DESIGN OF ROBUST LOAD FREQUENCY CONTROLLER FOR MULTI-AREA INTERCONNECTED POWER SYSTEM USING SDO SOFTWARE

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Abstract: *The multi-area interconnected electrical power system's frequency control problem is much more complex with variations in size, load and changing structure. This paper deals with Frequency Control of three area interconnected Power system having Reheat, Non-reheat and Reheat turbines in all three areas respectively. The response of the load frequency control problem in an multi-area interconnected power system is improved by designing PID controller using different tuning techniques and proved that the PID controller which was designed by Simulink Design Optimization Software gives the superior performance than other controllers for step perturbations. Finally the validity and robustness of controller was checked against system parameter variations.*

Key words: *Load Frequency Control, Tie line Power, Interconnected Power System, PID Tuning techniques.*

1. Introduction.

For large scale power systems which consists of inter-connected 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 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 need another controller like Integral (I) or Proportional plus Integral (PI), Proportional plus Integral plus Derivative (PID) controller.

1.1 Over on Load Frequency Control Schemes

Automatic generation control (AGC) can be defined as, the regulation of power output of controllable generators within a prescribed area in response to change in system frequency, tie-line loading, or a relation of these to each other, to maintain the scheduled system frequency and/or the established interchange with other areas within predetermined limits (Elgerd, 2001). Therefore, a control strategy is needed that not only maintains constancy of frequency and desired tie-power flow but also achieves zero steady state error and inadvertent interchange. However, there are few notable contributions of the early stages of AGC, which have set the landmarks in the development of AGC schemes [5].

The first attempt in the area of AGC has been to control the frequency of a power system via the governor of the synchronous machine, but this technique was found to be insufficient and requires a supplementary control for the governor with the help of a signal which is directly proportional to the frequency deviation plus it's integral. This scheme constitutes the classical approach to the AGC of power systems. Cohn has done very early works in this important area of AGC. Concordia et al and Cohn have presented basic important works on *tie-line* power and frequency control and tie line bias control in interconnected systems [1- 4].

The Current Operational Problems working group has discussed the problems and requirements of the regulation of generation on interconnected power systems in short notes namely, Regulation requirement imposed on operators beyond the considerations of long term planners and Regulation performance criteria, Operating problems of system regulation and factors influencing interconnected operations. Among the various types of load frequency controllers, the most commonly used one is conventional Proportional Integral (PI) controller. The PI controller is very simple for construction, implementation and gives better dynamic response, but their performance is unsatisfied when the complexity of the system increases due to load disturbances or load variations. Today's power systems are more complex and require operation in

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uncertain less structured environment. Consequently, secure, economic and stable operation of a power system requires improved and innovative methods of control. Optimal control techniques provide a high adaption to changing conditions and have ability to make decisions quickly by processing imprecise information. Some of these techniques are ZN-Pessen Integral Rule, Integral Square Error (ISE) and Simulink Design Optimization (SDO) Software etc.

1.2 Over on Power System Models

In Feb'84, the UEA began implementation of a test to identify the improvement to electric system automatic generation and tie line control that could be achieved by the application of variable, non-linear tie line frequency bias. The test showed that when tie line frequency bias is better matched to system response, the result would be that, the area control error performance would be improved and generating unit regulation would be reduced. In addition the interconnection reliability was enhanced. This work has been discussed by T. Kennedy et al. K.C. Divya have discussed the simulation model of two area hydro-hydro interconnected system and they showed that the difficulty in extending the traditional approach. They prepared the model by ignoring the frequency deviations between the control areas [1]. Engin Yesil, Aysen Demiroren, Erkin Yesil have presented a three area power with two reheat turbine type thermal units and a hydro unit. So far, many authors were discussed dynamic responses of interconnected power system for step load perturbations only, this paper deals with dynamic responses of interconnected power system for step load perturbations.

2. Mathematical Modeling of Power System

The main difference between Load Frequency Control of multi-area system and that of 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. To illustrate the decentralized PID tuning method, consider a Three-Area power system with load perturbations as shown in Fig.(1). The system frequency deviation Δf_i, the deviation in the tie-line power flow ΔP_{tiei}, load disturbance ΔP_{Li}. The system parameter values are given in Appendix.

