# Journal of Applied Sciences

ISSN 1812-5654

Journal of Applied Sciences 7 (22): 3381-3390, 2007
ISSN 1812-5654


# A New Systematic Procedure to Design an Automatic Generation Controller

A. Khodabakhshian
Faculty of Engineering, Isfahan University, Isfahan, Iran

**Abstract:** A new method to tune the controller parameters is presented in study for Automatic Generation Control (AGC) of hydro turbine power systems. The controller parameters are adjusted such that the maximum phase is located on the right-most point of the ellipse, corresponding the maximum peak resonance on the Nichols chart. For this system making the open-loop frequency response curve tangent to a specified ellipse is an efficient method for controlling the overshoot, the stability and the dynamics of the system. The robustness of the feedback PID controller has been investigated on a multimachine power system model and the results are shown to be consistent with the expected performance. The results are also compared with a conventional PI controller and shown to be superior; especially since the transient droop compensator of the speed governor is removed a much faster response is obtained. The region of acceptable performance for the LFC covers a wide range of operating and system conditions.

**Key words:** Power systems, load frequency control, PID controller

## INTRODUCTION

Electric power systems consist of a number of control areas, which generate power to match the power demand. However, poor balancing between generated power and demand can cause the system frequency to deviate away from the nominal value and creates inadvertent power exchanges between control areas (Kundur, 1994; Saadat, 1999; Gross and Lee, 2001). To avoid such a situation, Automatic Generation Control (AGC) or in other words, Load Frequency Controller (LFC) (Kundur, 1994) is designed and implemented to automatically balance generated power and demand in each control area.

The general practice in the design of a LFC is to use the PI decentralized controller. This gives adequate system response considering the stability requirements and the performance of its regulating units. Conventional PI controllers of fixed structure and constant parameters are usually tuned for one operating condition. Since the characteristics of the power system elements are non-linear, these controllers may not be capable of providing the desired performance for other operating conditions (Hiyama, 1989; Dash *et al*., 1998). Therefore, the response of this controller is not satisfactory enough and large oscillations may occur in the system (Rerkpreedapong *et al*., 2003; Kumar *et al*., 1985; Tripathy *et al*., 1998). Moreover, the dynamic performance of the system is highly dependent on the selection of the PI controller gain. A high gain may deteriorate the system performance having large oscillations and in most cases it causes instability (Tang *et al*., 2002; Kundur *et al*., 1994). Subsequently, a number of decentralized load frequency controllers were developed to eliminate the above drawback (Liu *et al*., 2003; Lim *et al*., 1996; Rahi and Feliachi, 1998). However, most of them are complex state-feedback or high-order dynamic controllers, which are not practical for industry practices. This problem is more complicated when the system is non-minimum-phase. These real characteristics make the performance limitation of the system occur.

To cope with the variation of the plant parameters the adaptive techniques have been applied (Valk *et al*., 1985; Kanniah *et al*., 1984) but they require information on the system states or an efficient on-line identifier. The model reference approach may be also difficult to apply since the order of the power system is large.

It is well known that the hydro turbine is non-minimum-phase and in this regard the speed governor of the hydro turbine needs to be equipped by a transient droop compensator. This ensures that the system will be stable when the load changes (Kundur, 1994). However, this makes the system response to be comparatively sluggish (Kundur, 1994).

In control theory Poulin and Pomerleau (1997) introduces a new method to obtain the parameters of the PI (or PID) controllers based on an optimization technique using the constant-M circles in Nichols chart. The main idea is to keep the maximum overshoot of the system response in a predetermined value following a step change in the reference input. The predetermined bandwidth and phase margin guarantee the stability of the system.

This technique has been modified and applied for the first time in power systems by Khodabakhshian and

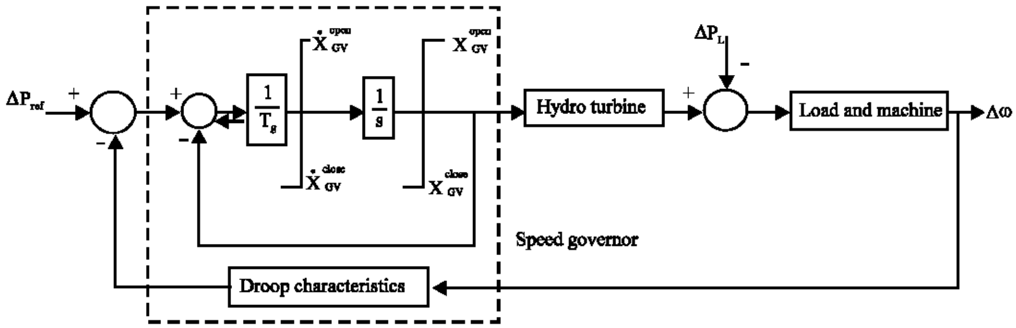


Fig. 1: Block diagrams of turbine, governor, load and machine

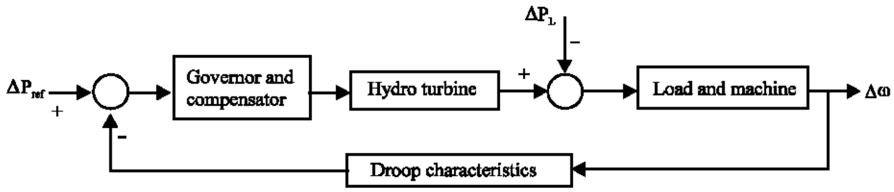


Fig. 2: Hydro power system with the transient droop compensator

Golbon (2005) to design a new PID load-frequency controller for a single-machine infinite bus hydro system. This study extends and applies this technique to design a robust PID controller for a decentralized LFC in a multimachine system. Comparative results will be given for the conventional PI controller and the proposed one for a multimachine hydro power system example. The performance is shown to be comparably desirable and robust, especially when there are large changes in the parameters of the system. More importantly, since for the speed governor a compensator is not used, a much faster response is achieved.

