Performance Analysis of Load Frequency Control for a Two-Area Interconnected Power System using Twisting Control

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***Abstract*—The control of load frequency is an important power system area. This paper proposes a higher order sliding mode (HOSM) controller for load frequency control (LFC) of two area thermal interconnected power system with nonlinearities. The proposed second order sliding mode controller (SMC) utilizes twisting algorithm. When a disturbance occurs on system, twisting SMC will maintain the frequency error, tie-line power error and area control error within limit. The performance of twisting SMC is also compared with the traditional integral controller.**

***Index Terms*—load frequency controller, higher order sliding mode controller, automatic generation controller, sliding mode controller, twisting algorithm**

I. Introduction

Power system contains generation, transmission and distribution of electrical energy. It will transform the natural resources into a worthwhile high quality electrical energy. For the optimized use of electrical equipment, the electrical energy obtained should be at high quality under any load fluctuations i.e. the frequency and voltage should be a constant value. The swing in these parameters indicate the operating point shifting of equipment. This will ruin the entire system.

The deviation of frequency and voltage occurs due to the discrepancy of active and reactive power between generation and consumption [1]. It is a fact that, the active and reactive power balance should be maintained for any circumstances. Hence we need a dominant control system to oppose the load fluctuations and contingency conditions. The variations of active and reactive power cause the frequency and voltage fluctuations respectively. Hence the control problem can be separated into two independent problems based on the above fact.

The LFC is recognized as the automatic generation control (AGC) deals with the frequency and active power. It has two goals, one is to maintain the frequency of the system to the anticipated value and another goal is to maintain the interchange power between tie line at its scheduled value for any riot condition [2]. The LFC can be done in various ways. A discrete or continuous model of power system given in [3]. Earlier centralized controller based techniques has been used, which is highly reliable and low cost. But it causes communication delays in interconnected power system and it requires high computational and storage complexities with distance travel [4].

In 1980's decentralized control technique is presented to overcome the drawbacks of centralized method [5]. Because of its reliability and efficiency, it becomes a dominant control method in power system [6]. Each area in the interconnected power system have its own decentralized control based on locally available state variables. Its control objectives are analogous to the centralized controller and which eradicates the computational complications.

In LFC, conventional PI/PID control is typically used as a decentralized control method [7]. These controllers are not easy to tune but simple to implement. However, they infer from the problem of long settling time and large overshoot in frequency's transient response. In addition, PI/PID controllers are not robust enough for system uncertainties and disturbances. Therefore, an advanced controller has to be developed to improve the transient response of load frequency and to enhance the control quality of power systems despite the presence of load disturbances and system uncertainties.

In recent years, many diverse control algorithms have been proposed. They are robust control algorithms includes fuzzy logic [8], neural networks [9], predictive control model [10], optimal control [11]. In general, approaches to design LFC is classified into several categories such as classical techniques, adaptive methods, variable structure methods, robust control methods and methods based on artificial intelligence.

A sliding mode controller is a robust variable structure control technique which has been effectively implemented under uncertainty conditions in abundant electromechanical plants. The SMC's main advantage is invariance to matched uncertainties, reduction of order, simplicity of design and robustness against disturbance. It is a powerful tool for controlling nonlinear uncertain systems.But this method has some problems such as restrictions on relative degrees and chattering effects [10].

In recent times, number of efforts are made to overcome the problem of chattering in SMC by introducing new control methods such as sliding sector method, method of add a boundary layer around the switching surface, sigmoid approximations and high gain control with saturation etc. Apart from these, an approach called HOSM control [12] is the current important topic of research. HOSM controllers are promising to embrace the advantages of conventional SMCs to higher relative degree systems. It upholds the standard SMC gain and delivers unchattered finite time convergence.