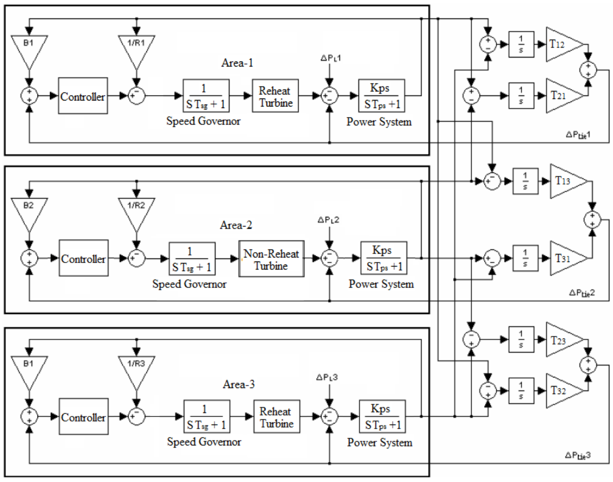


Fig.1: Three Area interconnected power system with step load perturbations

The system state-space model can be represented as [9]

$$\dot{x} = Ax + Bu \quad \text{and} \quad Y = Cx$$

Where A is system matrix, B is input matrix; u is control matrix; Y = output matrix and x is State matrix.

2.1 Mathematical 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 modeled by transfer functions [1].

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 can be of the non-reheat turbine is represented as

$$G_{Nr}(s) = \frac{1}{(1 + sTt)} = \frac{NUMt(s)}{DENt(s)}$$

Because of different stages due to high and low steam pressure in the *Reheat turbines*, it was modeled 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.

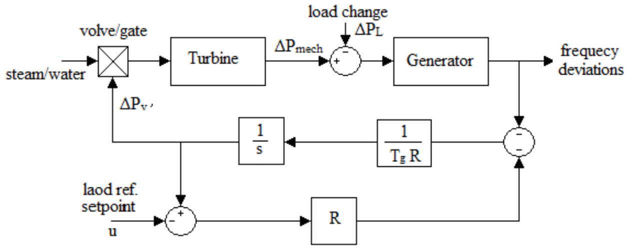


Fig (2): Block diagram of Speed Governorning unit

The block diagram representation of a speed governing system is shown in Fig. (2), 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 is to compensate the frequency deviations due 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 canceled by the power generation rather than resulting in a frequency deviation. The transfer function of fig.2 is

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

A *generator* converts the mechanical power developed by the turbine into electrical power. Because of difficulty of storage of electrical power in large amounts, the balance has to be maintained between the generated power and the load demand to maintain the system stability. 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.3 shows the block diagram of generator with load damping (D) effect.

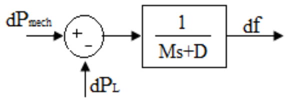


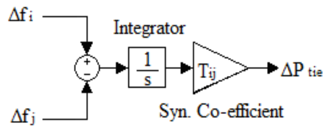
Fig (3): Block diagram of generator with load damping

The Laplace transform of generator with load damping is

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

$$G_{ps}(s) = \frac{1}{(D+Ms)} = \frac{K_{ps}}{(1+sT_{ps})} = \frac{NUM_{sg}(s)}{DEN_{sg}(s)}$$

In an interconnected power system, different areas are connected with each other with the help of tie-lines. When the frequency variations in 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.(4).



Fig(4): Block diagram representation of tie-line link

The laplace transform of tie line in Fig.4 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].

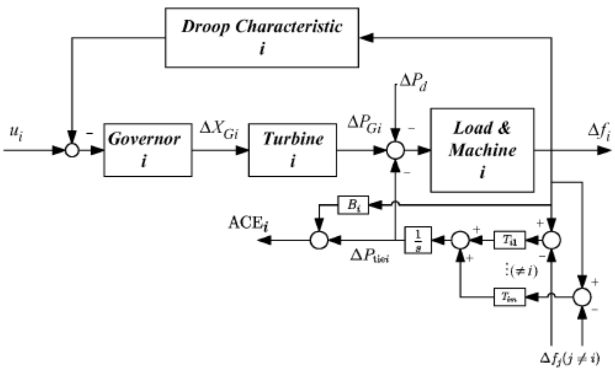


Fig (5): Block diagram of control area i

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.5)