## SYSTEM MODEL

Most hydro turbo-generators (and also steam turbines) now in service are equipped with turbine speed governors. The function of the speed governor is to monitor continuously the turbine-generator speed and to control the gate position in hydro turbines (or control the throttle valves which adjust steam flow into the steam turbines) in response to changes in system speed or frequency.

Since all the movements are small the frequency-power relation for turbine- governor control can be studied by a linearized block diagram (Kundur, 1994). However, the computer simulation will be carried out using the actual nonlinear system. The linear model is shown in Fig. 1 for a single-machine infinite-bus (SMIB) (Kundur and Saadat) where the blocks are:

$$\text{Hydro turbine} = \frac{1 - T_W s}{1 + 0.5 T_W s}$$

$$\text{Load and machine} = \frac{1}{2Hs + D}$$

$$\text{Droop characteristics} = 1/R_P$$

The $R_P$, $T_w$, D and H are the regulation constant, water starting time, damping ratio and machine inertia, respectively.

**Transient droop compensator:** Hydro turbine transfer function is inherently non-minimum-phase because of water inertia. Therefore, any step change on valve position creates negative reflex on output power of turbine. Using the nominal values for the speed governor, turbine and machine parameters implies that in order to have a stable system the permanent regulation constant of the speed governor should be 20% (Kundur, 1994). However, this coefficient is usually about 5% and this makes the gain margin and phase margin both to be negative and therefore, the system response following a small change in load will be unstable (Kundur, 1994). A compensator is then suggested to be included in the speed governor as shown in Fig. 2 to solve this problem (Kundur, 1994).

The compensator transfer function is:

$$G_c(s) = \frac{1 + sT_R}{1 + (R_T / R_P) T_R s}$$

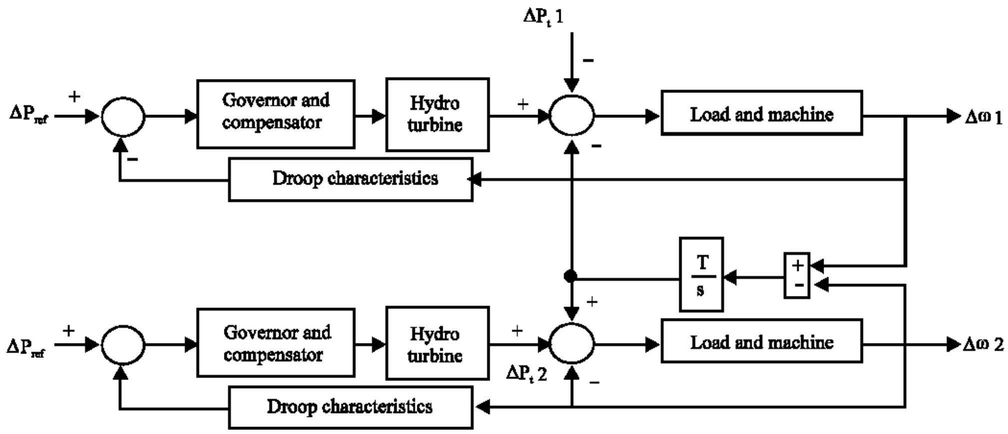


Fig. 3: Block diagram of a two-machine system including turbines, governors, load and machines

where, $T_R$ and $R_T$ are obtained using the equations given in (Kundur) as follows;

$$\begin{cases} R_t = [2.3 - 0.15(T_w - 1.0)](T_w / T_M) \\ T_R = \{5.0 - 0.5(T_w - 1.0)](T_w) \end{cases}$$

in which $T_M$ = 2H.

**Multimachine system:** Although the design of any supplementary controller on a one-machine system is logically the best place to begin an evaluation of the controller, a more through investigation has to be done with a multimachine model. For a multimachine case the linearized block diagram which is an extension of Fig. 1 with also considering the effect of tie-line power is shown in Fig. 3 (Kundur, 1994).

## PERFORMANCE REQUIREMENTS

In load frequency control each control area has a central facility called the energy control center, which monitors the system frequency and the actual power flows on its tie lines to neighboring areas. The deviation between desired and actual system frequency is then combined with the deviation from the scheduled net interchange to form a composite measure called the area control error, or simply ACE.

In general, for satisfactory operation of power units running in parallel it is most desirable to have the frequency and tie-line power fixed on their nominal and scheduled values even when the load alters and therefore, to remove area control error (ACE = 0).

In a vertically integrated electric power system made up of interconnected control areas the dynamics of the system is usually non-linear and the parameters change and therefore, special cares must be taken into account for designing any fixed parameter controller. In this regard, the following conventional requirements are considered (Kundur, 1994; Stankovic *et al*., 1998; Kumar *et al*., 1985).

