การออกแบบระบบควบคุมการผลิตอัตโนมัติ โดยใช้วิธีอสมการ

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บทคัดย่อ

บทความฉบับนี้นำเสนอหลักการออกแบบแบบใหม่สำหรับระบบ AGC (Automatic Generation Control) ที่อยู่ในระบบไฟฟ้ากำลังสองพื้นที่ นอกจากนี้ยังนำเสนอวิธีการแก้ปัญหาการออกแบบระบบ AGC ด้วยวิธีอสมการ หลักการออกแบบแบบใหม่นี้นำเงื่อนไขทางการตลาดมาเป็นเงื่อนไขในการพิจารณาออกแบบเพื่อเพิ่มความเชื่อมั่นของระบบทั้งในเชิงเทคนิคและเชิงเศรษฐศาสตร์ โดยการกำหนดรูปแบบของปัญหานั้นอาศัยเซตของอสมการที่เป็นไปตามธรรมชาติของปัญหาซึ่งเป็นปัญหาการออกแบบที่มีหลายเงื่อนไข จากผลลัพธ์ของการออกแบบพบว่าวิธีที่นำเสนอสามารถนำไปใช้ในการออกแบบได้อย่างมีประสิทธิภาพ

คำสืบค้น

ระบบควบคุมการผลิตอัตโนมัติ, แบบแผนการซื้อขายและบริการทางไฟฟ้า, วิธีอสมการ, การออกแบบระบบควบคุม

DESIGN OF AUTOMATIC GENERATION CONTROL USING THE METHOD OF INEQUALITIES

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ABSTRACT

This paper describes a new design strategy for a multiarea Automatic Generation Control (AGC) system and a procedure for solving it using the method of inequalities. In this strategy, electricity market constraints are taken into consideration in order to increase technical and economical reliability of the system. The design problem is formulated as a set of inequalities in accordance with the multiobjective nature of the problem. As a result, the design can be carried out in an effective way.

KEYWORDS

Automatic generation control, Ancillary service, Method of inequalities, Control systems design

1. Introduction

Nowadays, electricity market criteria have significant impact in power system operation. The violation of these criteria should be firstly prevented by a proper design of the AGC controller system taking into account the required criteria as constraints. With this design concept, we can increase technical and economical reliability compliance to the power system.

In the past, methods for designing an AGC controller are generally based on optimal control [1-3], fuzzy control [4], and state feedback control concepts. However, the mathematical formulation employed by these methods does not easily enable the designers to fulfill all the design requirements. When the design process has been finished, they need to perform simulations on the obtained system so as to check whether the results satisfy all the design criteria. If the system does not satisfy all the criteria, they have to conduct a trial and error process in redesigning the system again. As a result, the design process can be time-consuming.

The method of inequalities [5] gives rise to a formulation in the form of a set of inequalities that represent all the design requirements. After the design process, provided the formulation is accurate and realistic, the designer can see whether the obtained design satisfies all the requirements without having to perform a number of unnecessary simulations for verification. For this reason, we employ the method of inequalities in designing the AGC system.

2. Mathematical Model of AGC System

In this paper, we consider an interconnected power system with two identical control areas. Each area consists of thermal and hydro power generating units. The block diagrams of the system are shown in Figures 1-4 [6-8]. The values of the system parameters are given in Table 1.