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

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 Mathematical Modeling of Power System Areas

Let area 1, 2, 3 are non identical systems as shown in Fig.1. The transfer function of each area with generator drooping characteristics can be defined as

$$G_p(s) = \frac{Gsgi(s)\ Gti(s)\ Gpsi(s)}{1 + Gsgi(s)\ Gti(s)\ Gpsi(s)/Ri} Bi$$

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

The transfer functions of all three areas of interconnected power system are as follows (see Appendix for Turbine, Speed Governor and Power system parameters)[2]:

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

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

3. Tuning of Load Frequency Controller

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]. 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 = Integral Time constant; K_d = Derivative gain constant; T_d = derivative time constant.

The tuning of 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 area-i , the 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 Ziegler-Nichols (Z-N) Method

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 [7-8].

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}.

Now the controller gains can be evaluated as follows

Z-N Tuning	P I D Constants		
	K_P	K_I	K_D
Pessen Integral Rule	$0.7K_{cr}$	$2.5K_p/P_{cr}$	$3K_P(P_{cr}/20)$

Area-i	Pessen Integral Rule		
	K_P	K_I	K_D
Area-I	8.1795	20.4487	1.2269
Area-II	3.7429	9.3572	0.5614
Area-III	7.8414	19.6035	1.1762

Table-I: Pessen Integral Rule

3.2 Automatic PID Tuner

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 using Automatic PID Tuner are

Area-i	Automatic PID Tuner		
	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

Table-II: Automatic PID Tuner

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. The transfer function for PID Controllers of different areas in interconnected power system with Integral Square Error (ISE) Optimization technique are given as

For Area-I:

$$G_c(s) = 6.4506 + \frac{4.9620}{s} + 4.8627\,s$$

For Area-II:

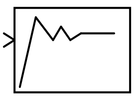
$$G_c(s) = 6.9775 + \frac{4.9839}{s} + 4.9839\,s$$

For Area-III:

$$G_c(s) = 7.4557 + \frac{4.9705}{s} + 4.8711s$$

3.4 Simulation Design Optimization (SDO) Software

The Signal Constraint block is connected in developed MATLAB/Simulink model to optimize the model response for known inputs. The symbol of Signal Constraint block is as shown below:



Signal Constraint

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 you want toget specified design requirments.

The transfer function for PID Controllers of different areas in interconnected power system with Simulink Design Optimization Software are given as

For Area-I:

$$G_c(s) = 2.9626 + \frac{1.8214}{s} + 5.3726\,s$$

For Area-II:

$$G_c(s) = 1.3383 + \frac{3.0743}{s} + 0.3381s$$

For Area-III:

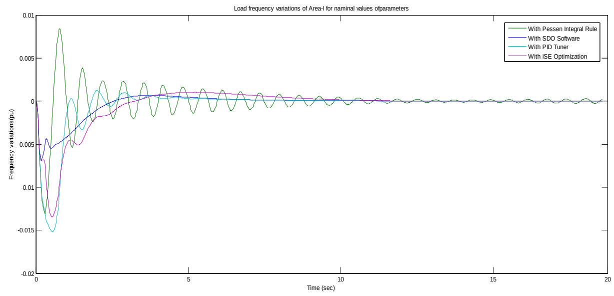
$$G_c(s) = 14.3220 + \frac{5.5195}{s} + 4.6921s$$

4. Simulation and Result Analysis

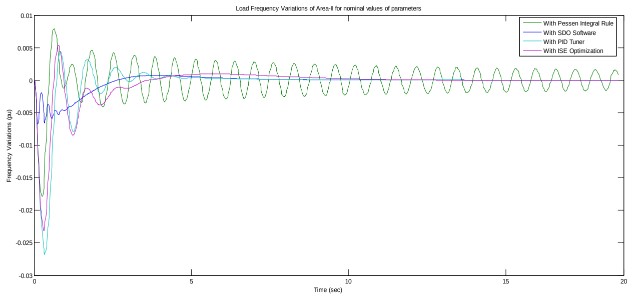
Let Areas 1, 2, and 3 are non identical. The parameters of all three areas are collected from various steam power stations in India (Appendix). To estimate the performance of the decentralized PID controller, a step load of dP_{L1} = 0.01pu, dP_{L2} = 0.02pu and dP_{L3} = 0.015pu is applied respectively at t = 0sec.

