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A Robust Decentralized Controller Design for Interconnected Power System with Random Load Perturbations using SDO Software

Pasala Gopi[a,*], Potla Linga Reddy[b]

[a] *Research Scholar, Dept. of EEE, K L University, Grean Fields, Guntur (Dt) -522502, India*
[b] *Professor, Dept. of EEE, K L University, Grean Fields, Guntur(Dt)-522502, India*

Abstract

Because of increase in load, size and change in power system structure, the response of load frequency control problem of the interconnected power system is more complex. This paper deals with Load Frequency Control of three area interconnected Power system having Reheat, Non-reheat and Reheat turbines in all areas respectively. The response of the load frequency control problem in a multi-area interconnected power system is improved by designing a PID controller using different tuning techniques and proved that the proposed controller, which was designed by Simulink Design Optimization Software gives the superior performance than other controllers for both Step load and Random load perturbations. Finally the validity and robustness of the proposed controller was checked against various Step load and Random load perturbations.

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Keywords: Load Frequency Control; Interconnected Power System; PID Tuning Techniques; Simulink Design Optimization(SDO) Software.

1. Introduction

For large scale power system which consists of interconnected control areas, load frequency then it is important to keep the frequency and inter area tie power near to the scheduled values. The input mechanical power is used to control the frequency of the generators and the change in the frequency and tie-line power are sensed, which is a measure of the change in rotor angle. A well designed power system should be able to provide the acceptable levels of power quality by keeping the frequency and voltage magnitude within tolerable limits. Changes in the power

* Corresponding author. Tel. +918500624007
E-mail address: pasala.epe07@gmail.com

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system load affects mainly the system frequency, while the reactive power is less sensitive to changes in frequency and is mainly dependent on fluctuations of voltage magnitude. The AGC or LFC system solely cannot control the disturbances, it needs another controller like Integral (I) or Proportional plus Integral (PI), Proportional plus Integral plus Derivative (PID) controller [8]. In [1], the same authors were explained about literature review on AGC strategies in interconnected power system very clearly.

2. Mathematical Modeling of Power System

The main difference between Load Frequency Control of multi-area system and that of the single area system is, the frequency of each area of multi-area system should return to its nominal value and also the net interchange through the tie-line should return to the scheduled values. So a composite measure, called area control error (ACE), is used as the feedback variable. A decentralized controller can be tuned assuming that there is no tie-line exchange power, $P_{tiei} = 0$. In this case the local feedback control will be $ui = -K_i(s)B_i\,\Delta f_i$. Thus load frequency controller for each area can be tuned independently.

2.1. Modeling of Power Generating Units

In power systems, a turbine unit is used to transform the natural energy (like energy from steam or water) into mechanical power (ΔP_m) that is supplied to the generator. In LFC model, there are three different types of commonly used turbines; those are Non-Reheat, Reheat & hydraulic turbines, all of which can be modelled by transfer functions [1, 2].

Non-reheat turbines are first-order units. A time delay (T_t) occurs between switching the valve and producing the turbine torque. The transfer function of the non-reheat turbine is represented as

$$GNr(s) = \frac{1}{(1 + STt)} = \frac{NUMNt(s)}{DENNt(s)}$$

Because of different stages due to high and low steam pressure in the *Reheat turbines*, it was modelled as second-order units. The transfer function of reheat turbine can be represented as

$$Gr(s) = \frac{1 + SCTtr}{(1 + STtr)(1 + STlpr)} = \frac{NUMt(s)}{DENt(s)}$$

Where T_{lpr} is the low pressure reheat time and *C* represents the high pressure stage rating, T_{tr} is the reheat turbine time constant. The *Speed Governors* are used in power systems to sense the frequency variations (Δf) which are caused by the load change (ΔP_L) and are cancelled by varying the turbine inputs.

