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Comparative Study of Load Frequency Controller Designs for Interconnected Power Systems

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دراسة مقارنة لطرق تصميم نظم التحكم في تردد التيار الكهربائي نتيجة تغير الأحمال في نظم القوى الكهربائية المرتبطة

محمد البادي ، أحمد أولاد ثاني ، بدر العميري ، و خالد الليثي

خلاصـة : تـناقش هذه الورقة ثلاث طرق لتصميم نظم التحكم في تردد التيار الكهربائي والطاقة المنقولة بين الشبكات في نظم القـوى الكهربائية المرتبطة. يسمى التصميم الأول بالتحكم التفاضلي الكلاسيكي. أما التصميم الثاني فهو يعتمد على طريقة تحديد أقطـاب مصـفوفة الـنظم. أما التصميم الثالث فيدعى نظام التحكم الكهربائي الأفضل (Optimal Control). تهدف جميع هذه التصـميمات الى تحسين استجابة الشبكات المرتبطة (التردد والطاقة المنقولة) تحت تأثير تغير مفاجىء في الحمل الكهربائي أو انفصال احدى وحدات التوليد عن الشبكة. وقد أظهرت النتائج المستخرجة من برنامج المحاكاة (MATLAB) فعالية التصميمات الـثلاثة. كما أظهرت النتائج أيضا ان استخدام تصميم يجمع بين نظام التحكم الكهربائي الأفضل (Optimal Control) و نظام التحكم التفاضلي الكلاسيكي يعطي أفضل النتائج.

ABSTRACT: This paper presents a comparative study of three different load frequency (LF) controller designs for interconnected power systems. They are the conventional integral controller, a controller based on the pole-placement technique, and a controller based on optimal control law. Each controller has been designed to improve the dynamic response of system frequency and tie line power flow under a sudden load change. The results obtained using a MATALB computer program show the effectiveness of the LF controller designs. The results also show that the combined optimal controller with conventional integral controller can provide good damping to the system and reduce the overshoot.

KEYWORDS: Load Frequency Control, Integral Control, Pole Placement, Optimal Control, Decentralized Control.

1. Introduction

Large-scale power systems are normally composed of control areas or regions representing coherent groups of generators. The various areas are interconnected through tie lines. The tie lines are utilized for energy exchange between areas and provide inter-area support in case of abnormal condition (Fosha and Elgerd, 1999; Wood, 1996). Area load-changes and abnormal conditions, such as outages of generation, leads to mismatch in scheduled power interchanges between areas. These mismatches have to be corrected via supplementary control.

In recent years, usually large tie-line power fluctuations have been observed as a result of increased system capacity and very close interconnection among power systems. This observation suggests a strong need for establishing a more advanced Load Frequency Control (LFC) scheme.

LFC of interconnected systems is defined as the regulation of power output of generators within a prescribed area, in response to change in system frequency, tie-line loading so as to maintain scheduled system frequency and/or established interchange with other areas within predetermined limits (Fosha and Elgerd, 1999; Wood, 1996). In general, LFC is a very important item in power system operation and control for supplying sufficient and reliable electric power with good quality. The basic load frequency control (LFC) loop is shown in Figure 1. It is known that changes in real power affect mainly the system frequency and thus the rotor angle. The input mechanical power to generators is used to control the frequency of the output electrical power. The change in tie line real power (ΔP_{tie}) and the change in frequency (Δf) are sensed and transformed into a real power command signal ΔP_v which is sent to the prime mover to call for the increment in the input torque or input mechanical power to the generator. Therefore, the prime mover makes change in the generator output by an amount of ΔP_g, which will changes the values of Δf and ΔP_{tie} within a specified tolerance. A simple control strategy for any LF controller design is to keep the frequency approximately at the nominal value i.e. 50 Hz, to maintain the tie-line flow at about the schedule and each area should absorb its own load changes to minimize the cost.