4.1 Case-I: Nominal values of system parameters

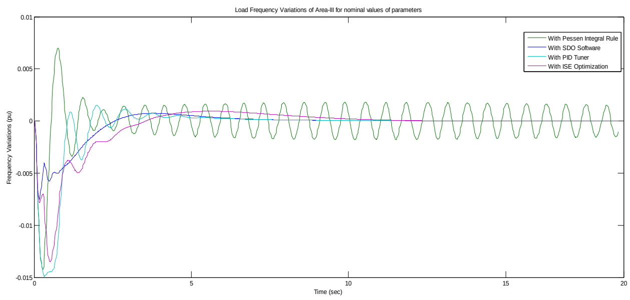
The responses of Frequency variations (pu) and Tie line power variations (pu) of the system are shown in Figs. 6 and 7 for nominal values of system parameters.



(a) Area-I Frequency variations (df_1)

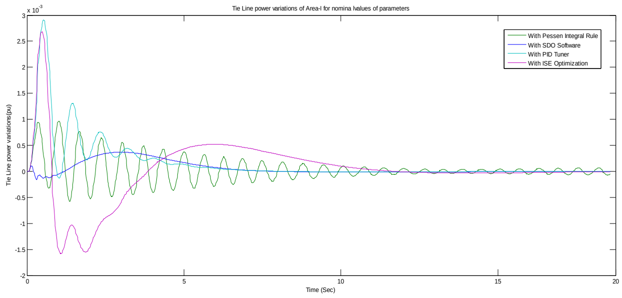


(b) Area-II Frequency variations (df_2)

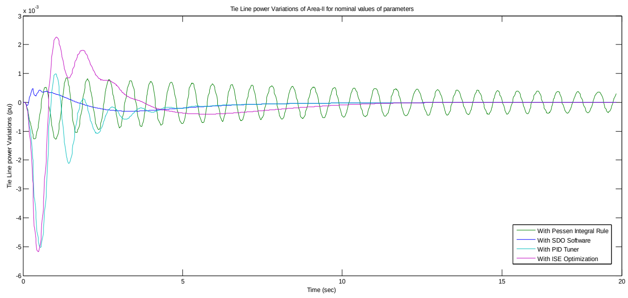


(c) Area-III Frequency variations(df_3)

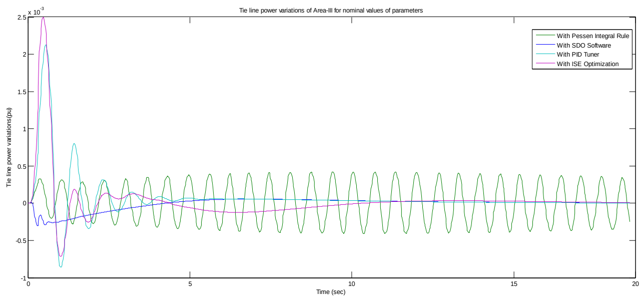
Fig.6: Frequency deviations of interconnected power system.



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



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

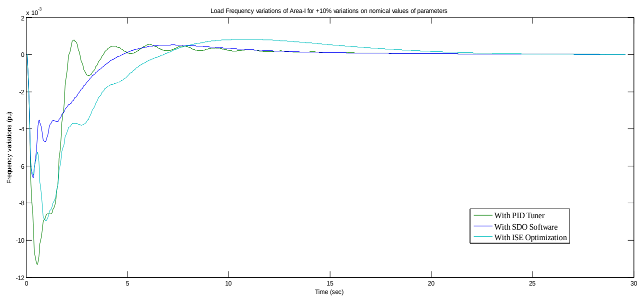


(c) Area-III Tie Line Power variations(dP_{tie3})

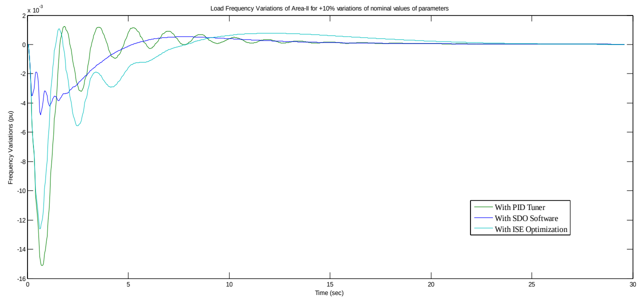
Fig.7: Tie Line Power deviations of interconnected power system