- Each area contributes to the control of system frequency.
- Each area regulates its own load variations.
- Optimal transient behavior should be reached.
- In steady state, system frequency in all areas and tie line power interchanges are, respectively, returned to their nominal and scheduled values (ACE = 0).
- The controller should be robust when the system parameters change. Many robust control design methodologies rely on prescribed parameterizations of the system uncertainty set. Due to the complexity of actual uncertainties in power systems such pre-formatted descriptions are often either unavailable or very conservative. As shown by Stankovic *et al.* (1998) since a power system, especially for circuits and electro-mechanical parts, is frequently passive, closed-loop passivity, rather than the dynamic model, can be the key factor in the robustness of the control design. For a scalar linear time-invariant system, passivity is equivalent to the requirement that the closed-loop transfer function be positive real (i.e., stable with the phase of the Bode plot between +90 and -90 degrees) (Stankovic *et al*., 1998). Therefore, the stability robustness can be checked by the closed-loop passivity for a broad range of independent variations in parameters of the system (+50% has been used here).

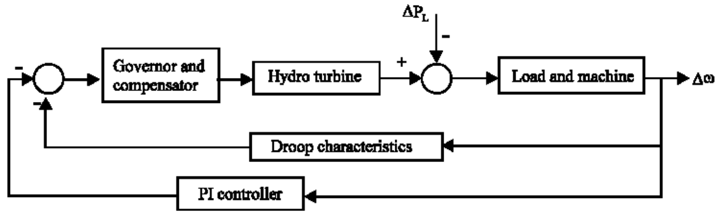


Fig. 4a: Block diagram of a SMIB system with PI controller

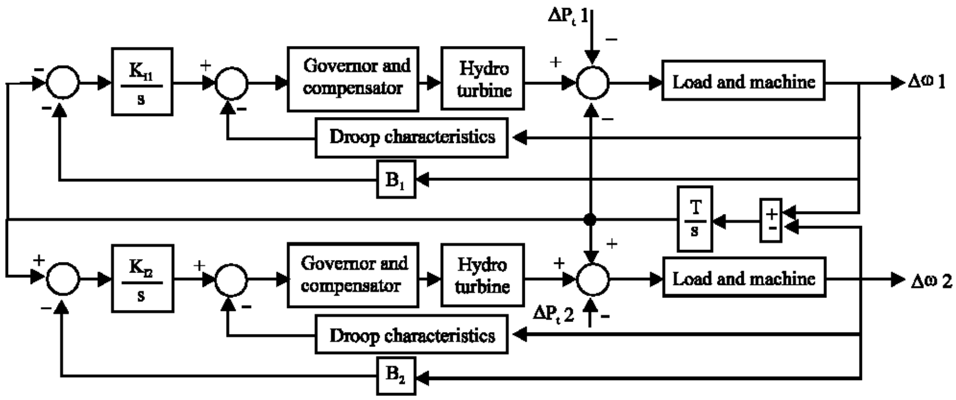


Fig. 4b: Block diagram of a multimachine system with PI controller

## CONVENTIONAL PI CONTROLLER

In order to always have the system frequency on its nominal value a supplementary control action such as a PI controller in the form

$$\frac{K_I}{s}$$

of is usually required. This is shown in Fig. 4a and b for a SMIB and multimachine systems, respectively. As can be seen this supplementary controller increases the type of the system and this ensures that the steady-state error for a step change in load will be always zero (Kundur, 1994).

The controller gain $K_I$ has to be chosen in such a way that a good shape of the transient response be obtained. It cannot be too high, otherwise instability may result (Kundur, 1994; Saadat, 1999). Although different techniques have been addressed to choose the gain $K_I$, there is no guarantee to have the most desirable response, especially when the parameters of the system change.

For the multimachine case the selection of the coefficient $B_i$, called frequency bias constant in area control error equation ($ACE_i = \Delta P_{tie} + B_i\Delta f_i$)), is also important. The frequency bias $B_i$ should be high enough such that each area adequately contributes to frequency control. It has been suggested by Kundur that this coefficient be obtained by the equation ($B_i = 1/R_i + D_i$) in which $R_i$ and $D_i$ are the regulation constant and damping ratio of the ith system, respectively.

A new PID controller is then presented further to make sure that all performance requirements are satisfied.

## DESIGNING A PID CONTROLLER USING MAXIMUM PEAK RESONANCE SPECIFICATION (MPRS)

Proportional Integral (PI) and Proportional Integral Derivative (PID) controllers are widely utilized in industries. The simplicity and ability of these controllers are the most important advantage and many methods are given in the literature to obtain their parameters.

Poulin (1997) has presented a unified approach for the design of PI and PID controllers, based on the constant M circles of the Nichols chart. The controller parameters are tuned such that the open-loop frequency curve follows the corresponding constant-M circle using a predetermined maximum peak resonance. This approach gives the possibility of having the desirable maximum overshoot, the phase and gain margins and the bandwidth of the closed-loop system simultaneously. An optimization procedure is first introduced to show the basic idea. Some simplifications are then given to ease the use of this method. This approach is applicable for stable, unstable and integrating processes.

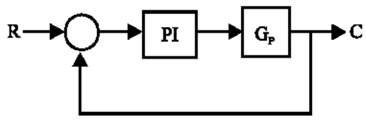


Fig. 5: Block diagram of a typical control system

The main design is first given for a PI controller and then easily extended to a PID one. For example, assume the block diagram given in Fig. 5.