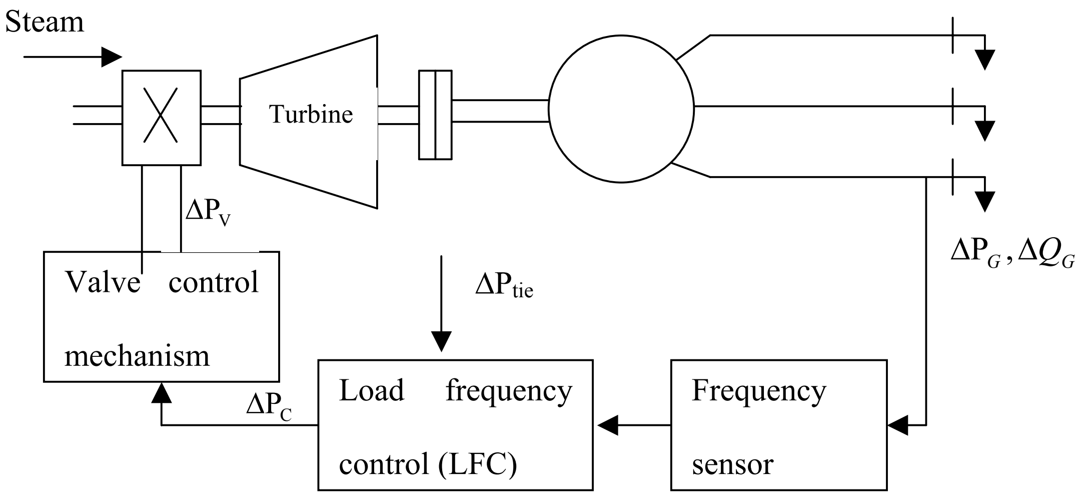

Figure 1. Schematic diagram of LFC and AVR of a generator.

Many investigations in the area of LFC problem of interconnected power systems have been reported and a number of control strategies have been employed in the design of LF controller in order to achieve better performance (Talaq and Albassi, 1999; Yang *et al.,* 1998; Hiyana, 1982). A comparative of three different controller designs for LFC is presented in this paper. The effectiveness of each controller on the system dynamic performance is investigated using MATALB computer software.

2. System Modelling

The single line diagram the two interconnected systems (two-area) is shown in Figure 2. The block diagram representing the interconnection of two areas is shown in Figure 3. Each area is assumed to have only one equivalent generator. The generator is equipped with governor- turbine system as shown in Figure 3.

The state variable (state-space) (Fosha and Elgerd, 1999; Yang *et al.,* 1998; Fellach, 1987) will be used to design the LF controller. The standard form of state-space equations of a linear time invariant is given by the equations

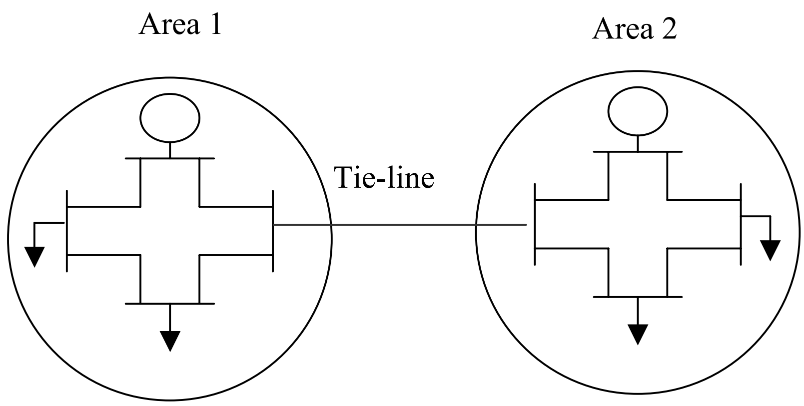

Figure 2. Single-line diagram of two-area.

$$\dot{\Delta x} = A\Delta x + B\Delta u + \Gamma \Delta P_L \tag{1}$$

$$\Delta y = C\Delta x + D\Delta u \tag{2}$$

Where:

$$A = \begin{bmatrix} \frac{-D_1}{2H_1} & \frac{1}{2H_1} & 0 & 0 & \frac{-1}{2H_1} & 0 & 0 & 0 & 0 \\ 0 & \frac{-1}{\tau_{T1}} & \frac{1}{\tau_{T1}} & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{-1}{R_1\tau_{g1}} & 0 & \frac{-1}{\tau_{g1}} & \frac{1}{\tau_{g1}} & 0 & 0 & 0 & 0 & 0 \\ -K_1B_1 & 0 & 0 & 0 & -K_1 & 0 & 0 & 0 & 0 \\ T_{12} & 0 & 0 & 0 & 0 & -T_{12} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{2H_2} & \frac{-D_2}{2H_2} & \frac{1}{2H_2} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \frac{-1}{\tau_{T2}} & \frac{1}{\tau_{T2}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{-1}{R_2\tau_{g2}} & 0 & \frac{-1}{\tau_{g2}} & \frac{1}{\tau_{g2}} \\ 0 & 0 & 0 & 0 & K_2 & -K_2B_2 & 0 & 0 & 0 \end{bmatrix}$$

$$\Delta x = \begin{bmatrix} \Delta f_1 & \Delta P_{c1} & \Delta P_{m1} & \Delta P_{v1} & \Delta P_{12} & \Delta f_2 & \Delta P_{c2} & \Delta P_{m2} & \Delta P_{v2} \end{bmatrix}^T$$

$$B = \begin{bmatrix} 0 & 0 & \frac{1}{\tau_{G1}} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{\tau_{G2}} & 0 \end{bmatrix}^T$$