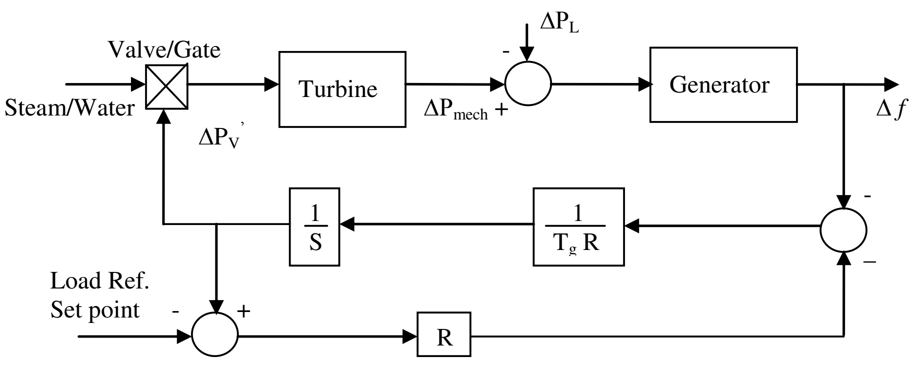


Fig.1 Block diagram representation of Speed Governing unit

The block diagram representation of a speed governing system is shown in Fig.1, where *R* is the speed regulation and T_{sg} is the time constant of the Speed Governor [6]. Suppose if there is no load reference and there are load changes occurs, some part of the change may be compensated by the valve or gate settings and the remaining of the change is represented in the form of frequency variations. The goal of Load Frequency Control (LFC) is to compensate the frequency deviations due to active power load variations. Thus, the load reference set-point can be used to adjust the valve/gate positions so that all the load change is cancelled by the power generation rather than resulting in a frequency deviation as shown in Fig.2. The transfer function can be represented as

$$Gsg(s) = \frac{1}{(1 + sTsg)} = \frac{NUMsg(s)}{DENsg(s)}$$

A *generator* converts the mechanical power developed by the turbine into electrical power. Once the load variations occurs, the mechanical power (P_{mech}) from the turbine will not match the electrical power (P_{ele}) generated by the generator. The error between the mechanical (ΔP_{mech}) and electrical powers (ΔP_{ele}) is integrated into the rotor speed deviation ($\Delta\omega_r$), which can be converted into the frequency variations (Δf) by multiplying with 2π. The Fig.2 shows the block diagram of generator with load damping (D) effect.

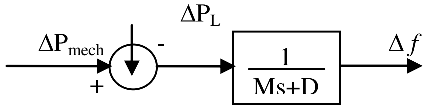


Fig .2 Block diagram of generator with load damping effect

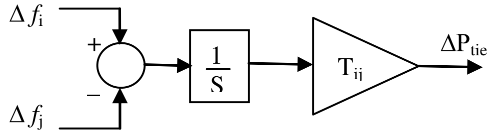


Fig. 3 Block diagram representation of tie-line link

The Laplace transform of generator with load damping is

$$\Delta P_{mech}(s) - \Delta P_L(s) = (Ms + D)\Delta F(s)$$

$$Gps(s) = \frac{1}{(D + MS)} = \frac{Kps}{(1 + STps)} = \frac{NUMps(s)}{DENps(s)}$$

In an interconnected power system, different areas are connected with each other with the help of tie-lines. When the frequency variations in the two areas are different, a power exchange occurs through the tie-line between the connected two areas. The block diagram representation of tie-line is as shown in Fig.3. The laplace transform of tie line in Fig.3 is given by

$$\Delta P_{tieij}(s) = \frac{T_{ij}(\Delta F_i(s) - \Delta F_j(s))}{s}$$

Where ΔP_{tieij} is tie line power exchange between areas i and j, and T_{ij} is the tie-line synchronizing coefficient between area i and j [6].