The process transfer function is:

$$G_P(s) = \frac{K_P(1 - T_0 s) \quad e^{-\theta s}}{(1 + T_1 s)(1 + T_2 s)} \tag{1}$$

where, $\theta$ is the time delay and is considered to be zero for the design of LFC.

The PI controller is then given by:

$$G_c(s) = \frac{K_c(1 + T_i s)}{T_i s} \tag{2}$$

The parameters $T_i$ and $K_c$ are obtained using the formula given in Appendix I.

## DESIGNING A NEW DECENTRALISED LFC USING MPRS METHOD

Before the design procedure for a new decentralized LFC is given the following considerations must be taken into account.

- In Fig. 5 the control system is with a negative unity feedback. However, the system shown in Fig. 1 indicates that the governor speed droop characteristics ($1/R_P$) is in the feedback path. Although by some simple modifications this may be easily changed to a unity feedback, this will make the system to be very complicated for the purpose of this study.
- The process transfer function ($G_p$) given in Fig. 5 is with the degree of 2. On the other hand, by looking at Fig. 1, it can be seen that the degree of the open-loop system including governor without compensator, turbine, electrical machine and load is 3. It should be noted that in the proposed design algorithm in this study the compensator will not be considered.
- The PI controller is normally inserted in the forward path as used by Poulin and Pomerleav (1997) (Fig. 5). However, in the LFC discussion the main purpose is to stabilize the system following a step change in load ($\Delta P_L$).

Therefore, in practice, as shown in Fig. 4 the PI controller will be placed in the feedback path for $\Delta\omega/\Delta P_L$.

The above-mentioned points indicate that there should be some changes for the system given by Poulin and Pomerleav (1997) in order that it can be utilized in LFC design. Therefore, the following procedure is proposed.

- First it is assumed that the reference signal is $\Delta p_{ref}$. Note that the poles of the closed-loop transfer functions $\Delta\omega/\Delta P_L$ and $\Delta\omega/\Delta P_{ref}$ are the same.
- In Fig. 6, $1/R_p$ is considered to be 1. This coefficient will be considered after designing the PID controller.
- In order to reduce the degree of the system to 2 a PD compensator in the form of 2Hs+D is inserted in the forward path of Fig. 6. The reason for this selection is that the open-loop pole

$$s_1 = \frac{-D}{2H}$$

is much closer to the imaginary axis in comparison with the other open-loop poles

$$s_2 = \frac{1}{0.5T_w} \text{ and } s_3 = \frac{1}{T_g}\ .$$

It should be also noted that since the damping ratio D is small, even it changes, when compared with 2H the pole

$$s_1 = \frac{-D}{2H}$$

can be considered to be constant.
- The compensator has been omitted and the new controller must provide a stable system. This can be easily achieved because this method has been originally designed for non-minimum phase systems (Eq. 1).
- A PI controller based on the transfer function

$$G_P(s) = \frac{1 \ - \ T_w s}{(1 + T_g s)(1 + 0.5T_w s)}$$

is designed exactly based on the formula given in Appendix I. It is known that the water starting time ($T_w$) changes when the load varies. It is also known that if the open-loop pole

$$(\text{say, } s_2 = -\frac{1}{0.5T_w})$$

is close to the origin, the performance may be degraded considerably. Therefore, to make sure that the worst situation is considered for the design procedure, the maximum possible value of $T_w$ (i.e., $T_w$ = 4.0 sec (Kundur, 1994) is chosen.

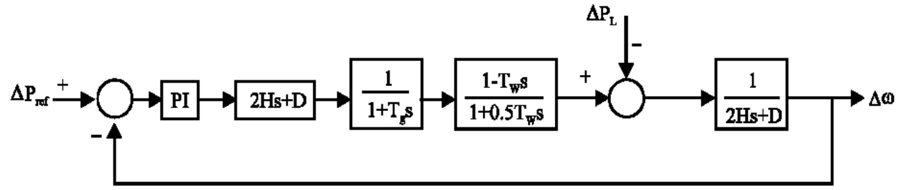


Fig. 6: PD and PI controller in forward path

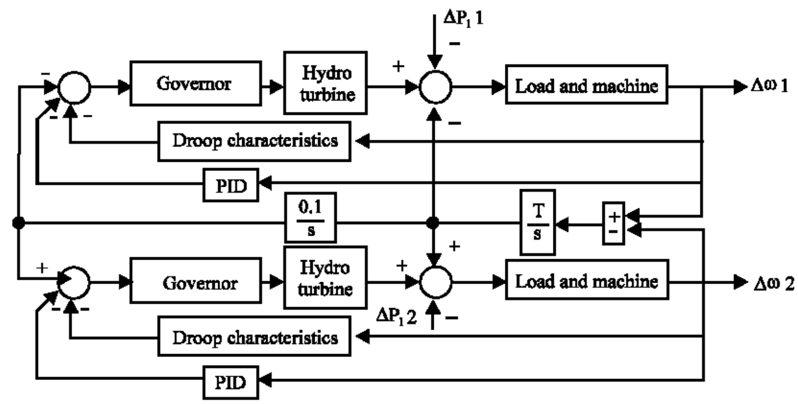


Fig. 7: Multimachine system with the new controller

- The PID (=PI +PD) controller parameters, therefore, will be:

$$(2Hs + D)\frac{K_C(1 + Tis)}{Tis} = K_{P\,Design} + \frac{K_I}{s} + K_d s$$

where:

$$K_{P\,Design} = \frac{2HK_C}{Ti} + K_C D$$

$$K_I = \frac{DK_C}{Ti}$$

$$K_d = 2HK_C$$

- The designed PID controller will be then placed in feedback path for each power system, for example, in a two-machine system as shown in Fig. 7.
- It is evident that $K_{P\,Design} = K_{P\,Controller} + 1/R_P$.
- With respect to industrial considerations, in order to remove high frequency noise effects when a PD controller is used, it is imperative that $K_d s/(1+T_d s)$ (in which $T_d \ll K_d$) be used rather than $K_d s$ (Eitelberg, 1987).
- An integral action for the tie-line power changes is used and the integrated signal is inserted to the summing point where the governor is connected (Fig. 7). This ensures that the tie-line power changes go to zero as the load changes.
- Since the control strategy here is different, it is not necessary to determine the frequency bias constant and it will be considered to be zero. Using PID controller with the integrator explained above guarantees that ACE will be zero. In other words, $\Delta\omega$ and $\Delta P_{tie}$ go to zero as time goes to infinity.
- Since hydro turbine is inherently a non-minimumphase system, this makes the overshoot of tie-line power changes grow rapidly and the system response may be unstable as a result. In order to reduce the amplitude of these oscillations a gain of 0.1 is utilized for the integrator (Fig. 7).

## SIMULATION RESULTS

Simulation studies were performed on the system with a third-order generator modeled by a set of non-linear differential equations based on Park's equations (Yu, 1983). The simulation model includes typical rate limiters and gain saturation in power plants. Consider, for example, a typical power system taken from (Sadaat, 1999) (Appendix II).

For the conventional PI controller by using the method given in (Kundur, 1994) it was found that $K_{I1} = K_{I2} = 0.1$ were the best selections for having the best performance. The frequency bias constants will be $B_1 = B_2 = 21$ and as suggested by Kundur (1994).

By using MPRS method the PID controller parameters would be:

System A:

$T_d = 0.01$  $K_I = 0.117$  $K_{P\,Design} = 1.42$  $K_d = 2.5$

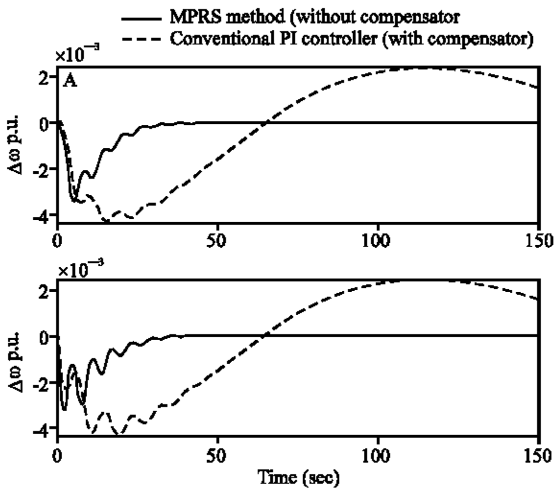


Fig. 8: Frequency variation following a small change in load in system B only $\Delta P_{L2} = 0.01$ p.u.)

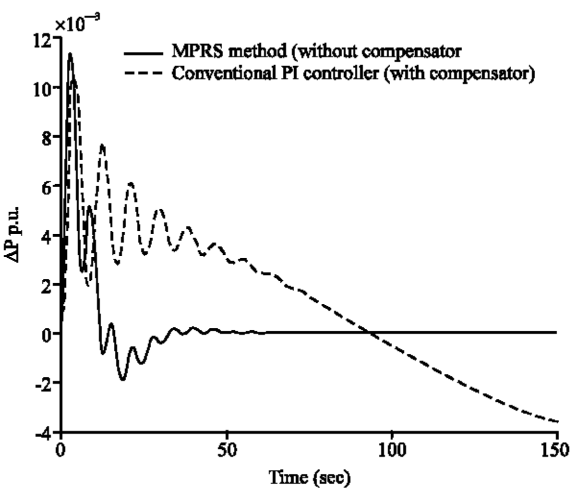


Fig. 9: Tie-line power variations following a small change in load in system B only $\Delta P_{L2} = 0.01$ p.u.)

System B:

$T_d = 0.01$   $K_I = 0.122$  $K_{P\,Design} = 0.983$   $K_d = 1.5$

Figure 8 shows the frequency changes of both systems following a small step change in load of power system B only ($\Delta P_{L2}$ = 0.01 p.u.). The tie-line power variations and governor output are also depicted in Fig. 9 and 10, respectively. As can be seen from Fig. 8 to 10 the first 4 requirements have been easily obtained by the proposed controller (MPRS). The results clearly show that because of removing the transient droop compensator of the speed governor in the proposed controller algorithm a much faster dynamic performance is obtained.

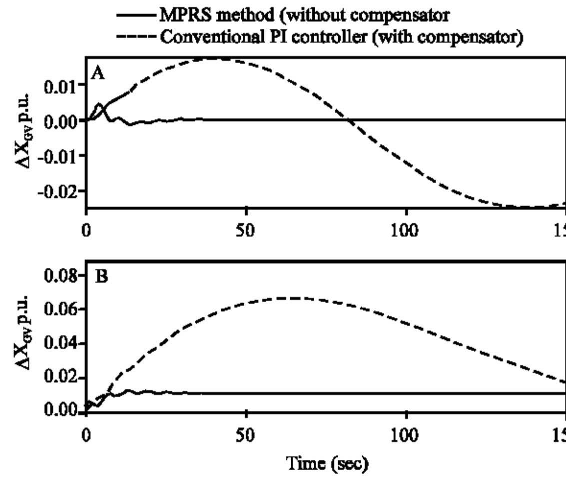


Fig. 10: Governor output following a small change in load in system B only $\Delta P_{L2} = 0.01$ p.u.)