$u = [u_1 \; u_2]^T$ is the input vector

The disturbance matrix Γ equals to

$$\Gamma = \begin{bmatrix} \frac{1}{2H_1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{2H_2} & 0 & 0 & 0 \end{bmatrix}^T$$

The disturbance to the system is

$$\Delta P_L = \begin{bmatrix} \Delta P_{L1} & \Delta P_{L2} \end{bmatrix}$$

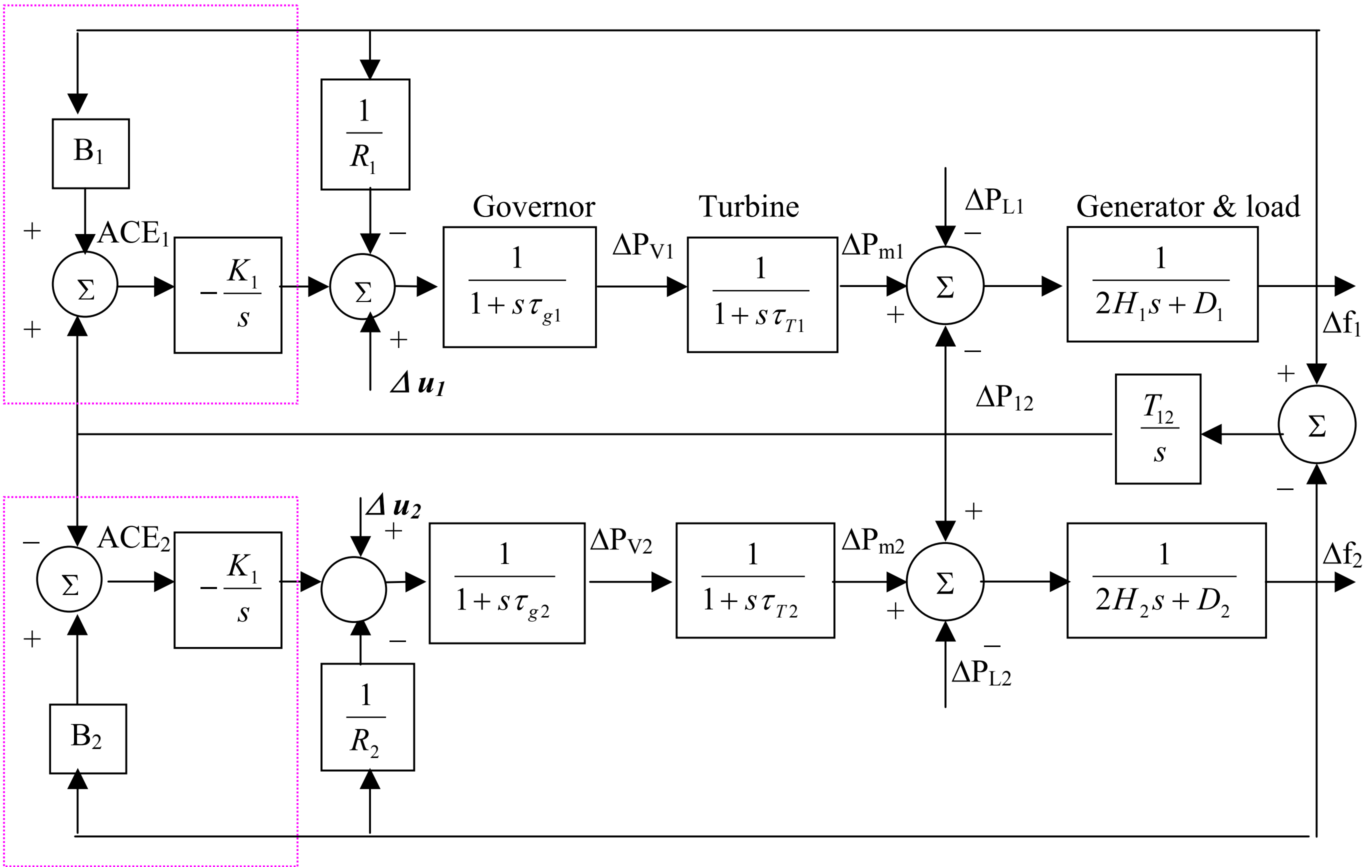

Figure 3. Block diagram of load frequency control (LFC) of two-area.