4.2 Case-II: +10% Variations in Nominal values of system parameters

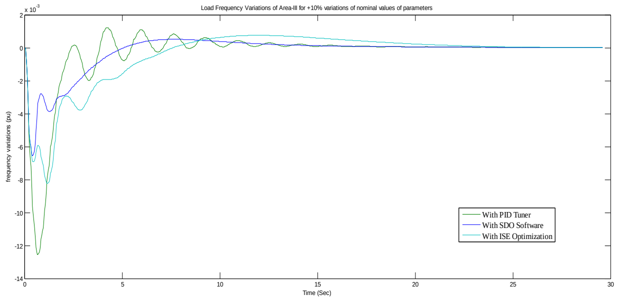
The Fig. 8 and 9 shows the responses of Frequency variations (pu) and Tie line power variations (pu) of the system for +10% variations of nominal values of system parameters with a step load variations of dP_{L1} = 0.01pu, dP_{L2} = 0.02pu and dP_{L3} = 0.015pu is applied to Area-I, Area-II and Area-III respectively at t = 0sec.



(a) Area-I Frequency variations (df_1)

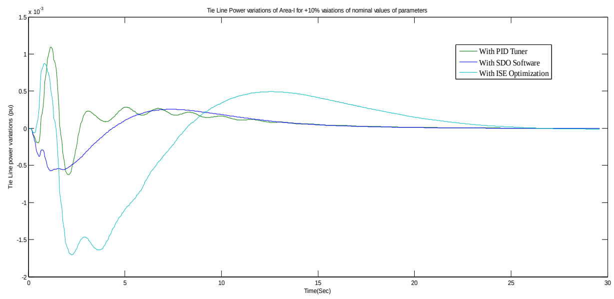


(b) Area-II Frequency variations (df_2)

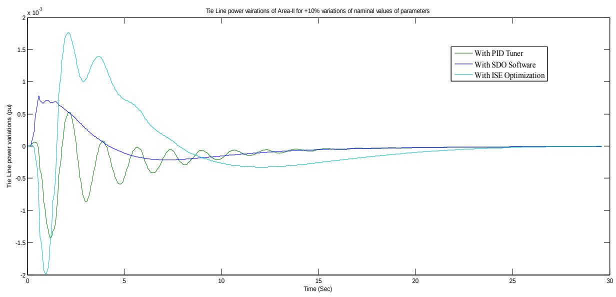


(c) Area-III Frequency variations (df_3)

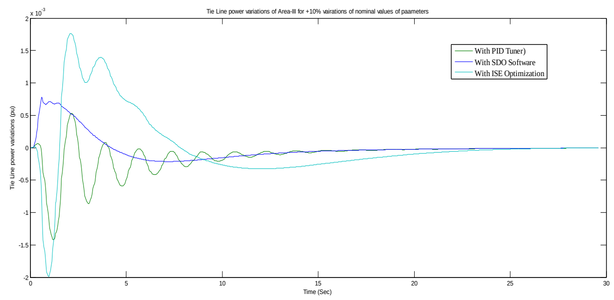
Fig.8: Frequency deviations of interconnected power system



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



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

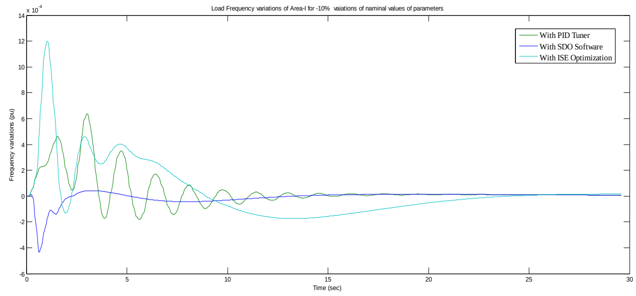


(c) Area-III Tie Line Power variations (dP_{tie3})