Among various second order sliding mode controllers, one of the first algorithm proposed for nonlinear systems is twisting algorithm [12]. With discontinuous control action, it guarantees finite time convergence and disturbance rejection. In this paper, a twisting SMC is proposed for a two-area thermal interconnected power system with nonlinearities governor dead band (GDB) and generation rate constraints (GRC). Our control objective is to regulate the area control error (ACE) to zero, i.e. the interconnected system's frequency and tie-line power errors for any load shifts.

The following is the order of this paper. A nonlinear two area thermal interconnected power system is modeled in Section II. Section III explains the twisting algorithm based LFC. An integral controller based LFC described in section IV. The results of the simulation will be shown in Section V and the final remarks and future works will be given in Section VI.

II. TWO AREA THERMAL INTERCONNECTED POWER SYSTEM MODEL

Here we are looking at a nonlinear model of two interconnected thermal power system shown in Fig. 1. It consists of two single areas connected to each other by tie line.The area on top is referred as area 1, and the one at the bottom is referred as area 2. Each area contains generator, turbine, governor and controller. The turbine used is different for two areas. Reheat type turbine is used in area 1 and non-reheat type turbine in area 2. The nonlinearities considered are GDB and GRC which has been shown separately in the Fig. 1. The occurrence of disturbance in any area affects both areas frequency and power flow through tie-lines, resulting a significant ACE value for each area. The twisting controllers placed in each area will bring the varying factors to steady state zero value. Table 1 shows the parameters used in the block diagram.

A governor is mainly designed for improving the frequency response in about 20 seconds following disturbances (such as an abrupt generator loss etc.). The transfer function of a governor $G_H(s)$ is given by

$$G_H(s) = \frac{\Delta X_g(s)}{\Delta P_V(s)} = \frac{1}{1 + sT_G} \tag{1}$$

The range of governor time constant is $80ms \leq T_G \leq 100ms$ [1] and the expression for input of speed governor

TABLE I: PARAMETERS USED IN BLOCK DIAGRAM

$\Delta P_{L1}, \Delta P_{L2}$	Load disturbance in area 1 and area 2.
$\Delta f_1, \Delta f_2$	Frequency error in area 1 and area 2.
$\Delta P_{tie1}, \Delta P_{tie2}$	Tie line power change between area 1 and area. 2
$\mathrm{ACE}_1, \mathrm{ACE}_2$	Area control error in area 1 and area 2.
u_1, u_2	Control input in area 1 and area 2.
B_1,B_2	Frequency response coefficient of area 1 and area 2.
$\Delta X_{g1}, \Delta X_{g2}$	Valve/gate position change of the power system in area 1 and area 2.
R_1,R_2	Speed droop coefficient of area 1 and area 2.
$\Delta P_{g1}, \Delta P_{g2}$	Mechanical power in area 1 and area 2.
T_{12}, T_{21}	Tie-line coefficients in area 1 and area 2.
T_{G1}, T_{G2}	Time constants of governors in areas 1 and area 2.
ΔP_v	The input of speed governor.
T_t	Steam chest time constant.
K_r	Reheat coefficient.
T_r	Reheat time constant.
K_p	Power system gain constant.
T_p	Power system time constant.

is $\Delta P_v = u_i - \frac{1}{R_i}\Delta f_i$ $(i = 1, 2)$. Equation (1) represents the governor's linear model excluding the dead band. The governor's non-linearity is GDB. The governor may not react immediately for a change in the input signal until the input reaches a specified value known as the dead band. The dead band's value is 0.036 [9]. As the change of input frequency is ranging between ±0.036Hz, there are no output responses for the governor. The rate of change for the generation of electricity is known as GRC [2] which has maximum and minimum limits shown by a saturation block in the Fig. 1. A typical thermal unit value for GRC is 3 %/min, which is bounded by ±0.0005 p.u.MW/sec for the AGC to prevent excessive control.