3. Design of LF Controller

3.1 Conventional Integral Controller Design

Conventional LF controller is based upon tie-line bias control, where each area tends to reduce the Area Control Error (ACE) to zero. The block diagram of two-area power system including area control error is shown in Figure 3. The control error for each area consists of a linear combination of frequency and tie-line power deviation (Saadat, 1999).

$$ACE_i = \sum_{j=1}^{n} \left(\Delta P_{ij} + \gamma_i \Delta \omega \right) \tag{3}$$

An overall satisfactory performance is achieved when γ_i is selected to be equal to the frequency bias factor of that area. So $\gamma_i = B_i = \frac{1}{R_i} + D_i$.

Thus, the ACEs for a two-area are

$$\begin{aligned} ACE_1 &= \Delta P_{12} + B_1 \Delta\omega_1 \\ ACE_2 &= \Delta P_{21} + B_2 \Delta\omega_2 \end{aligned} \tag{4}$$

To get the simulation results, use the prameters given in Table 1.

Table 1: The prameters of two area systems.

Area	1	2
Speed regulation –R	R_1=0.05	R_2=0.0625
Frequency sensitive load coefficient –D	D_1=0.6	D_2=0.9
Inertia constant –H	H_1=5	H_2=4
Governor time constant - τ_G	τ_{G1} =0.2 s	τ_{G2} =0.3 s
Turbine time constant - τ_T	τ_{T1} =0.5 s	τ_{T2} =0.6 s
Synchronizing coefficient –T_{12}	T_{12}=2 pu	
Load disturbance - ΔP_L	ΔP_{L1} =0.1875 pu	ΔP_{L2} =0

The system response having the integral controller is shown in Figures 5-7. The integral controller satisfies the desired objectives of the LFC. The only problem of this type of controller is that the system response is less damped and the overshot is large. To solve this problem, another control signals (Δu_1,Δu_2) are added to the system in presence of integral controller. These signals are derived from the controller designed based on pole-placement technique or based on the optimal control theory. Both controllers uses the same control law

$$u = -K\Delta X \tag{5}$$

where $K =[k_1\ k_2\ \ldots\ldots\ k_n]$ is the controller gain vector.

3.2 Design Based on Pole-Placement technique

Pole placement technique (Phillips and Harbor, 1998) depends on shifting the poles of the open-loop system (system without controller) to desired locations on the left-half of the complex plane.The characteristic equation of the closed-loop system (system with controller) is given by

$$/SI\text{-}A+BK/=0 \tag{6}$$

Suppose that the design specifications require that the poles of the equation (6) at $-\lambda_1$, $-\lambda_2$, ….., $-\lambda_n$. The desired characteristic equation for the system is

$$S^n + \alpha_{n-1}S^{n-1} + \ldots\ldots + \alpha_1 S + \alpha_0 = (S+\lambda_1)(S+\lambda_2)\ldots\ldots(S+\lambda_n)=0 \tag{7}$$

The pole-placement design procedure results in a gain vector K such that equation (6) is equal to equation (7), that is

$$/SI\text{-}A+BK/= S^n+\alpha_{n-1}S^{n-1}+\ldots\ldots+\alpha_1 S+\alpha_0 \tag{8}$$

In equation (8) there are n unknowns (k_1 k_2 …..... k_n). Equating coefficients in equation (8) yields n equations in the n unknowns. A program using MATLAB is developed to design the LF controller based on pole-placement technique. *Ackerman* formula (Phillips and Harbor *et al.,* 1998) is used in the program to calculate the gain vector K to satisfy equation (8).

Table 2 shows the poles of the system having integral controller and the desired ones, which will be achieved by the pole-placement technique. Table 3 shows the damping ratio of the complex poles. From Table 3, it can be observed that the damping ratio of the closed-loop system (with the pole-placement controller) is increased. The effect of the damping ratio improvement can be seen from the system dynamic response shown in Figures 5-7. It can also be seen from Figures 5-7 that the overshoot of the frequency deviations and tie-line power flow deviation is decreased.