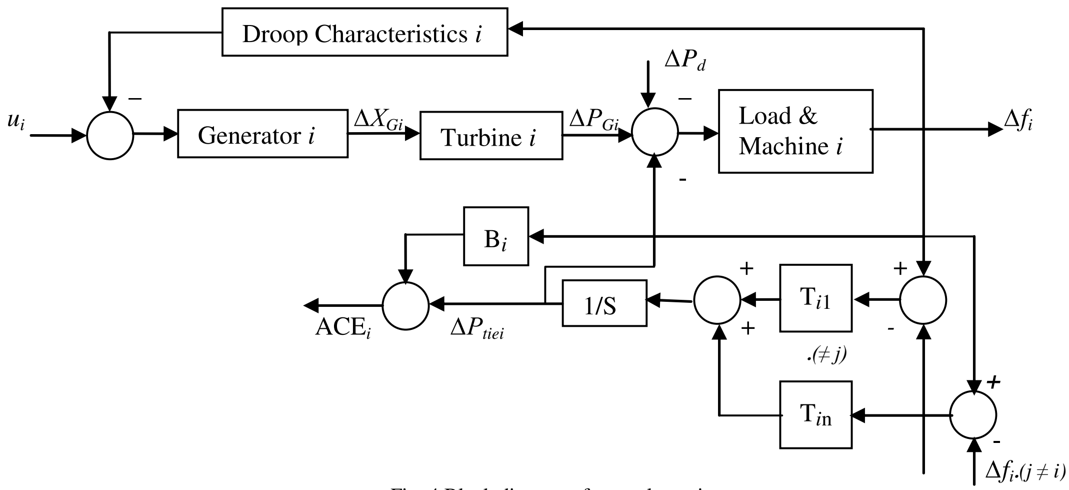


Fig .4 Block diagram of control area i

The goal of Load Frequency Control is not only to compensate the frequency error in each area, but also to control the tie-line power exchange according to schedule [6]. Because the tie-line power error is the integral of the frequency difference between each pair of areas, if we control frequency error to zero, any steady state errors in the frequency of the system would result in tie-line power errors. Therefore, we need to include the information of the tie-line power deviation into our control input. As a result, an area control error (ACE) is defined as (referred to Fig.4)

$$ACEi = \sum_{j=1,2\ldots n,\, j\neq i} \Delta Ptieij + Bi\Delta fi$$

Where B_i is the frequency bias constant for area-*i* and $B_i = 1/R_i + D_i$. This ACE signal is used as the plant output of each power generating area [6].

2.2. Modeling of Power System Areas

Let Area-I, Area-II and Area-III are the non identical interconnected power system with Reheat, Non-reheat and Reheat turbines in all three areas respectively. The transfer function of each area with generator drooping characteristics can be defined as

$$G_p(s) = \frac{NUMsg(s)\ NUMt(s)\ NUMps(s)}{DENsg(s)\ DENt(s)\ DENps(s) + NUMsg(s)\ NUMt(s)\ NUMps(s)/R} B$$

The transfer functions of all three areas of interconnected power system are as follows (see appendix for Turbine, Speed Governor and Power system parameters):

For Area-1, the transfer function is

$$G_1(s) = \frac{1*(3s+1)*115*0.5087}{(1+0.08s)(1+10.3s+3s^2)(1+15s)+1*(3s+1)*115/2} = \frac{48.75s+16.25}{s^4+16s^3+44.312s^2+55s+16.25}$$

For Area-2, the transfer function is

$$G_2(s) = \frac{1*1*120}{(1+0.08s)(1+0.3s)(1+20s)+1*1*120/2.4} 0.425 = \frac{106.25}{s^3+15.88s^2+42.46s+106.25}$$

For Area-3, the transfer function is

$$G_3(s) = \frac{1*(5s+1)*120*0.425}{(1+0.08s)(1+10.3s+3s^2)(1+20s)+1*(5s+1)*120/2.7} = \frac{53.125s+10.625}{s^4+15.98s^3+44.05s^2+58.41s+10.625}$$

3. PID Controller Tuning

For industrial plant process, the conventional PID controllers are most commonly used. They are doing some challenges to control, instrumentation and power engineers in the area of *tuning* of the gains of controllers required for best transient performance and stability. There are several prescriptive rules used for tuning of PID controller [3-5]. The parallel form of a PID controller has transfer function:

$$Gc(s) = Kp + \frac{Ki}{s} + sKd = Kp(1 + \frac{1}{sTi} + sTd)$$

K_p = Proportional Gain constant; K_i = Integral Gain constant; T_i = Reset Time constant $=K_p/K_i$, K_d = Derivative gain constant; T_d = Rate time or derivative time constant.

The tuning of the PID load frequency controller of multi-area power system that it has to bring frequency of each area to its nominal value and also the change in tie-line power should return to the scheduled values. So the combination of both, called Area Control Error (ACE), is used as feedback variable. For i^{th} area , the Area Control Error (ACE) is defined as $ACE_i = \Delta P_{tiei} + B_i \Delta f_i$ and Feedback control signal for area-i is $u_i = - K_i(s)\ AEC_{i.}$ A PID load frequency controller can be tuned assuming that there is no tie line power exchange i.e $\Delta P_{tiei} = 0$. Now the feedback control signal $u_i = - K_i(s)\ B_i \Delta f_i$.