A thermal turbine is used to transform the thermal energy from pressurized steam into mechanical power which is directly given to the generator. Here we are using reheat and non-reheat type turbines for two areas respectively. If we use the same steam for number of times is called as reheat type turbine otherwise it is non reheat type turbine. A non-reheat turbine's transfer function $G_T(s)$ is expressed by

$$G_T(s) = \frac{\Delta P_g(s)}{\Delta X_g(s)} = \frac{1}{1 + sT_t} \tag{2}$$

Normally the value of steam chest time constant range is $100ms \leq T_t \leq 500ms$ [1]. Equation (2) represents the linear model of the turbine excluding GRC. A reheat turbine's transfer function $G_{TRH}(s)$ is given by

$$G_{TRH}(s) = \frac{\Delta P_g(s)}{\Delta X_g(s)} = \frac{1 + sK_rT_r}{(1 + sT_t)(1 + sT_r)} \tag{3}$$

A generator changes over the mechanical power received from the turbine into electrical power. The transfer function for a generator $G_p(s)$ is shown as

$$G_p(s) = \frac{\Delta f(s)}{\Delta P_g(s) - \Delta P_L(s) - \Delta P_{tie}(s)} = \frac{K_p}{1 + sT_p} \tag{4}$$

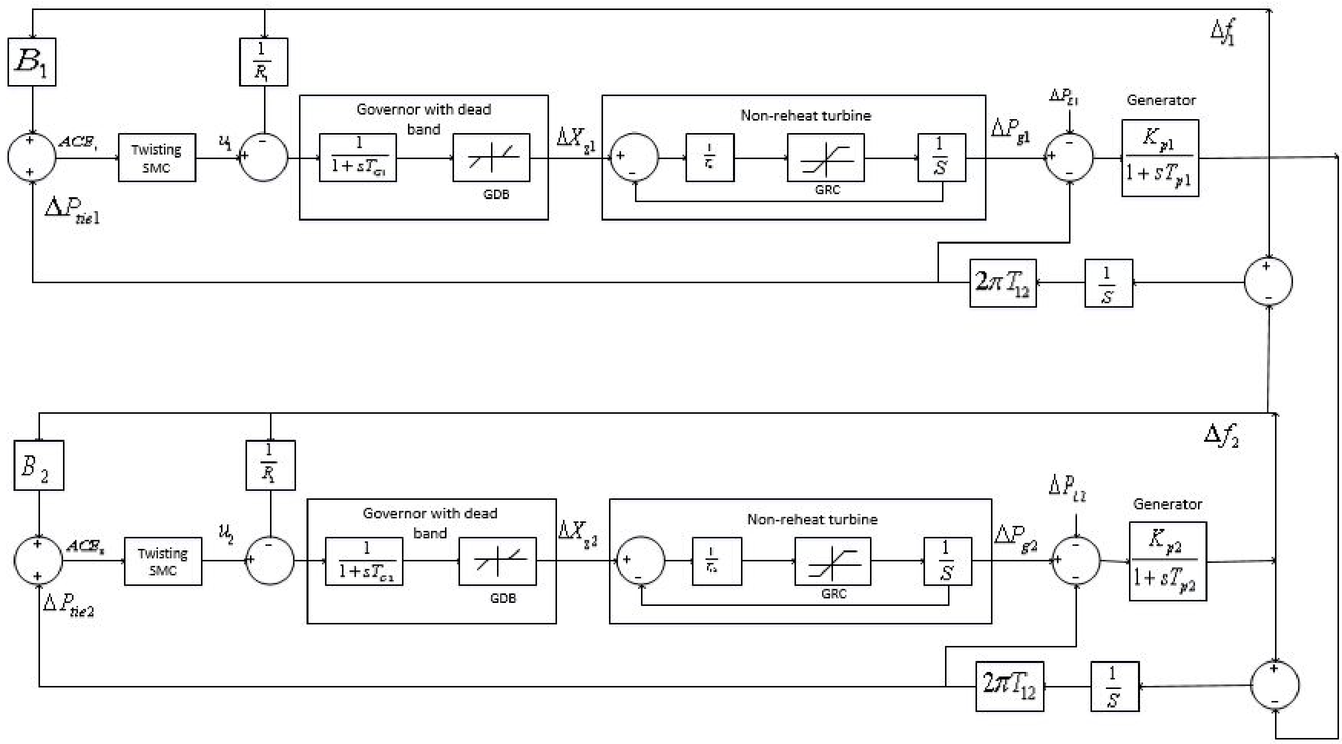

Fig. 1: A nonlinear interconnected two-area power system with controller.