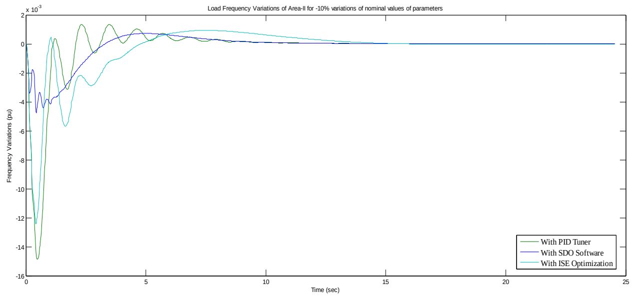
Fig.9:Tie Line Power deviations of interconnected system

4.2 Case-II: -10% Variations in Nominal values of system parameters

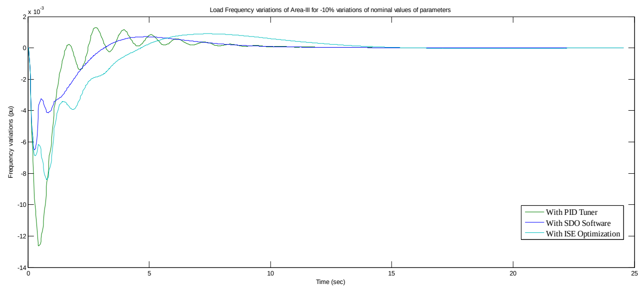
The figures 10 and 11 show responses of Frequency variations (pu) and Tie line power variations (pu) of the system for -10% variations of nominal values of system parameters with a step load perturbations of dP_{L1} = 0.01pu, dP_{L2} = 0.02pu and dP_{L3} = 0.015pu is applied respectively at t = 0sec.



(a) Area-I Frequency variations (df_1)

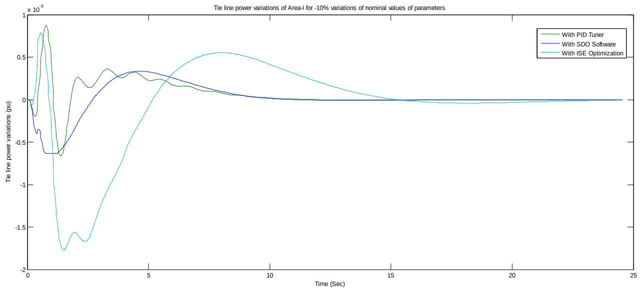


(b) Area-II Frequency variations (df_2)

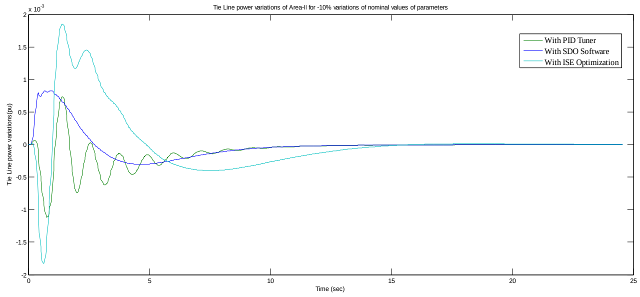


(c) Area-III Frequency variations (df_3)

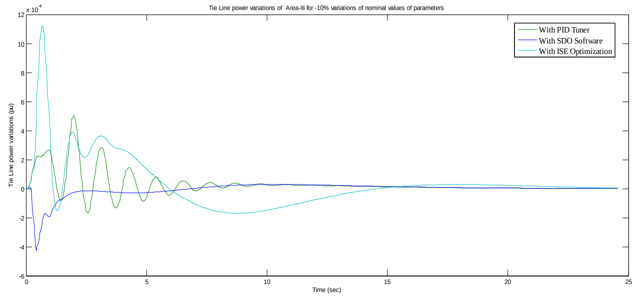
Fig.10: Frequency deviations of interconnected power system.



(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.11: Frequency deviations of interconnected power system

In this paper, the robustness of the designed PID controllers are checked for ±10% variations of system parameters (see appendix-I). For ±10% variations of system parameters, the PID controller which was designed by Z-N Pessen Integral Rule makes the system unstable. The following tables shows the summary of all above simulation results for ±10% variations of system parameters.