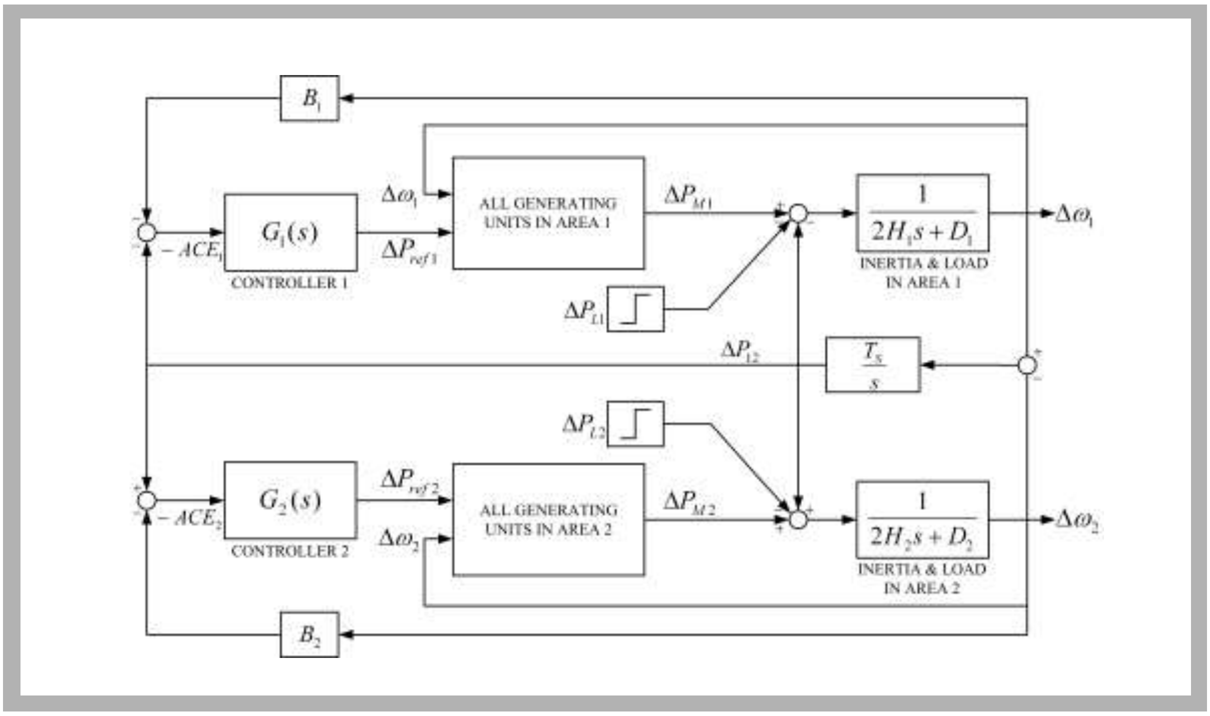

Figure 1 Two area interconnected AGC model.

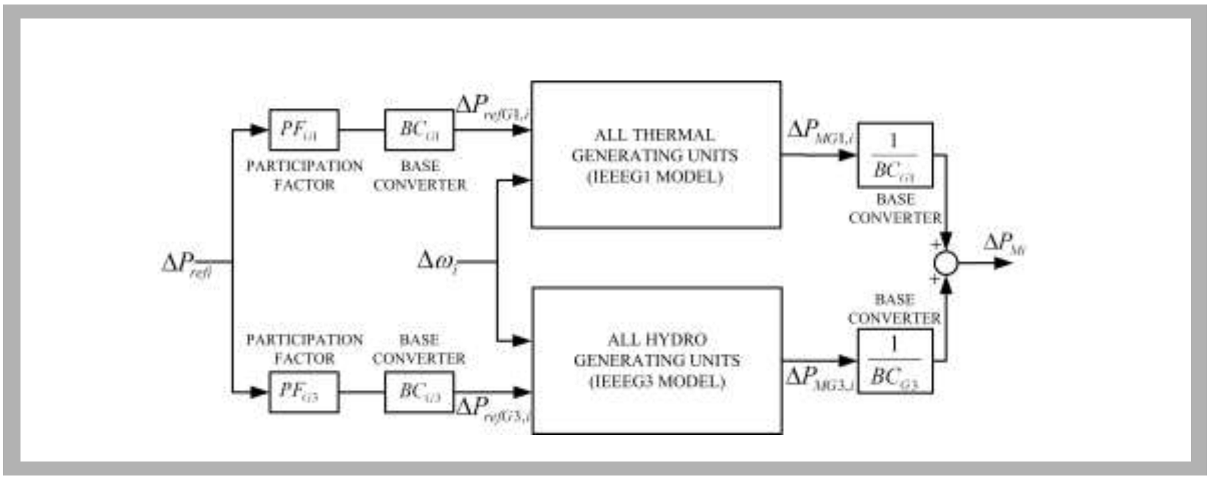

Figure 2 Model of all generating units of area i.

