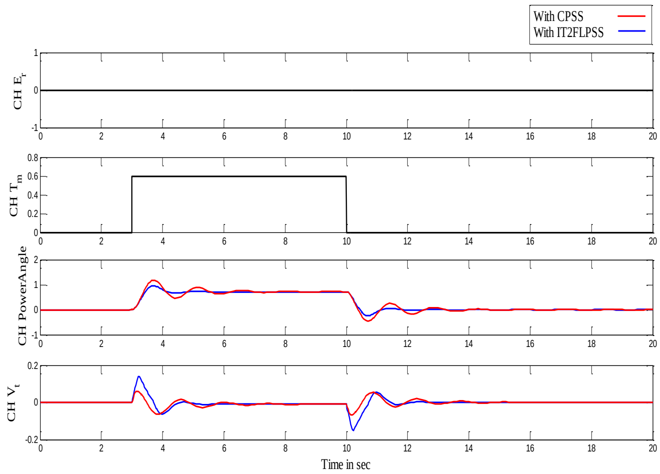

Fig. 10. Effect of instant change of ΔTm on power angle with using PSS

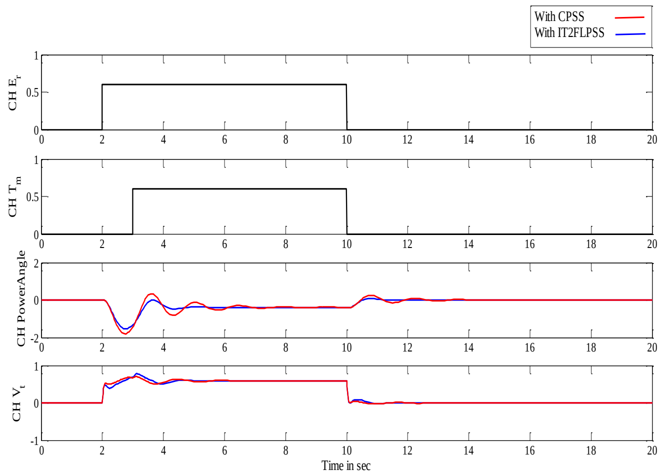

Fig. 11. Effect of instant change of ΔTm and ΔEref on power angle with using PSS

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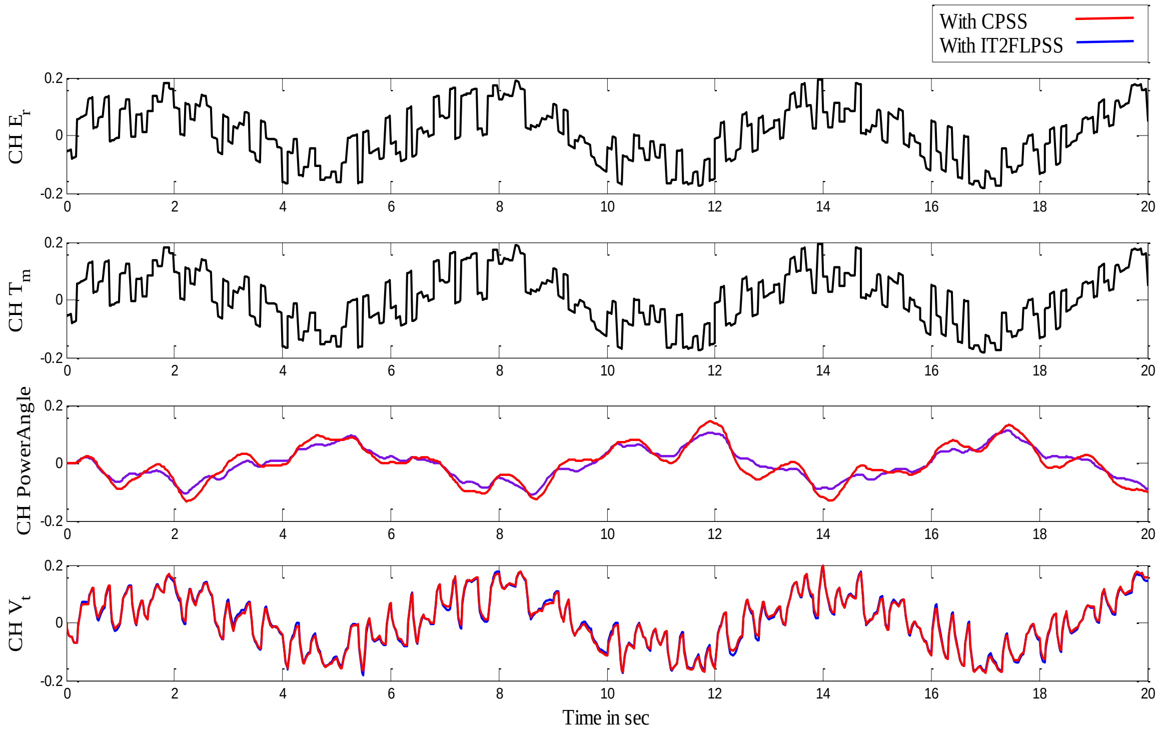