3.1. Pessen Integral Rule (PIR) Tuning

Recently a new tuning rule for PID controller was prepared by Ziegler-Nichols called Pessen Integral Rule (PIR). The procedure for tuning a PID controller using Pessen Integral Rule (PIR) is similar to 2nd method of Ziegler-Nichols PID tuning [7].

The steps for tuning a PID controller using Pessen Integral Rule is as follows:

1. Reduce the integrator and derivative gains to 0.
2. Increase proportional gain K_p value from 0 to some critical value at which sustained oscillations occur.
3. Note the value K_{cr} and the corresponding time period of sustained oscillations, P_{cr}.

3.2. Automatic PID Tuning

To tune PID controller of single loop control system having PID automatically, use Simulink control design PID Tuner. With PID tuner it is possible to achieve good balance between performance and robustness. The procedure for automatic PID tuning is as follows:

1. Create a Simulink model with a PID controller for any order and any time delay in MATLAB/Simulink.
2. Double click on PID controller block to open the PID controller dialog box.
3. In dialog box, click 'Tune', it automatically linearizes the plant and designs an initial controller.

The K_P, K_I and K_D values of PID controller for all three areas with Pessen Integral Rule (PIR) and Automatic PID tuning methods are shown in Table 1 and Table 2 respectively.

Table.1 Pessen Integral Rule (PIR) Tuning

Area-i	K_P	K_I	K_D
Area-I	8.1795	20.4487	1.2269
Area-II	3.7429	9.3572	0.5617
Area-III	7.8414	19.6035	1.1762

Table.2 Automatic PID Tuning

Area-i	K_P	K_I	K_D
Area-I	5.7166	4.7307	1.7216
Area-II	1.2954	1.8696	0.2225
Area-III	5.2724	4.6325	1.4896

3.3. Integral Square Error (ISE) Optimization

A measure of system performance formed by integrating the square of the system error over a fixed interval of time; this performance measure and its generalizations are frequently used in linear optimal control and estimation theory. In this paper, the transfer function of PID Controller with Integral Square Error Optimization technique was obtained by the SISO tool in MATLAB/Simulink. The transfer function for PID Controllers of different areas in the interconnected power system with Integral Square Error (ISE) Optimization technique are given as
For Area-I $G_c(s) = 6.4506 + 4.9620/S + 4.8627S$, for Area-II $G_c(s) = 6.9775 + 4.9839/S + 4.9839S$ and for Area-II $G_c(s) = 7.4557 + 4.9705/S + 4.8711S$.

3.4. Simulink Design Optimization (SDO) Technique

Signal Constraint block is connected in developed MATLAB/Simulink model to optimize the model response for known inputs. To get optimized parameters of a Simulink model, the following steps have to follow:

1. Develop and open the Simulink model.
2. Open the Simulink design optimization block by typing *sdolib* at MATLAB command prompt.
3. Drag and drop the signal constraint block in the developed MATLAB/Simulink model.
4. Connect the signal constraint block to signal to which we want to get specified design requirements.

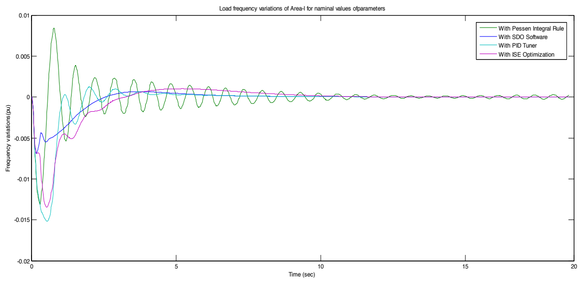
To design the controllers for interconnected power system using SDO Software, it requires Simulink Design Optimization toolbox. The transfer function for PID Controllers of different areas in an interconnected power system having different turbine units in each area with Simulink Design Optimization Software are given as, for Area-I $G_c(s) = 2.9626 + 1.8214/S + 5.3726S$, for Area-II $G_c(s) = 1.3383 + 3.0743/S + 0.3381S$ and for Areas-III $G_c(s) = 14.3220 + 5.5195/S + 4.6921S$.