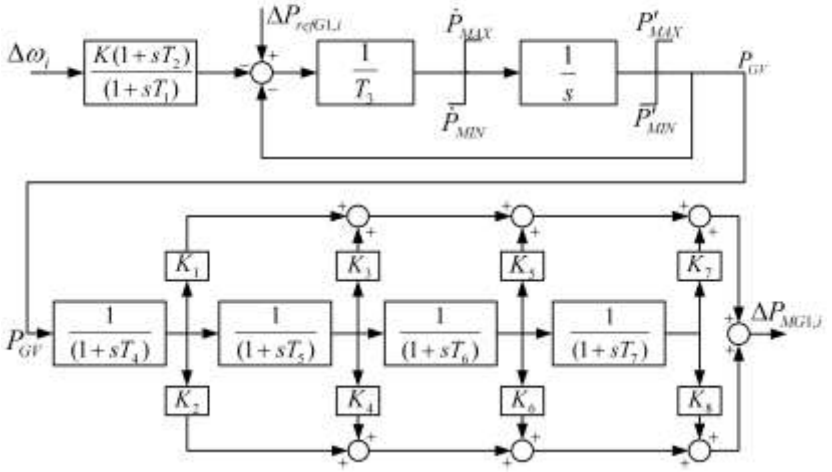

Figure 3 Thermal generating unit model (IEEEG1 model) of area i.

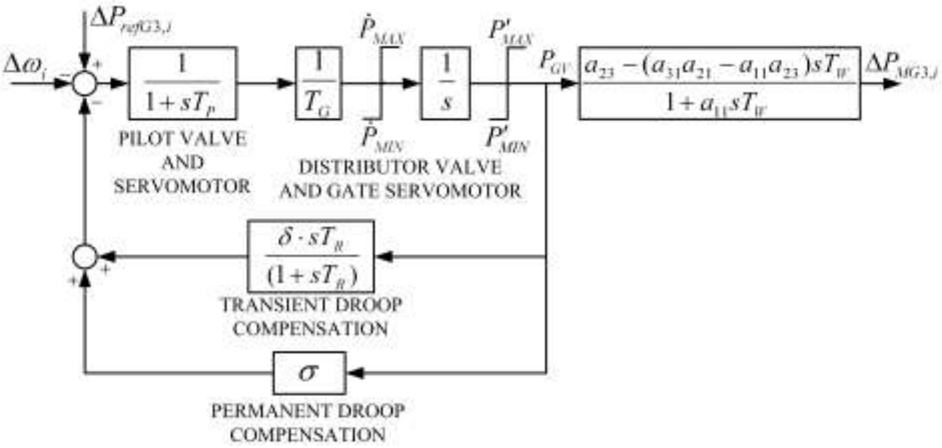

Figure 4 Hydro generating unit model (IEEEG3 model) of area i.

Table 1 Model Parameters

Parameters of all generating unit	PF_{G1} = 0.75		PF_{G3} = 0.25	
	BC_{G1} = 500/400		BC_{G3} = 500/70	
Two area AGC parameters	$H_1 = H_2$ = 4.1526		$D_1 = D_2$ = 0.9760	
	$B_1 = B_2$ = 27.3		T_s = 2	
IEEEG1 parameters	K = 20	K_1 = 0.3	K_2 = 0	K_3 = 0.4
	K_4 = 0	K_5 = 0.3	K_6 = 0	K_7 = 0
	K_8 = 0	T_1 = 0.25	T_2 = 0	T_3 = 0.1
	T_4 = 0.3	T_5 = 10	T_6 = 0.4	T_7 = 0
	$\dot{P}_{MIN}$ = -0.1	P_{MIN} = 0	$\dot{P}_{MAX}$ = 0.1	P_{MAX} = 1
IEEEG3 parameters	T_G = 0.2	T_P = 0.04	T_R = 5	T_W = 1
	a_{11} = 0.5	a_{13} = 1	a_{21} = 1.5	a_{23} = 1
	σ = 0.04	δ = 0.4	$\dot{P}_{MIN}$ = -0.1	P_{MIN} = 0
	$\dot{P}_{MAX}$ = 0.1	P_{MAX} = 1		

3. Electricity Markets

Ancillary services [9] generally consist of voltage support, regulation and frequency, energy imbalance, operating reserve and black start capacity services, etc. The energy imbalance service which service balances the interconnection system frequency, called as Direct Frequency Control (DFC). The DFC which is one of the most essential services consists of regulation and load following services.

The primary difference between the regulation and load following service is the time frame of consideration. Regulation service is defined to be the higher frequency of power service following the minute-to-minute load variation, whereas the load following service is intended to follow the lower frequency component of load variation, the time scale of which normally covers period of hours [9].

In this paper, we consider only regulation service as a constraint in the design process of the AGC controller.