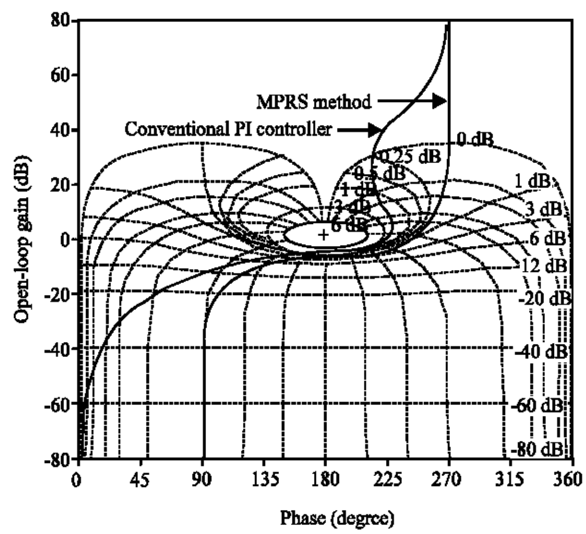


Fig. 11: Open-loop frequency response system A on Nichols chart

To obtain a stable closed-loop system for all frequency range, the open-loop frequency response curve must be on the right-hand side and far from the critical point (-180 degree, 0 dB) (Vegte, 1994). This important objective is achieved easily when using PID (MPRS) controller as can be shown from Fig. 11 for system A. The same result was also obtained for the system B. The open loop frequency curve, as depicted in Fig. 11, is also tangent to the specified contour Mr = 0.0 dB given in the design procedure as a main goal (Appendix I).

The stability robustness will be also tested by changing the parameters of both systems (+50%). The closed loop Bode diagrams are shown in Fig. 12 for

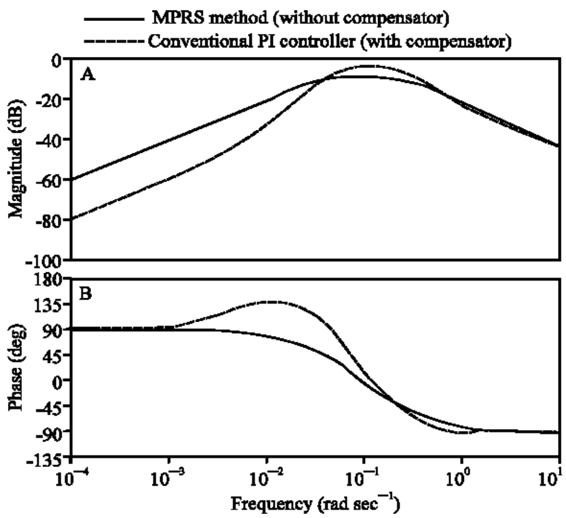


Fig. 12: Bode plots of the closed-loop system for system A when the parameters change (50%)

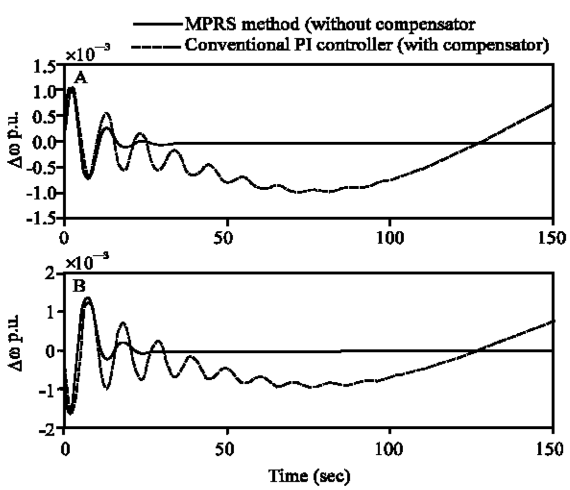


Fig. 13: Frequency variation following a small change in loads ($\Delta P_{L1} \geq 0.01$ and $\Delta P_{L2} \geq 0.01$) when the parameters of both systems change by 50%

system A with also having the same results for system B confirming that the passivity is still satisfactory for the proposed PID controller. However, the conventional PI controller violates passivity (the phase gets more than 90 degree and lower than -90 degree for some frequencies). Figure 13 and 14 also show the responses of the two-area interconnected power system following a small step change in load for both systems. The results obtained demonstrate the robustness of the proposed control scheme against parameter variations.