4. Simulation and Result Analysis

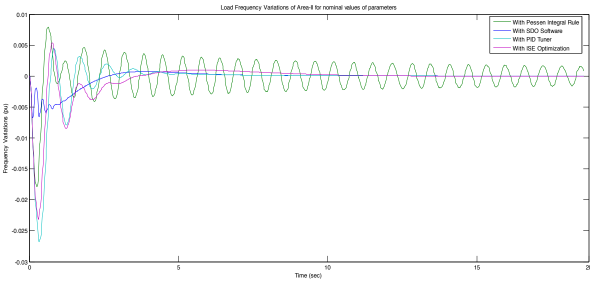
Let Areas-I, Areas-II and Areas-III are non identical, i.e. all areas of interconnected power system incorporating Reheat, Non-reheat and Reheat turbines respectively. The parameters of all three areas are collected from various steam power stations in India and are shown in Appendix-A. The Robustness of the designed controller can be estimated by the following two illustrations.

4.1 Illustration-I:

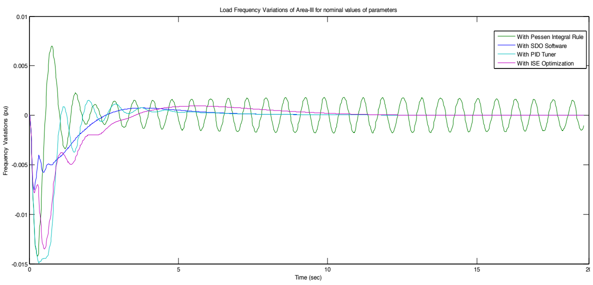
To estimate the performance of the designed decentralized PID controller, different step load perturbations are assumed as dP_{L1} = 0.01pu, dP_{L2} = 0.02pu and dP_{L3} = 0.015pu is applied to Area-I, Area-II and Area-III respectively at t = 0sec. The responses of Frequency variations (pu) and Tie line power variations (pu) of the system are shown in Fig. 5 and Fig.6 for nominal values of system parameters.



(a) Area-I Frequency variations (df_1)

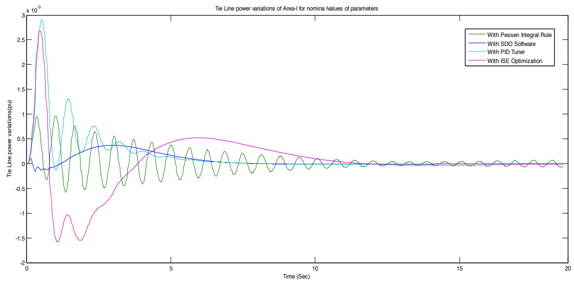


(b) Area-II Frequency variations (df_2)

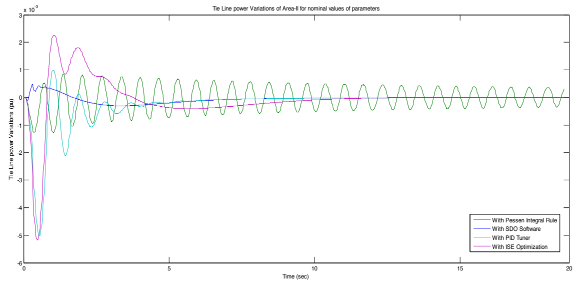


(c) Area-III Frequency variations(df_3)

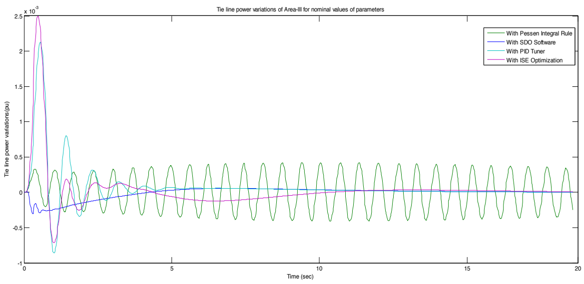
Fig.5 Frequency deviations of Three area interconnected power system



(a) Area-I Tie Line Power variations (dP_{tie1})



(b) Area-II Tie Line Power variations (dP_{tie2})



(c) Area-III Tie Line Power variations(dP_{tie3})

Fig. 6 Tie Line Power deviations of Three area interconnected system

The performance of the designed decentralized PID controller is also checked by applying various step load perturbations (like dP_{Li} = 0.01pu and dP_{Li} = 0.02pu) in all three areas at t = 0sec. The summary of performance of all controllers for various step load perturbations is as shown in Table 3.