3.1 Regulation Components

In hourly generation scheduling, the boundary between regulation and load following occurs at a frequency with a period length of twice the scheduling period, i.e. two hours [9]. All variation in load with full cycle period less than two hours is considered as part of the regulation service and all variations in load with full cycle periods equal to or greater than two hours are considered as load following service.

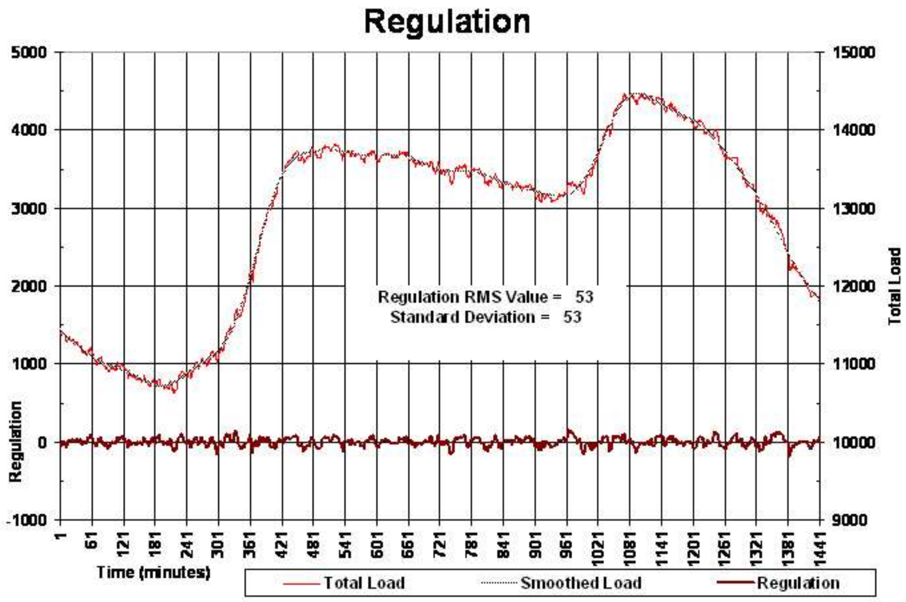

Figure 5 The regulation component of total load.

A regulation example is shown in Figure 5, comprising total load, smoothed load, and regulation. The regulation component is calculated by using Fourier transforms to decompose the total load into the regulation component and the smoothed load component. With the decomposition in this manner, the regulation component of the load has a net integrated energy of zero. In other words, there is no energy or energy imbalance associated with the regulation component. The root mean square (RMS) value for regulation is also calculated. In this case, since the net integrated energy of the regulation ($\bar{x}$) is zero, then the standard deviation (σ) for regulation has the same value as the RMS. The equations for the standard deviation (σ) and the RMS values can be written as (1) and (2).

$$\sigma^2 = \frac{1}{n}\sum x_i^2 - \overline{x}^2 \tag{1}$$

$$RMS^2 = \sigma^2 + \overline{x}^2 \tag{2}$$

3.2 Real energy service measurement

The measurement standard presented in [10-12] called Control Performance Standard 1 ($CPS1$) uses compliance factor (CF) to measure controller performance of each area. The CF is defined as:

$$CF = \frac{1}{n}\sum \frac{\overline{ACE} * \overline{\Delta F}}{B} \tag{3}$$

where $\overline{ACE}$ is the one minute average ACE and $\overline{\Delta F}$ is average standard error of frequency in one minute. A positive CF means the control area is acting as a burden to the interconnection regulation requirement. On the other hand, a negative CF indicates that the area is supporting the interconnection regulation requirement.

The $CPS1$ is a standard reference for defining capacity and measurement of regulation and load following services. Illiam and Hoffman [10] showed the importance of coincidence between scheduled errors of interconnection systems. Regulation and load following service measurement should use the RMS value combined with coincidence factor as follows:

$$C_{reg}^2 = \frac{1}{n}\sum \overline{\Delta T} * \overline{\Delta F} \tag{4}$$

where $\overline{\Delta T}$ is the schedule error over one minute period.

4. The method of inequalities

The method of inequalities [5, 13] requires that a design problem be formulated as a set of inequalities:

$$\Phi_i(p) \le C_i, \qquad i = 1, 2, \ldots, m \tag{5}$$

where $p \in \mathbf{R}^n$ is a design parameter, $\Phi_i(p)$ is a real number representing an aspect of the behaviors of the system, and the bound C_i is the maximum tolerable value of $\Phi_i(p)$. Any value of p that satisfies (5) is called a solution of the inequalities (5) and characterizes an acceptable design.