3.3 Optimal Controller Design

Many approaches have been proposed for LF controller design. The most promising approach is the application of linear optimal control (Fosha and Elgerd, 1999; Yang *et al.,* 1998; Fellach, 1987). The linear optimal control has excellent characteristics in that it is able to control a system with small transients and relatively short settling time. The optimal controller is design to minimize the quadratic performance index of the following form

$$J = \int_0^\infty (\Delta x^T Q \Delta x + \Delta u^T R \Delta u)\, dt \tag{9}$$

Subject to the dynamic system equation in (9), Q is a positive semi-definite matrix and R is a positive definite matrix. The optimal gain vector is given by

$$K = R^{-1} B^T P \tag{10}$$

Where P is determined by solving the following Riccati equation (Nobele and Daniel *et al.,* 1988).

$$PA + A^T P - PBR^{-1} B^T P + Q = 0 \tag{11}$$

Table 2: Poles of the system having integral controller and the desired ones.

The poles	The system with integral controller only	The system with integral controller and Pole-Placement Controller
λ_1	-5.8468	-5.8178
λ_2	-4.2717	-4.1669
$\lambda_{3,4}$	$-0.3768 \pm j1.7234$	$-1.2480 \pm j2.8824$
$\lambda_{5,6}$	$-0.2231 \pm j1.5992$	$-0.8596 \pm j2.1385$
$\lambda_{7,8}$	$-0.2537 \pm j0.0484$	-2.9886 , -0.2155
λ_9	-0.3468	-1.7282

Table 3: Damping ratio of the complex poles.

The system	Poles	Damping ratio (ζ)
With integral controller only	$-0.3768 \pm j1.7234$	0.2136
	$-0.2231 \pm j1.5992$	0.1382
	$-0.2537 \pm j0.0484$	0.9823
With integral controller and the pole-placement	$-1.2480 \pm j2.8824$	0.3937
	$-0.8596 \pm j2.1385$	0.3730

In an interconnected power system, each area takes charge of the LFC functions that is, it is operating its own LFC without any commitment from other systems except the case of determining the amount of power exchange. Table 4 listed the gains of the centralized optimal LF controller.
It is impractical to adopt a centralized LFC for interconnected systems. Therefore, it is useful to apply the decentralized LFC (Fosha and Elgerd, 1999; Yang *et al.,* 1998) in which each system in the interconnected system makes use of locally available information to compute the control signal Δu.

Table 4: Gains of centralized optimal LF controller.

State variable X	Gain vector K of Area 1 (Δu_1= Kx)	Gain vector K of Area 2 (Δu_2= Kx)
Δf_1	86.8	-32.16
ΔP_{m1}	2.53	-0.79
ΔP_{v1}	0.72	-0.196
ΔP_{c1}	-20	7.73
ΔP_{12}	1.68	-0.69
Δf_2	-41.35	71.1
ΔP_{m2}	-1.27	3.06
ΔP_{v2}	-0.29	0.99
ΔP_{c2}	12.12	-17.8