The controller must ensure the frequency error to zero and maintain tie line power to a scheduled value in a multi-area power system. The term ACE refers to the sum of the terms of frequency and tie line power error. Finally, the main objective becomes the control of ACE value to zero for any kind of nonlinear disturbances. The tie line power error and ACE are defined as

$$\Delta P_{tiei} = \frac{2\pi T_{ij}}{S}\left(\Delta f_i - \Delta f_j\right) \tag{5}$$

$$ACE_i = B_i \Delta f_i + \Delta P_{tie} \tag{6}$$

where j=2 as i=1 and j=1 as i=2.

For system variables and their derivatives, we assume zero initial conditions in the following equations. For area 1, an ordinary differential equation (ODE) model can be obtained from (4) to represent the relationship between the mismatch power $(\Delta P_{g1} - \Delta P_{L1} - \Delta P_{tie1})$ and the frequency error (Δf_1).

$$\Delta \dot{f}_1 = \left(\frac{K_{p1}}{T_{p1}}\right)\left(\Delta P_{g1} - \Delta P_{tie1} - \Delta P_{L1}\right) - \left(\frac{1}{T_{p1}}\right)\Delta f_1 \tag{7}$$

The relationship between mechanical power and the change in position of the valve/gate in area 1 is obtained from (2).

$$\Delta \dot{P}_{g1} = \left(\frac{1}{T_{t1}}\right)\Delta X_{g1} - \left(\frac{1}{T_{t1}}\right)\Delta P_{g1} \tag{8}$$

The relationship between the control input, the frequency error and the position of the valve / gate changes from (1)

$$\Delta \dot{X}_{g1} = \left(\frac{1}{T_{G1}}\right)u_1 - \left(\frac{1}{T_{G1}R_1}\right)\Delta f_1 - \left(\frac{1}{T_{G1}}\right)\Delta X_{g1} \tag{9}$$

The tie-line power error in area 1 is linearly proportional to the integral of frequency error between areas 1 and 2. From (5), the model is

$$\Delta \dot{P}_{tie1} = 2\pi T_{12}\left(\Delta f_1 - \Delta f_2\right) \tag{10}$$

For area 2, we can obtain an ODE model from (4) to represent the relation between the mismatch power $(\Delta P_{g2} - \Delta P_{L2} - \Delta P_{tie2})$ and the frequency error is

$$\Delta \dot{f}_2 = \left(\frac{K_{p2}}{T_{p2}}\right)\left(\Delta P_{g2} - \Delta P_{tie2} - \Delta P_{L2}\right) - \left(\frac{1}{T_{p2}}\right)\Delta f_2 \tag{11}$$

From (3), we obtain the following two equations where ΔX_{gr} is a medium variable.

$$\frac{\Delta P_{g2}}{\Delta X_{gr}} = \frac{1 + K_r T_r s}{1 + T_r s} \tag{12}$$

$$\frac{\Delta X_{gr}}{\Delta X_{g2}} = \frac{1}{1 + T_{t2} s} \tag{13}$$

From (13), we can express ΔX_{gr} as

$$\Delta \dot{X}_{gr} = \frac{1}{T_{t2}}\Delta X_{g2} - \frac{1}{T_{t2}}\Delta X_{gr} \tag{14}$$