One can solve inequalities (5) either by analytical or numerical method. But, in general, it is necessary and practical to use numerical methods. In this work, an algorithm called the moving boundaries process (MBP) is used to solve inequalities (5). The details of the MBP algorithm can be found in Zakian's original article [5], and also in chapters 1 and 6 of Zakian's recent book [13].

The inequalities (5) include two principal subsets. One is the subset that represents required performance. Whereas constraints have traditionally been represented by inequalities, the representation of desired performance by a set of inequalities is a significant departure from the traditional that requires that performance be represented by a single number $\Phi(p) = \sum_{i=1}^{m} w_i \Phi_i(p)$ (the w_i are weights chosen by the designer), which is to be minimized.

The method of inequalities recognizes that desired performance is appropriately stated by means of several distinct criteria, thus allowing greater insight into the design process.

Over the last thirty years or more, it has been shown that a wide range of practical design problems can be formulated in the form of (5). See [5, 13-14] and the references therein.

5. AGC controller system design

We apply the method of inequalities to the design of a multiarea AGC system. The following assumptions are used in our design formulation.

- We consider only Load Frequency Control (LFC) in the AGC system and discard the coupling effects of automatic voltage regulator.
- Load disturbance, which is demand change, is a step function.
- We consider only small signal dynamic of the system. Therefore, the magnitude of the disturbance is 0.01 p.u.
- We discard the time delay of system.

When a small step disturbance occurs, the AGC system is normally required to fulfil the following objectives.

- Keep frequency deviations $\Delta\omega_i$ equal to zero in steady state.
- Keep the tie-line power flow deviation ΔP_{12} equal to zero in steady state.

According to the concept of tie-line bias control, the area control error in area i (ACE_i) is given by

$$ACE_1 = \Delta P_{12} + B_1 \Delta\omega_1 \tag{6}$$

$$ACE_2 = \Delta P_{21} + B_2 \Delta\omega_2 \tag{7}$$

where B_i is the frequency bias factor in area i. In order that the control system can drive $\Delta\omega_i$ and ΔP_{12} to zero in steady state, it is necessary that the controller employ the integral feedback of ACE_i (see (11) and (13)).

In addition to the above design objectives, we also include some significant electricity market constraints (as described in section III) in the formulation so as to increase the technical and economical reliability of the power system. The details of the design are given below.

5.1 Design Formulation

Since both areas are identical, it suffices to assume further that only a 0.01 p.u. load disturbance occurs in area 1 (i.e. ΔP_{L1} = 0.01 p.u. and ΔP_{L2} = 0 p.u.). See Figure 1. For the system to have good dynamic responses, it is required that (A) the maximum overshoot (OS), the rise time (T_r) and the settling time (T_s) of the total mechanical power deviation (ΔP_{M1}) are sufficiently small; (B) the maximum values of $|\Delta P_{12}|$, $|\Delta\omega_1|$, $|\Delta\omega_2|$, the total mechanical power deviations of thermal generating unit (IEEEG3 model) in area 1 and 2 ($\Delta P_{MG3,1}$ and $\Delta P_{MG3,2}$) are sufficiently small. The requirement (A) leads to the following design inequalities:

$$
\begin{aligned}
\Phi_1 &= OS \text{ of } \Delta P_{M1} && \le C_1 \\
\Phi_2 &= T_r \text{ of } \Delta P_{M1} && \le C_2 \\
\Phi_3 &= T_s \text{ of } \Delta P_{M1} && \le C_3
\end{aligned}
\tag{8}
$$

whereas the requirement (B) leads to

$$
\begin{aligned}
\Phi_4 &= \max\left\{|\Delta P_{12}(t)| : t \ge 0\right\} && \le C_4 \\
\Phi_5 &= \max\left\{|\Delta \omega_1(t)| : t \ge 0\right\} && \le C_5 \\
\Phi_6 &= \max\left\{|\Delta \omega_2(t)| : t \ge 0\right\} && \le C_6 \\
\Phi_7 &= \max\left\{\Delta P_{MG3,1}(t) : t \ge 0\right\} && \le C_7 \\
\Phi_8 &= \max\left\{\Delta P_{MG3,2}(t) : t \ge 0\right\} && \le C_8
\end{aligned}
\tag{9}
$$