Table.3 Summary of Illustration-I

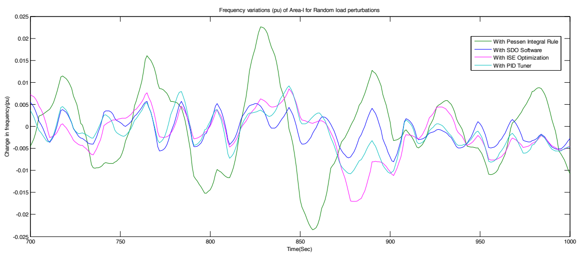
Tuning Methods	Area-I (dP_{L1}=**0.01pu**)			Area-II (dP_{L2}=**0.01pu**)			Area-III (dP_{L3}=**0.01pu**)		
	1st Peak Overshoot (10^{-3}) pu	Settle Time (sec)	Steady State Error (pu)	1st Peak Overshoot (10^{-3}) pu	Settle Time (sec)	Steady State Error (pu)	1st Peak Overshoot (10^{-3}) pu	Settle Time (sec)	Steady State Error (pu)
PIR	-11.61	55	0	-9.52	92	0	-9.56	88	0
PID Tuner	-11.25	12.5	0	-14.71	16.25	0	-10	13.75	0
ISE Optimization	-6.40	15	0	-12.31	15.12	0	-5.2	16.83	0
SDO Software	-6.56	15	0	-3.42	13.05	0	-5	12.10	0

Tuning Methods	Area-I (dP_{L1}=**0.01pu**)			Area-II (dP_{L2}=**0.02pu**)			Area-III (dP_{L3}=**0.015pu**)		
	1st Peak Overshoot (10^{-3}) pu	Settle Time (sec)	Steady State Error (pu)	1st Peak Overshoot (10^{-3}) pu	Settle Time (sec)	Steady State Error (pu)	1st Peak Overshoot (10^{-3}) pu	Settle Time (sec)	Steady State Error (pu)
PIR	-13	>100	0	-17.80	>100	0	-14.20	>100	0
PID Tuner	-15.30	11.55	0	-26.70	9.40	0	-14.90	12.50	0
ISE Optimization	-13.50	13.57	0	-23.10	14.52	0	-7.80	12.55	0
SDO Software	-6.90	11.55	0	-6.70	8.45	0	-7.50	12.30	0

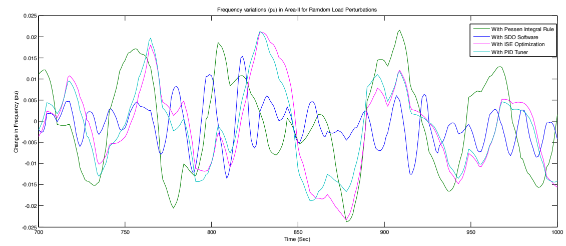
Tuning Methods	Area-I (dP_{L1}=**0.02pu**)			Area-II (dP_{L2}=**0.02pu**)			Area-III (dP_{L3}=**0.02pu**)		
	1st Peak Overshoot (10^{-3}) pu	Settle Time (sec)	Steady State Error (pu)	1st Peak Overshoot (10^{-3}) pu	Settle Time (sec)	Steady State Error (pu)	1st Peak Overshoot (10^{-3}) pu	Settle Time (sec)	Steady State Error (pu)
PIR	-29.10	56	0	-23.95	78	0	-23.75	82	0
PID Tuner	-28.10	17	0	-30.60	16.10	0	-24.71	16.12	0
ISE Optimization	-16.10	15	0	-36.80	15.20	0	-13	17	0
SDO Software	-16.40	12.50	0	-8.50	9.20	0	-12.40	13.93	0