The ODE model of (12) is

$$\Delta \dot{P}_{g2} = \frac{1}{T_r}\left(\Delta X_{gr} - K_r T_r \Delta \dot{X}_{gr} - \Delta P_{g2}\right) \tag{15}$$

Substituting (14) into (15), we obtain an ODE model to express the relations between mechanical power and medium variable $\Delta\ X_{gr}$ in area 2. The ODE model is given by

$$\Delta \dot{P}_{g2} = \frac{1}{T_r}\Delta X_{gr} + \frac{K_r}{T_{t2}}\Delta X_{g2} - \frac{K_r}{T_{t2}}\Delta X_{gr} - \frac{1}{T_r}\Delta P_{g2} \tag{16}$$

From (1), obtain an ODE model to represent the relations among control input, frequency error, and valve/gate position change in area 2, are given by

$$\Delta \dot{X}_{g2} = \frac{1}{T_{G2}}u_2 - \frac{1}{R_2 T_{G2}}\Delta f_2 - \frac{1}{T_{G2}}\Delta X_{g2} \tag{17}$$

From (5), the tie-line power in area 2 can be calculated as

$$\Delta \dot{P}_{tie2} = 2\pi T_{21}\left(\Delta f_2 - \Delta f_1\right) \tag{18}$$

III. TWISTING SMC

There are three procedures in the conventional SMC design. Such as design of sliding surface, switching control and equivalent control. Normally for any cases, controller action is to converge the steady state error value to zero with in short duration. Here the surface design includes state variables. So the surface moves to zero implies the convergence of state variables and desired state trajectories converges to zero. The switching control is a discontinuous which maintain the system trajectory on the surface and the equivalent control forces the system states to continue on the surface.

The HOSM removes the restriction of relative degree and removes chattering when using a continuous controller. There are few widely used controllers for second order SMC such as sub-optimal controller, terminal sliding mode controllers, twisting controllers and super-twisting controllers.

The twisting controller is one of the first second order SMC presented in [12]. For the second order SMC the control input u should appear on the second derivative of system state and for twisting SMC u should be in second derivative of sliding variable σ too.

$$\ddot{\sigma}\left(x,t\right) = p\left(x,t\right) + q\left(x,t\right)u \tag{19}$$

for all $(x,t) \in R^n \times R_+$

$$0 \le K_m \le \left|q\left(x,t\right)\right| \le K_m \text{ and } \left|p\left(x,t\right)\right| \le K_a$$

The twisting controller's control law

$$u = -r_1 sign\left(\sigma\right) - r_2 sign\left(\dot{\sigma}\right) \tag{20}$$

with the conditions

$$\begin{array}{l} \left(r_1 + r_2\right)K_m - K_a \succ \left(r_1 - r_2\right)K_M + K_a \\ \left(r_1 - r_2\right)K_m \succ K_a \end{array} \tag{21}$$

This controller brings the states to equilibrium in finite time with a discontinuous control action. Now consider the case of LFC problem, here the error variable i.e. ACE and its derivative is used to design the twisting controller as in (20). The idea is to make the ACE value to zero in finite time despite of any matched perturbation by properly chosing controller gain values.

IV. INTEGRAL CONTROLLER

The integral controller has wide uses especially in industries. Hence it is used for comparison with twisting SMC for LFC application. The integral controller's mathematical expression for the LFC application in the two interconnected power system is

$$y(t) = -K_I \int_0^t \left(ACE\right)dt \tag{22}$$

The integral gain K_I can be found by different methods such as relay control method, Z-N formula method, iterative feedback tuning (IFT), internal model control (IMC) and through online tuning during simulation etc.

V. Simulation Results

In order to compare twisting SMC and integral controller, we use Matlab/Simulink tool. Here we did the simulations on two area interconnected system with GDB and GRC nonlinearities. We have two cases

Case A: Disturbance applied to one area

We compare the controllers by applying a load disturbance of 0.02 pu on area 1 at 2 sec for a simulation time of 20 sec. There is no load disturbance added to area 2. Fig. 2-7 show the frequency error, tie-line power error and ACE for both areas under the control of twisting SMCs and an integral controller.