In order to increase the system's economical reliability, it is required that (C) the regulation service quality of area 1 (C_{reg1}) and the compliance factor of each area (CF_1 and CF_2) are in the acceptable range described in the market agreement. Since there is no disturbance in area 2, i.e. $C_{reg2} = 0$, we do not consider C_{reg2}. The requirement (C) leads to the following design inequalities.

$$
\begin{aligned}
\Phi_9 &= C_{reg1} && \le C_9 \\
\Phi_{10} &= CF_1 && \le C_{10} \\
\Phi_{11} &= CF_2 && \le C_{11}
\end{aligned}
\tag{10}
$$

Since the two control areas are identical, the transfer functions of both area controllers (see Figure 1) are chosen to be the same; that is, $G_1(s) = G_2(s)$.

In solving the inequalities given in (8), (9) and (10) for an acceptable design solution, various forms of $G_1(s)$ and $G_2(s)$ are chosen. Usually, it is a common practice to start with $G_1(s)$ and $G_2(s)$ with the least complexity; if a design solution is not found, then a more complex controller structure is used.

5.2 Numerical Results

First, choose

$$G_1(s) = G_2(s) = \frac{p_1}{s} \tag{11}$$

After a large number of iterations, the MBP cannot locate an acceptable design specified in Table 2. An approximate solution can be found by relaxing some design specification in Table 2. For example, by letting C_1 = 0.2, C_3 = 41 sec. and C_9 = 0.51, an approximate solution is found.

$$G_1(s) = G_2(s) = \frac{0.10816}{s} \tag{12}$$

where the corresponding values of $\Phi_i(p)$ are given in Table 3.

Then, reformulate the design problem by choosing

$$G_1(s) = G_2(s) = \frac{p_1}{s} + p_2 \cdot \left(\frac{s + p_3}{s + p_4} \right) \tag{13}$$

After a number of iterations, the MBP locates a successful design given by

$$G_1(s) = G_2(s) = \frac{0.02148}{s} + 0.03997 \cdot \left(\frac{s + 1.39888}{s + 0.06939} \right) \tag{14}$$

where the corresponding values of $\Phi_i(p)$ are given in Table 3 and the responses of the system are in Figures 6 and 7.

Table 2 Design specifications

Design specifications (C_i) in (8), (9) and (10)			
	C_1 = 0.1	C_2 = 2.5 sec.	C_3 = 27 sec.
	C_4 = 0.0045 p.u.	C_5 = 0.0015 p.u.	C_6 = 0.0015 p.u.
	C_7 = 0.0099 p.u.	C_8 = 0.0099 p.u.	C_9 = 0.3950
	C_{10} = 6.525×10^{-5}	C_{11} = 6.525×10^{-5}	

Table 3 Design results

For AGC with integral controller (12)	$\Phi_1 = 0.19457$	$\Phi_2 = 2.44116$ sec.	$\Phi_3 = 40.7617$ sec.
	$\Phi_4 = 0.00450$ p.u.	$\Phi_5 = 0.00125$ p.u.	$\Phi_6 = 0.00076$ p.u.
	$\Phi_7 = 0.00923$ p.u.	$\Phi_8 = 0.00289$ p.u.	$\Phi_9 = 0.50881$
	$\Phi_{10} = 2.078\times10^{-7}$	$\Phi_{11} = 7.254\times10^{-9}$	
For AGC with more complex controller (14)	$\Phi_1 = 0.09248$	$\Phi_2 = 2.33385$ sec.	$\Phi_3 = 26.9983$ sec.
	$\Phi_4 = 0.00438$ p.u.	$\Phi_5 = 0.00124$ p.u.	$\Phi_6 = 0.00059$ p.u.
	$\Phi_7 = 0.00895$ p.u.	$\Phi_8 = 0.00193$ p.u.	$\Phi_9 = 0.39338$
	$\Phi_{10} = 5.38\times10^{-6}$	$\Phi_{11} = -3.99\times10^{-8}$	