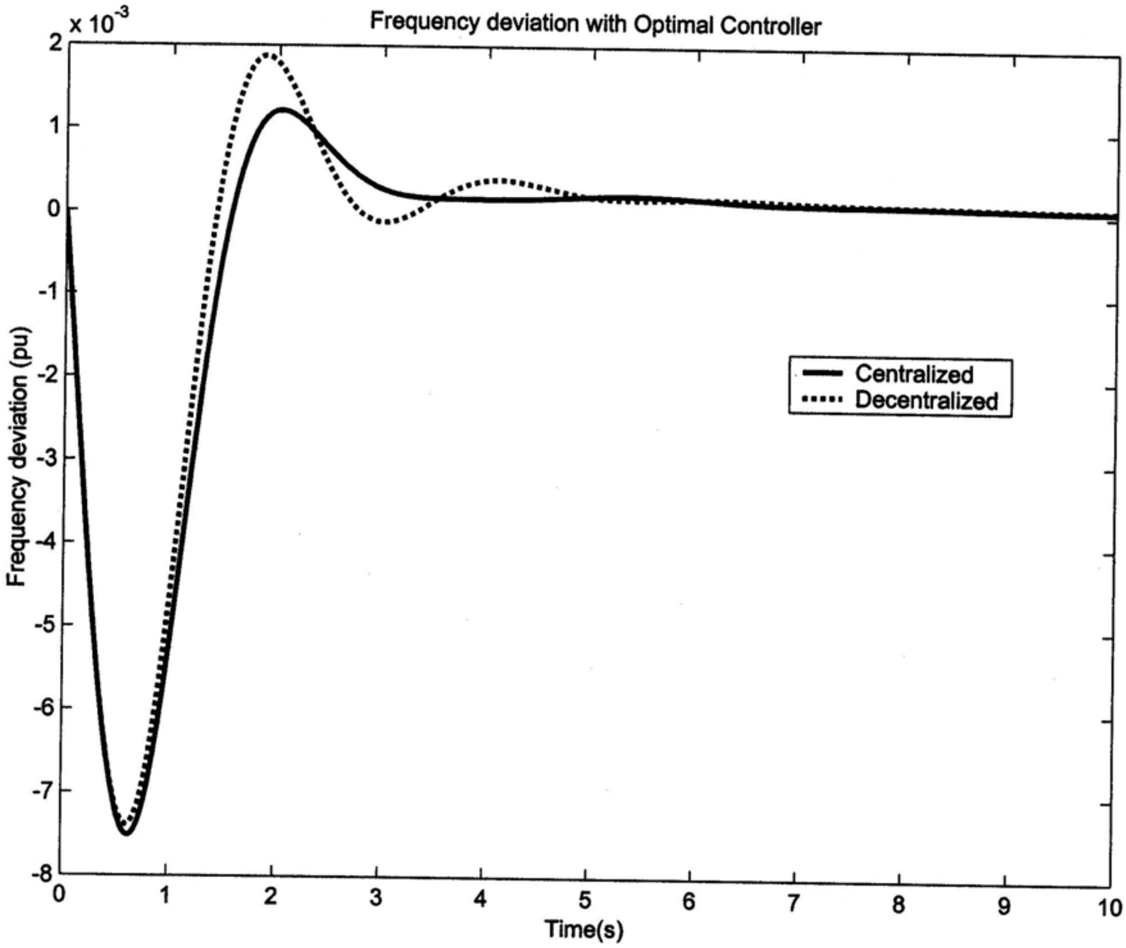

Figure 4. System dynamic response with centralized / decentralized optimal controller.

Table 5: Gains of decentralized optimal LF controller.

State variable X	Gain vector K of Area 1 (Δu_1= Kx)	Gain vector K of Area 2 (Δu_2= Kx)
Δf_1	86.8	0
ΔP_{m1}	2.53	0
ΔP_{v1}	0.72	0
ΔP_{c1}	-20	0
ΔP_{12}	1.68	-0.69
Δf_2	0	71.1
ΔP_{m2}	0	3.06
ΔP_{v2}	0	0.99
ΔP_{c2}	0	-17.8

It has been found that the decentralized optimal controller gives very close results to the Centralized optimal controller. This can be shown in Figure 4.

The effect of the optimal LF controller on the system performance can be seen from Figures 5-7. The overshoot of the frequency and tie line power flow deviations is decreased and the system response is well damped. Computer simulations for different sudden load change in area 1 and area 2 are reported in (Al-Badi *et al.,* 2000).