Case B: Disturbance applied to both areas

We compare the controllers by applying a load disturbance of 0.02 pu on area 1 at 2 sec and on area 2 at 4 sec for a simulation time of 20 sec. Fig. 8-13 show the frequency error, tie-line power error and ACE for both areas under the control of twisting SMCs and an integral controller.

For the above two cases, all of the errors are driven to zeros by the two controllers successfully. The settling time for the twisting SMC interconnected system response is shorter than that of the conventional integral controlled system. It shows the superiority of twisting controller.

VI. Conclusions

In this paper, twisting SMC and integral controllers are proposed for the LFC. The two area interconnected thermal power system considered have non linearities GDB and GRC. The non-reheat type of turbine is used for one area and reheat for other one. The mathematical model of the system is derived for analysis and two cases has been

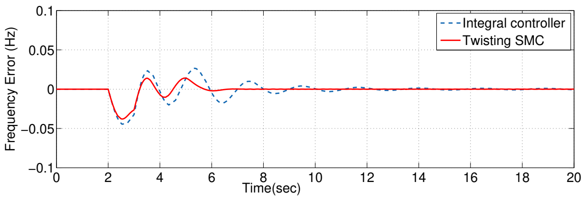

Fig. 2: Frequency error in area 1 under case A.

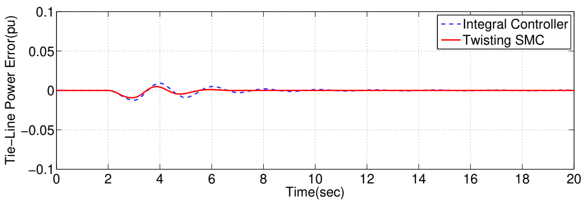

Fig. 3: Tie-line power error in area 1 under case A.

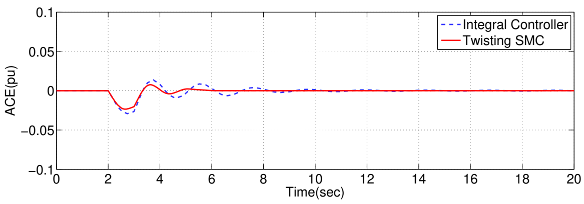

Fig. 4: ACE in area 1 under case A.

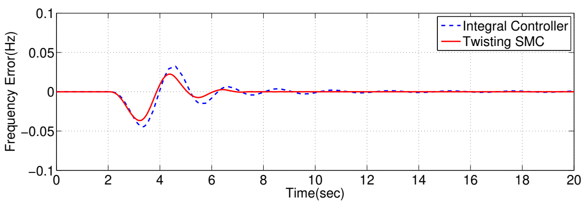

Fig. 5: Frequency error in area 2 under case A.

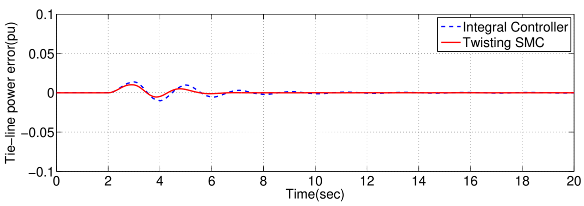

Fig. 6: Tie-line power error in area 2 under case A.

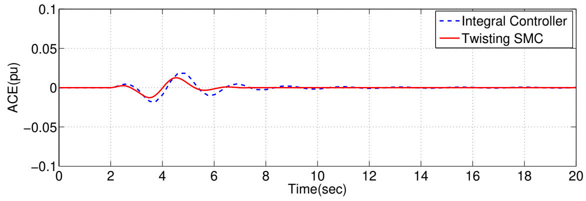

Fig. 7: ACE in area 2 under case A.