Tuning Methods	Area-I (Reheat Turbine)			Area-II (Non-Reheat Turbine)			Area-III (Reheat Turbine)		
	1st Peak Over shoot (10^{-3})	Settle Time	Steady State Error	1st Peak Over shoot (10^{-3})	Settle Time	Steady State Error	1st Peak Over shoot (10^{-3})	Settle Time	Steady State Error
ZN_PIR	-13	>100	0	-17.8	>100	0	-14.2	>100	0
PID Tuner	-15.3	15.58	0	-26.7	9.45	0	-14.92	12.50	0
ISE Optimization	-13.45	13.57	0	-23.1	14.42	0	-7.81	12.52	0
SDO Software	-6.91	11.55	0	-6.49	8.45	0	-7.65	12.26	0

Table-III: Nominal Values of system parameters

Tuning Methods	Area-I (Reheat Turbine)			Area-II (Non-Reheat Turbine)			Area-III (Reheat Turbine)		
	1st Peak Over shoot (10^{-3})	Settle Time	Steady State Error	1st Peak Over shoot (10^{-3})	Settle Time	Steady State Error	1st Peak Over shoot (10^{-3})	Settle Time	Steady State Error
ZN_PIR	Becomes unstable			Becomes unstable			Becomes unstable		
PID Tuner	-11.3	21.48	0	-15.15	20.15	0	-12.52	22.15	0
ISE Optimization	-6.45	27.7	0	-12.6	24.04	0	-6.9	24.52	0
SDO Software	-6.64	18.81	0	-3.39	16.15	0	-6.65	16.06	0

Table-IV: +10% Variations in Nominal Values of system parameters

Tuning Methods	Area-I (Reheat Turbine)			Area-II (Non-Reheat Turbine)			Area-III (Reheat Turbine)		
	1st Peak Over shoot (10^{-3})	Settle Time	Steady State Error	1st Peak Over shoot (10^{-3})	Settle Time	Steady State Error	1st Peak Over shoot (10^{-3})	Settle Time	Steady State Error
ZN_PIR	Becomes unstable			Becomes unstable			Becomes unstable		
PID Tuner	+0.47	22.8	0	-14.9	13.7	0	-12.65	12.4	0
ISE Optimization	+1.25	32.2	0	-12.6	15	0	-6.9	15.2	0
SDO Software	-0.44	22.2	0	-3.39	11.45	0	-6.55	14.6	0

Table-V: - 10% Variations in Nominal Values of system parameters

4.4 Robustness of Controller

From the observation of all above simulation results and tables, the dynamic performance and the robustness of PID controller designed by SDO software is better than all other PID controller for step load perturbations. The Z-N PIR tuned PID controller fails to stable the system for ±10% variations of nominal values of system parameters. Also the PID controller designed by SDO software gives the better result the PID tuner. The simulation results are summarized in table-1, 2 and 3 for ±10% variations of nominal values of system parameters and with a step load perturbations at t = 0sec.

5. Conclusion

The decentralized PID controllers were design for three area interconnected power system with different turbines in respective areas. From the results, the Load Frequency Controller designed by Simulink Design Optimization (SDO) Software gives the effective and superior performance than other controllers for step load perturbations in all three areas. The Simulink Design Optimization Software tuned PID Load Frequency Controller is more robust then other controller for system parameter variations.

Appendix:

The nominal parameters of Reheat and Non-Reheat Turbines are collected from various Thermal power plants in India and are as shown below [2]:

Parameters	Area-i		
	Area-I	Area-II	Area-III
Speed Governor Time constant	0.08±10 %	0.08±10%	0.08±10%
Speed Governor Regulation	2.4±10%	2±10%	2.4±10%
Power System gain constant	120±10%	115±10%	120±10%
Power System Time constant	20±10%	15±10%	20±10%
Turbine Time constant	0.3±10%	0.3±10%	0.3±10%
Coefficient of re-heat steam turbine (H.P)	0.3±10%	-	0.5±10%
Re-heater time constant (Low Pressure)	10±10%	-	10±10%

Rated capacity P_r = 2000MW; P_{tiemax}=200 MW; $(\delta_1 - \delta_2) = 30^0$ Rated frequency f^0 = 60Hz and $D_i = 8.33 \times 10^{-3}$; Syn. Co-efficient T_{ij} = 0.545.

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