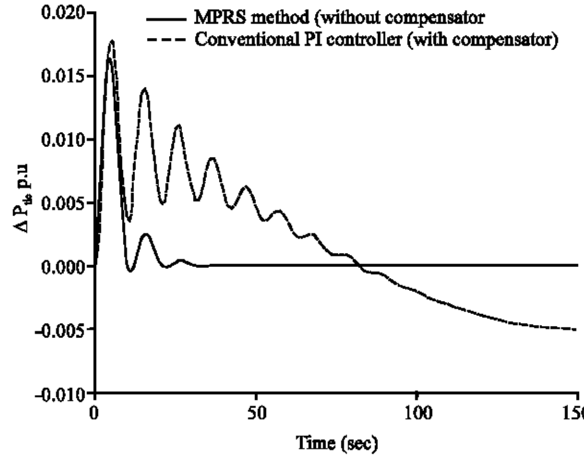


Fig. 14: Tie-line power variations following a small change in loads ($\Delta P_{L1} \geq 0.01$ and $\Delta P_{L2} \geq 0.01$) when the parameters of both systems change by 50%

## CONCLUSIONS

The load-frequency regulation characteristics of a two-machine system with hydro turbines have been studied. The proposed PID controller has been shown to enhance the damping of the power system following a small step change in load for different cases and gives a better performance than the conventional PI controller. By removing the transient droop compensator of the speed governor a much faster dynamic performance is also achieved. The controller performance was also desirable for a wide range of operating points confirming its robustness.

The major advantages of this new PID controller for LFC design are summarized as follows:

- The implementation is much easier and less on-line computational effort than the complex on-line adaptive techniques.
- The overshoot and settling time of the system response can be assured.
- Plant uncertainty due to different operating conditions can be easily managed by the controller.
- Non-minimum phase problem has been easily resolved for designing the controller.

## APPENDICES

**Appendix I: Tuning method:** The tuning method is based on the contours of the Nichols chart and the specification is given in terms of the maximum peak resonance Mr of the closed-loop system. The controller parameters are tuned such that the open-loop transfer function G (jω) = Gc (jω) Gp (jω), in which Gc and Gp are the controller and process transfer functions respectively, follows the contour corresponding the desired Mr. This approach gives the possibility of simultaneously handling the maximum peak overshoot Mp, the minimum phase and amplitude margins and the closed-loop bandwidth.

The maximum peak resonance Mr and the maximum peak overshoot Mp are closely related. For a second order system, the following equation is given by Poulin and Pomerleau (1997);

$$Mp = 100\exp\left[-\pi\left(\frac{1-\sqrt{1-10^{-0.1Mr}}}{1+\sqrt{1-10^{0.1Mr}}}\right)\right]^{1/2}$$

For instance, Mr = 5 dB and Mr = 4 dB correspond to the values of Mp = 10.75 and Mp = 32.75%, respectively. Meanwhile, the fact that G (jω) curve follows and does not cross, ensures that the minimum phase and gain margins are preserved (Poulin and Pomerleau, 1997). The frequency range that G (jω) curve should follow the specified contour affects the closed-loop bandwidth. The higher range of frequency will have a fast response.

The tuning method having the above criteria is based on an optimal concept and consists of minimizing the distance between the open-loop system G(jω) and the specified contour Mr. This distance is given by;

$$d_i = \sqrt{(x(\omega_i)-\frac{h^2}{1-h^2})^2 + y^2(\omega_i) + \frac{h}{1-h^2}}$$

where, X(ω) and Y(ω) are the real part and the imaginary part of G(jω) and h is the equation of the contour given by:

$$h = \frac{|G(j\omega)|}{|1+G(j\omega)|} = \frac{|X(\omega)+jY(\omega)|}{|1+X(\omega)+jY(\omega)|} = \frac{\sqrt{X^2(\omega)+Y^2(\omega)}}{\sqrt{(X(\omega)+1)^2+Y^2(\omega)}}$$

The minimized criterion for minimizing $d_i$ will be

$$J(\theta_c) = \begin{cases} \sum_{i=1}^{k} |X(\omega_i) + 1/2| & M_r = 0\text{ dB} \\ \sum_{i\ge 1}^{k}\left[\sqrt{(x(w_i)-\frac{h^2}{1-h^2})^2 + y^2(w_i) + \frac{h}{1-h^2}}\right] & M_r > 0\text{ dB} \end{cases}$$

where, $\theta_c$ is the controller parameters.

The constraints are:

$$20\text{Log}\,|H(j\omega_r)| = M_r \quad (1)$$

$$|H(j\omega)| \ge 1 \quad \omega \le \omega_r \quad (2)$$

$$\angle G(j\omega_{co}) > -180^\circ \quad (3)$$

where, $\omega_r$ and $\omega_{co}$ are the closed-loop resonance frequency and the open-loop crossover frequency, respectively. The first constraint ensures that the G(jω) curve follows but does not cross the contour. The second constraint ensures the relationship between Mr and Mp is preserved. The last constraint ensures that the system is stable.

Now simple tuning formulas are presented based on the contour concepts explained above for PI controllers with the following transfer function.

$$G_C(s) = \frac{K_c(1+T_i s)}{T_i s}$$

The process transfer function is:

$$G_P(s) = \frac{K_P(1-T_0 s)e^{-\theta s}}{(1+T_1 s)(1+T_2 s)}$$

where, $T_1 > T_2 \ge 0$.