Fig. 12. Effect of low noise come from ΔT_m and ΔE_{ref} on Power angle with using PSS

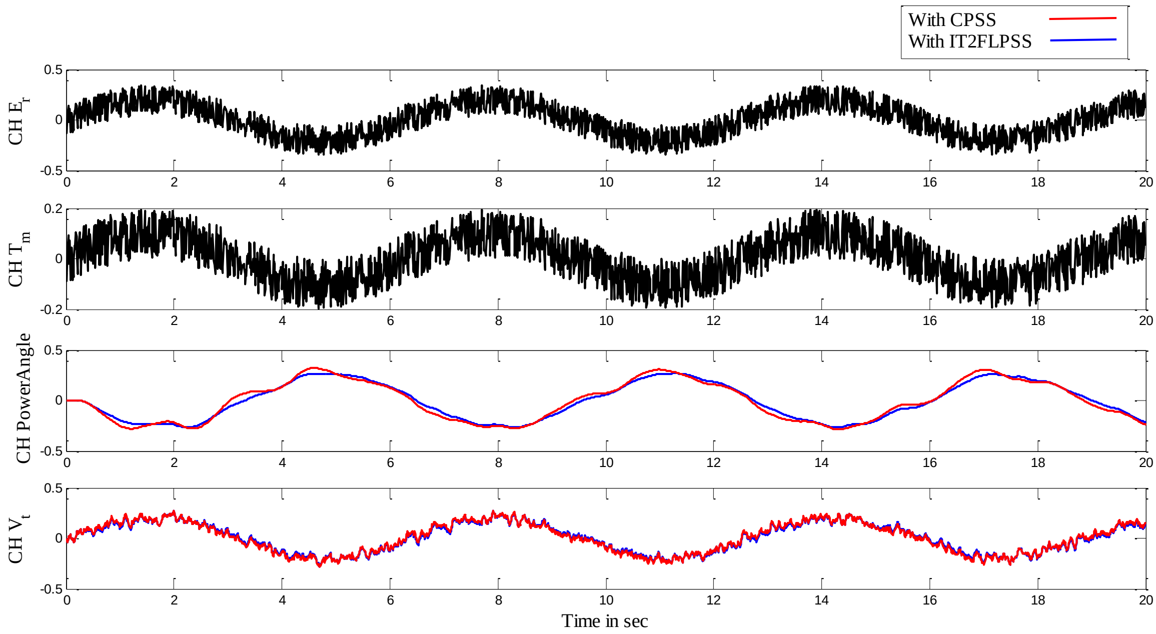

Fig. 13. Effect of high noise come from ΔT_m and ΔE_{ref} on Power angle with using PSS