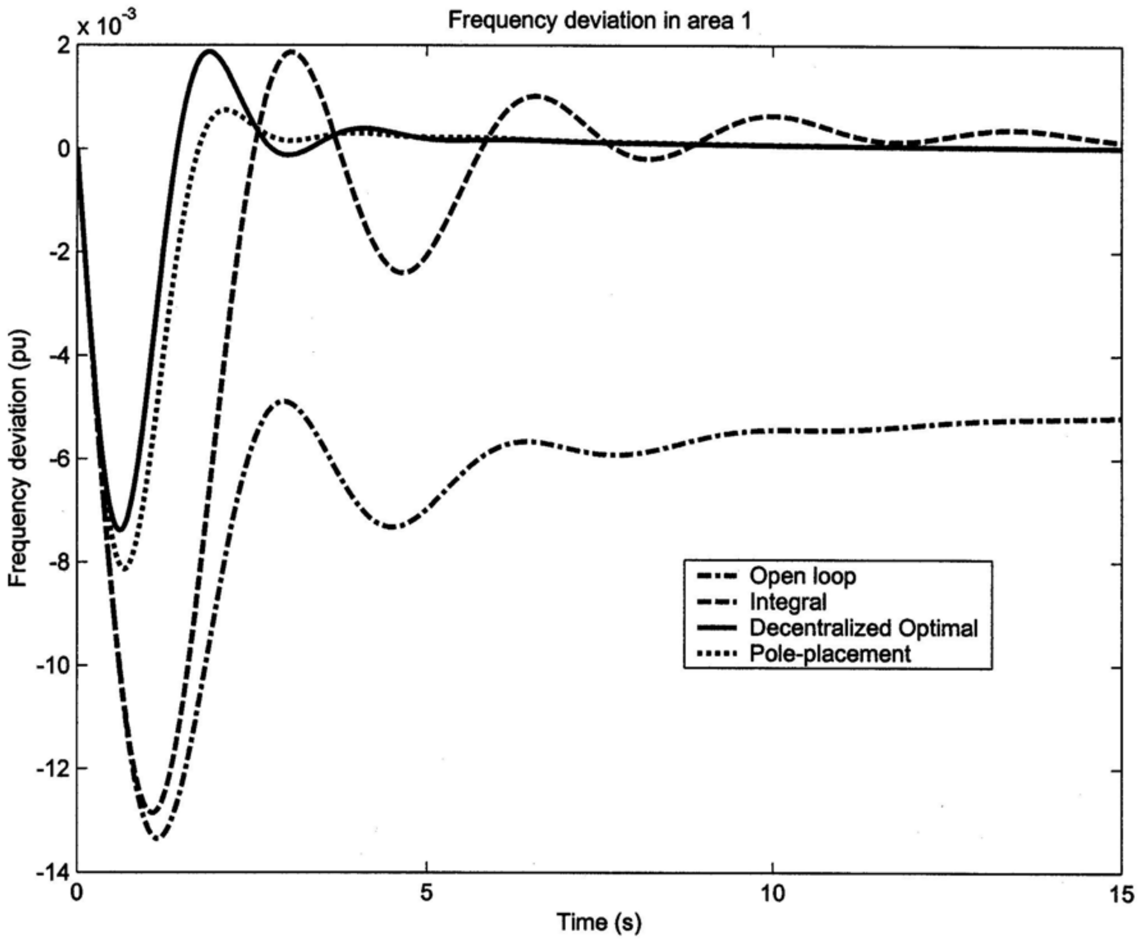

Figure 5. Area 1 dynamic response under a sudden load change in area 1.