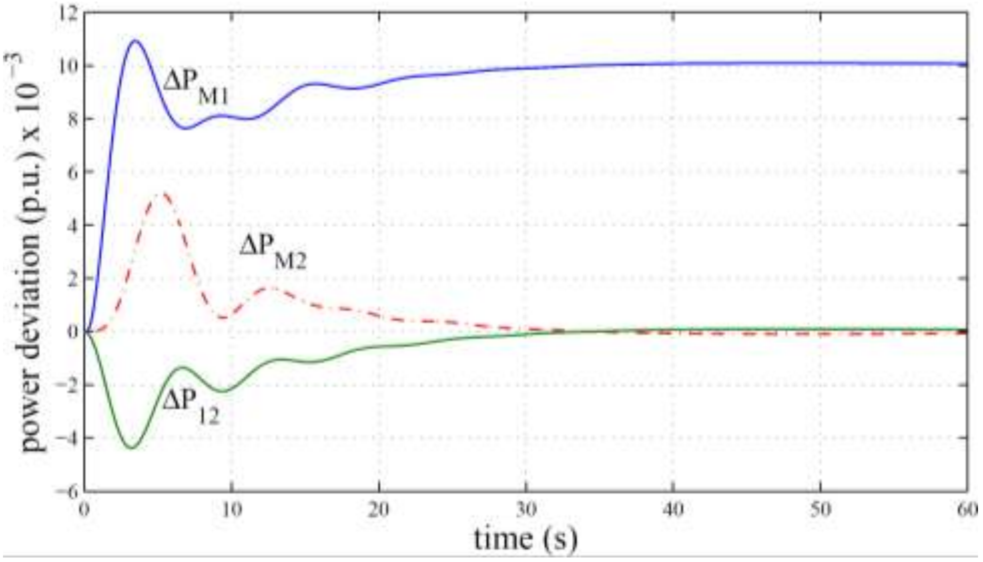

Figure 6 The responses with controller (14) of ΔP_{M1}, ΔP_{M2} and ΔP_{12} due to ΔP_{L1}.

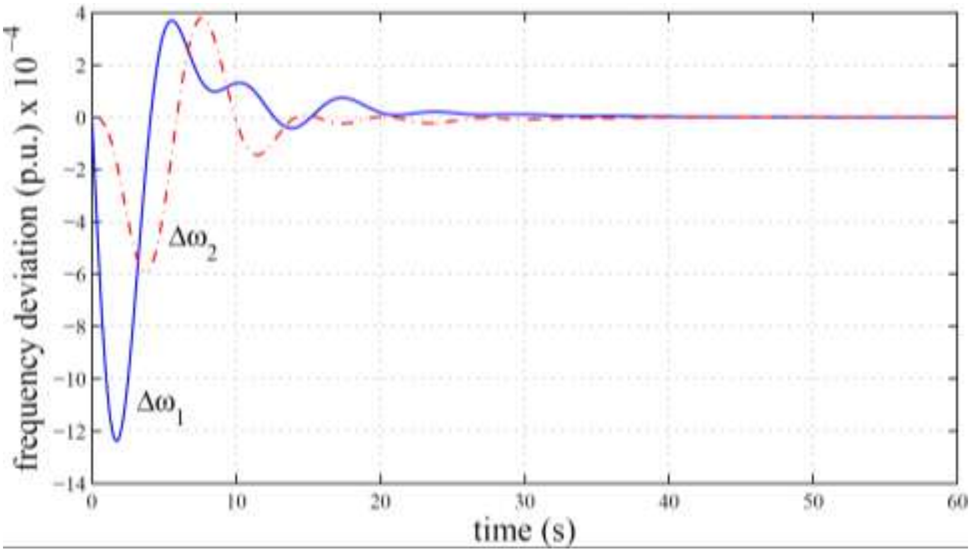

Figure 7 The responses with controller (14) of $\Delta\omega_1$ and $\Delta\omega_2$ due to ΔP_{L1} .

6. Conclusion

From the numerical results, we can see that the method of inequalities can solve this kind of design problem effectively so that the AGC system can have good dynamic responses and, at the same time, can increase its economical reliability. Furthermore, the advantage of this method is that new design criteria are easily incorporated into the design process in the form of additional inequalities. When the market criteria are changed, it is easy to update the parameters of the AGC controller in order to gain the system reliability. It is worth pointing out here that, by using the method of inequalities, we can choose to design not only the controller parameters but also the parameters in other parts of the power system.

7. Acknowledgment

The authors would like to gratefully acknowledge Chulalongkorn University Graduate Scholarship to Commemorate the 72nd Anniversary of His Majesty King Bhumibol Adulyadej.

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