4.2 Illustration-II:

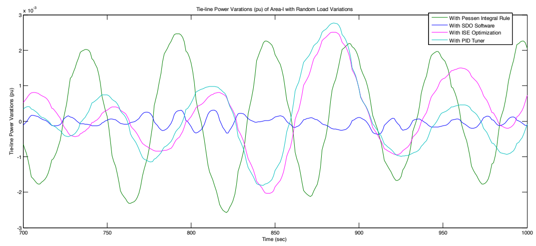
In this section, the performance of the designed decentralized PID controller was also estimated by applying Random load perturbations as dP_{L1} = 0.01pu, dP_{L2} = 0.02pu and dP_{L3} = 0.015pu to Area-I, Area-II and Area-III respectively at t = 0sec. The responses of Frequency variations (pu) and Tie line power variations (pu) of the system are shown in Fig. 7 and Fig.8 for nominal values of system parameters for certain time period.



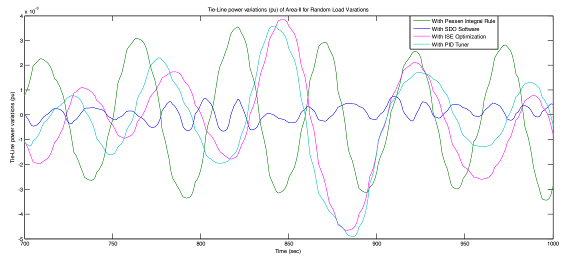
(a) Area-I Frequency variations (df_1)



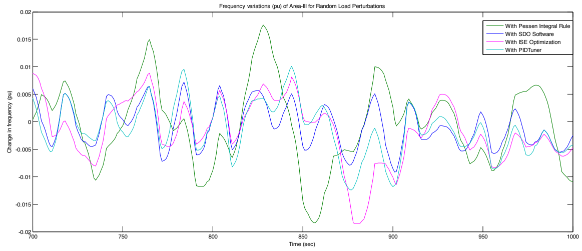
(b) Area-II Frequency variations (df_2)



(a) Area-I Tie Line Power variations (dP_{tie1})

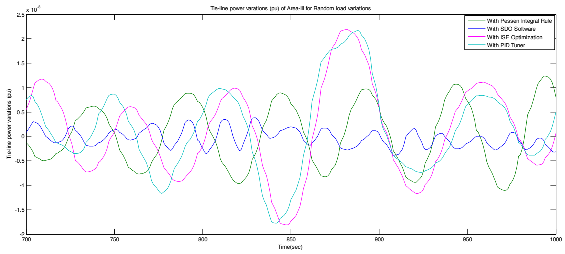


(b) Area-II Tie Line Power variations (dP_{tie2})



(c) Area-III Frequency variations (df_3)

Fig.7 Frequency deviations of Three area interconnected power system



(c) Area-III Tie Line Power variations (dP_{tie3})

Fig. 8 Tie Line Power deviations of Three area interconnected system

From the above illustrations, it can be observed that the controller designed by Simulink Design Optimization software gives better performance and more robust than other controllers for various values of step load and Random load perturbations.

5. Conclusion

The decentralized PID controllers were designed for three area interconnected power system with different turbines in respective areas using various PID tuning techniques. From the results, the Load Frequency Controller designed by Simulink Design Optimization Software gives the effective and superior performance than other controllers for various step load and random load perturbations in all three areas. Also the Simulink Design Optimization Software tuned PID Load Frequency Controller is more robust than other controllers for both various step load and random load perturbations in all three areas.

Appendix A.

The nominal parameters of Reheat and Non-Reheat Turbines are collected from various Thermal power plants in India and are as shown below [9]:

Parameters	Area-i		
	Area-I	Area-II	Area-III
Speed Governor Time constant	0.08	0.08	0.08
Speed Governor Regulation	2.7	2	2.4
Power System gain constant	120	115	120
Power System Time constant	20	15	20

Parameters	Area-i		
	Area-I	Area-II	Area-III
Turbine Time constant	0.3	0.3	0.3
Coefficient of re-heat steam turbine (High Pressure)	0.3	-	0.5
Re-heater time constant (Low Pressure)	10	-	10

Rated capacity = 2000MW; P_{tiemax} = 200 MW; $(\delta_1 - \delta_2) = 30^0$; Frequency f^0 = 60Hz; $D_i = 8.33x10^{-3}$; Syn. Co-efficient T_{ij} = 0.545.

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