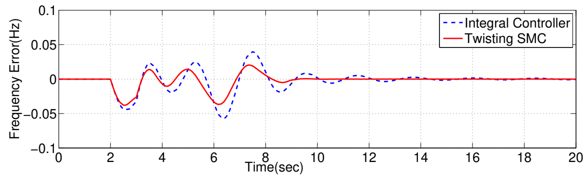

Fig. 8: Frequency error in area 1 under case B.

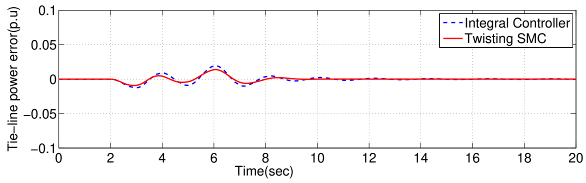

Fig. 9: Tie-line power error in area 1 under case B.

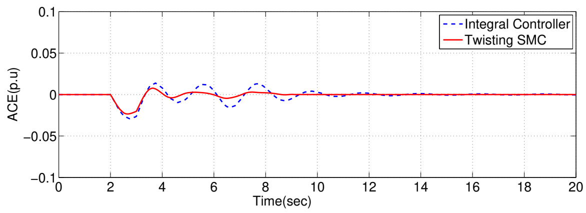

Fig. 10: ACE in area 1 under case B.

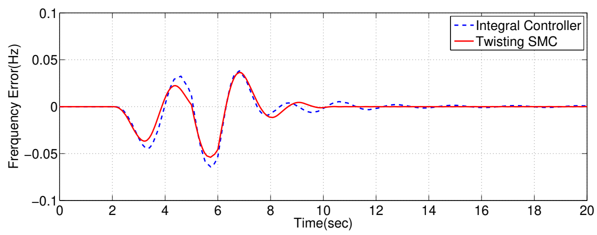

Fig. 11: Frequency error in area 2 under case B.

considered by apply a disturbance to one area and to both areas. Our control goal is to bring the value of ACE to zero even the presence of disturbance.

The results of the simulation show the convergence of ACE, which successfully includes frequency and tie-line error terms to zero and analyzed it separately. Twisting SMC is superior in terms of settling time than integral controller and which is validated using simulation results.

Appendix

The nominal system parameter values are listed below [13].

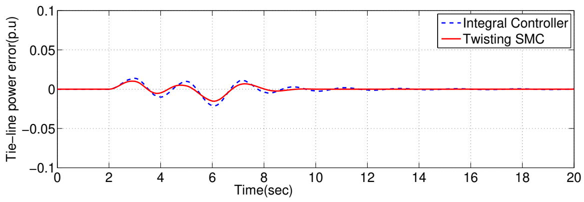

Fig. 12: Tie-line power error in area 2 under case B.

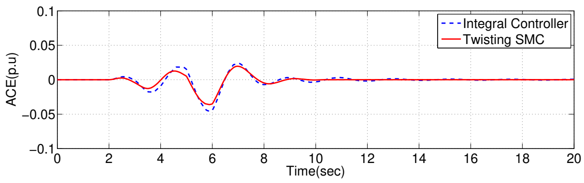

Fig. 13: ACE in area 2 under case B.

$$T_{g1} = 0.08s, T_{g2} = 0.09s$$
$$T_{t1} = 0.3s, T_{t2} = 0.4s$$
$$T_{p1} = 20s, T_{p2} = 25s$$

$$K_{p1} = 120Hz/pu.MW, K_{p2} = 130Hz/pu.MW$$

$$R_1 = 2.4Hz/pu.MW, R_2 = 2.6Hz/pu.MW$$

$$B_1 = 0.425puMW/Hz, B_2 = 0.44pu.MW/Hz$$

$$2\pi T_{12} = 0.545pu.MW/rad$$
$$2\pi T_{21} = 0.6pu.MW/rad$$

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