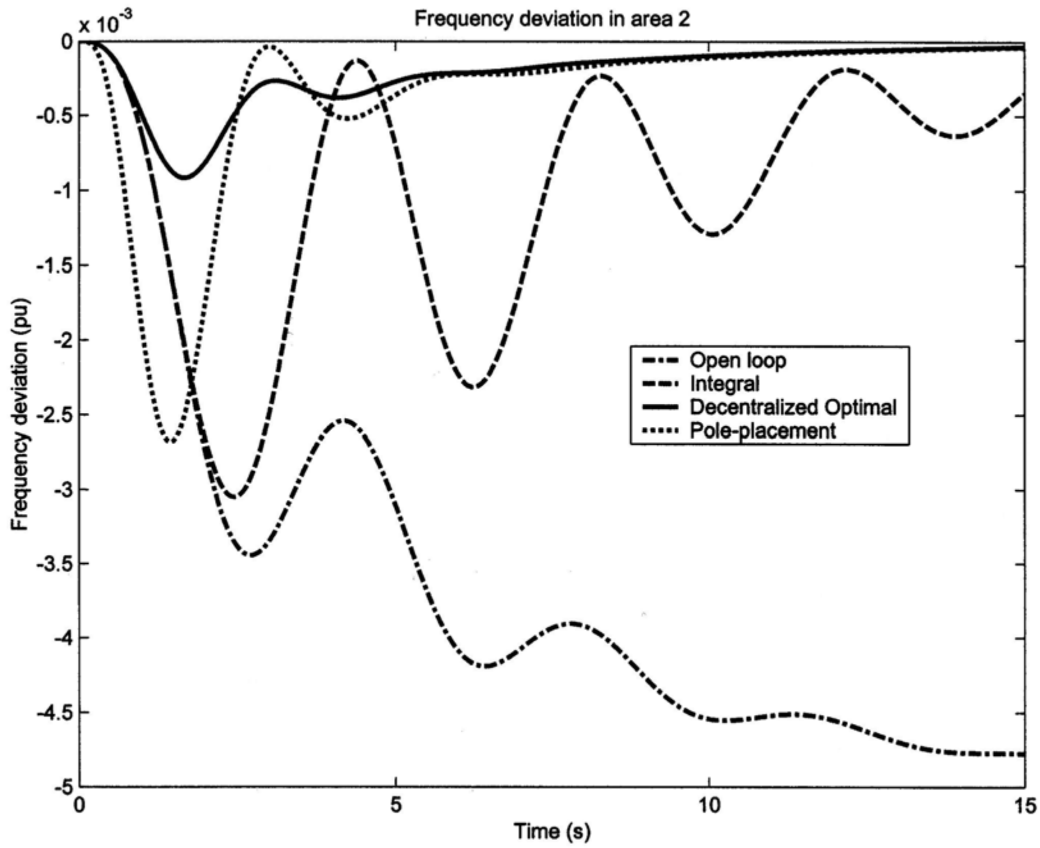

Figure 6. Area 2 dynamic response under a sudden load change in area 1.

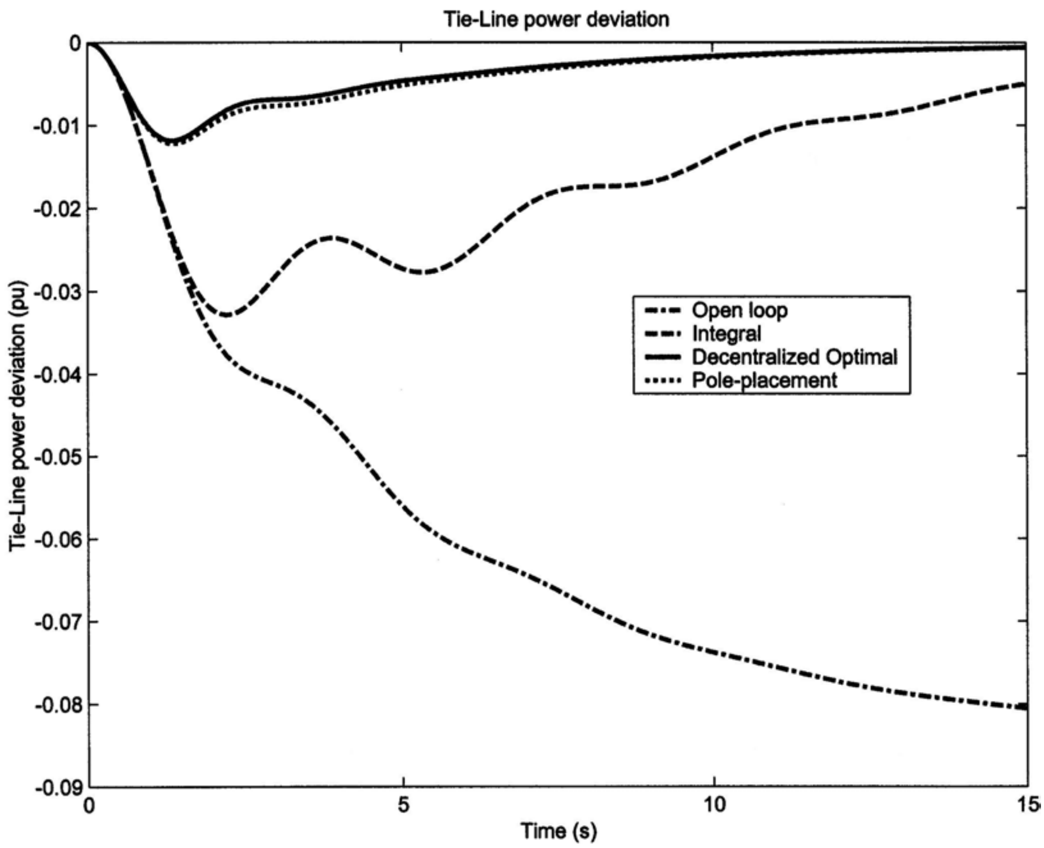

Figure 7. Tie-line dynamic response after a sudden load change in area 1.

4. Conclusions

A load frequency controller has been designed to improve the dynamic performance of interconnected power systems. The conventional integral controller, the controller based-pole placement technique and the controller based-optimal control law were considered and a comparative study between these controllers has been investigated.

The results of computer simulation show that the integral controller restores the original value of the frequency and the tie-line power deviations. Adding a signal derived from the optimal controller or derived from the pole-placement controller enhance the system damping and reduce the overshoot. The simulation results also show that the combined integral controller with optimal controller is more effective means for improving the dynamic performance of the system than the other controllers. The of optimal LF controller type is relatively simple and suitable for practical implementation for on-line implementation.

5. Acknowledgments

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