Using the optimal procedure and some simplifications lead to the following equation of controller integral time constant:

$$T_i = \begin{cases} \left(1+0.175\theta/T_1+0.3(T_2/T_1)^2+0.2T_2/T_1\right)T_1 & \theta/T_1 \le 2 \\ \left(0.65+0.35\theta/T_1+0.3(T_2/T_1)^2+0.2T_2/T_1\right)T_1 & \theta/T_1 > 2 \end{cases}$$

The proportional gain is then given by

$$K_C = \frac{T_i}{K_P}\left\{\frac{(T_1T_2)^2\omega_{co}^6 + (T_1^2+T_2^2)\omega_{co}^4 + \omega_{co}^2}{(T_iT_0)^2\omega_{co}^4 + (T_i^2+T_0^2)\omega_{co}^2 + 1}\right\}^{\frac{1}{2}}$$

where, $\omega_{co}$ is obtained by solving

$$\phi = -\pi/2 + \arctan(T_i\omega_{co}) - \arctan(T_0\omega_{co}) - \arctan(T_1\omega_{co}) - \arctan(T_2\omega_{co}) - \theta\omega_{co}$$

and the desired phase $\phi$ is given by:

$$\phi = \arccos\left(1 - 10^{-0.1M_r}/2\right) - \pi$$

Mr is considered to be 0 dB in this study. The open-loop frequency curve of system A is tangential to the ellipse Mr = 0.0 dB (Fig. 2).

**Appendix II:** The system parameters are as follows (Frequency = 60 Hz, MVA base = 1000);

System A: T'do = 4.5, xd = 1.3, x'd = 0.3, xq = 0.5, 2H = 10, D = 1.0, $T_g$ = 0.5, $T_W$ = 4.0, $1/R_P$ = 20 ($R_P$ = 0.05)$T_R$ = 14 $R_T$ = 0.74

System B: T'do = 4.5, xd = 1.3, x'd = 0.3, xq = 0.5, 2H = 6.0, D = 1.0, $T_g$ = 0.2, $T_W$ = 4.0, $1/R_P$ = 20 ($R_P$ = 0.05) $T_R$ = 14 $R_T$ = 1.233

The limiter values are taken from (Kundur, 1994;Anonymous, 1973) and are;

$$\dot{X}_{GV}^{open} = 0.16$$

$$\dot{X}_{GV}^{close} = 0.16$$

$$X_{GV}^{open} = 0.1$$

$$X_{GV}^{close} = 0.1$$

## REFERENCES


Anonymous, 1973. Dynamic models for steam and hydro turbines in power system studies. IEEE Committee Report, IEEE PES Winter Meeting, New York, pp: 1904-1915.

Dash, P.K., A.C. Liew and B.R. Mishra, 1998. An adaptive PID stabilizer for power systems using fuzzy logic. Elect. Power Syst. Res., pp: 213-222.

Eitelberg, E., 1987. A regulating and tracking PI(D) controller. Int. J. Control, 45: 91-95.

Gross, G. and J.W. Lee, 2001. Analysis of load frequency control performance assessment criteria. IEEE Trans. Power Syst., 16: 520-525.

Hiyama, T., 1989. Application of Rule Based Stabilizing Controller to Power Systems. IEE Proceedings C, 136: 175-181.

Kanniah, J., S.C. Tripathy, O.P. Malik and G.S. Hope, 1984. Microprocessor-based adaptive load-frequency control. IEE Proc. Part C, 131: 121-128.

Khodabakhshian, A. and N. Golbon, 2005. Robust load frequency controller design for hydro power systems. Proc. IEEE CCA, pp: 1510-1515.

Kumar, A., O.P. Malik and G.S. Hope, 1985. Variable structure system control applied to AGC of an interconnected power system. IEE Proc., 132, Part C, 1: 23-29.

Kundur, P., 1994. Power System Stability and Control. McGraw-Hill.

Lim, K.Y., Y. Wang and R. Zhou, 1996. Robust decentralized load-frequency control of multi-area power systems. Proc. Inst. Elect. Eng. Gen. Transm Dist., 143: 377-386.

Liu, F., Y.H. Song, J. Ma, S. Mei and Q. Lu, 2003. Optimal load frequency control in restructured power systems. IEE Proc. Gener. Transm. Distrib., 150: 87-95.

Poulin, E. and A. Pomerleau, 1997. Unified PID design method based on a maximum peak resonance specification. IEE Proceeding Control Theory Applied, 144: 566-574.

Rahi, M.H. and A. Feliachi, 1998. H-Infinity robust decentralized controller for nonlinear power systems. Optimal Control Applications and Methods, 19: 345-361.

Rerkpreedapong, D., A. Hasanovis and A. Feliachi, 2003. Robust Load Frequency Control Using Genetic Algorithms and Linear Matrix Inequalities. IEEE Trans. Power Syst., 18: 855-861.

Saadat, H., 1999. Power System Analysis. McGraw-Hill.

Stankovic, A.M., G. Tadmor and T.A. Sakharuk, 1998. On robust control analysis and design for load frequency regulation. IEEE Trans. Power Syst., 13: 449-455.

Tang, T.C., Z.T. Ding and H. Yu, 2002. Decentralized power system load frequency control beyond the limit of diagonal dominance. Elect. Power Energy Syst., 24: 173-184.

Tripathy, S.C., P.S. Chandramohanan and R. Balasubramanium, 1998. Self tuning regulator for adaptive load frequency control of power system. J. Inst. Eng. India, EL79: 103-108.

Valk, I., M. Vajta, L. Keviczky, R. Haber and J. Hettessy, 1985. Adaptive load-frequency control of Hungrian power system. Automatica, 21: 129-137.

Vegte, V.J., 1994. Feedback Control Systems. Prentice-Hall.

Yu, Y.N., 1983. Electric Power System Dynamics. Academic Press.