Unified Tuning of PID Load Frequency Controller for Power Systems via IMC

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***Abstract*—A unified PID tuning method for load frequency control (LFC) of power systems is discussed in this paper. The tuning method is based on the two-degree-of-freedom (TDF) internal model control (IMC) design method and a PID approximation procedure. The time-domain performance and robustness of the resulting PID controller is related to two tuning parameters, and robust tuning of the two parameters is discussed. The method is applicable to power systems with non-reheated, reheated, and hydro turbines. Simulation results show that it can indeed improve the damping of the power systems. It is shown that the method can also be used in decentralized PID tuning for multi-area power systems.**

***Index Terms*—Decentralized control, internal model control (IMC), load frequency control (LFC), PID tuning, robustness.**

I. Introduction

The problem of controlling the real power output of generating units in response to changes in system frequency and tie-line power interchange within specified limits is known as load frequency control (LFC) [1]. Due to the increased complexity of modern power systems, advanced control methods were proposed in LFC, e.g., optimal control [2]–[4]; variable structure control [5]; adaptive and self-tuning control [6], [7]; intelligent control [8], [9]; and robust control [10]–[14]. Recently, LFC under new deregulation market [16], [17], LFC with communication delay [18], and LFC with new energy systems [19], [20] received much attention. See [21] and [22] for a complete review of recent philosophies in AGC. Improved performance might be expected from the advanced control methods, however, these methods require either information on the system states or an efficient online identifier, thus may be difficult to apply in practice.

Meanwhile, PI or PID controllers for LFC were studied due to their simplicity in execution. References [23] and [24] suggested fuzzy PI controllers for load frequency control of power systems; [25] proposed a derivative structure which can achieve better noise-reduction than a conventional practical differentiator thus load frequency controller of PID type can be used in LFC; [26] proposed a PID load frequency controller tuning method for a single-machine infinite-bus (SMIB) system based on the PID tuning method proposed in [27], and the method is extended to two-area case [28]. It is shown that the resulted PID setting needs to be modified to achieve desired performance. However, the reason for such a modification is not clear.

In this paper, a unified method to design and tune PID load frequency controller for power systems with non-reheat, reheat and hydro turbines will be discussed. The method is based on internal model control method and is flexible in that the performance and robustness of the closed-loop systems are related to two tuning parameters. The method will also be extended to multi-area power systems.

All the symbols used in the paper are standard in power system control and are explained in Table I.

TABLE I
NOMENCLATURE

ΔP_d	load disturbance (p.u.MW)
K_P	electric system gain
T_P	electric system time constant (s)
T_T	turbine time constant (s)
T_G	governor time constant (s)
R	speed regulation due to governor action (Hz/p.u.MW)
T_r	constant of reheat turbine
c	percentage of the power generated in the reheat portion
T_w	time constant of hydro turbine
$\Delta f(t)$	incremental frequency deviation (Hz)
$\Delta P_G(t)$	incremental change in generator output (p.u.MW)
$\Delta X_G(t)$	incremental change in governor valve position

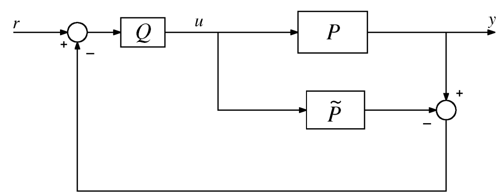

Fig. 1. IMC configuration.

II. IMC Design

Here we adopt an internal model control (IMC) method for load frequency controller design. IMC is a popular control structure in process control [29]. The IMC structure is shown in Fig. 1, where P is the plant to be controlled, $\tilde{P}$ is the plant model, and Q is the IMC controller to be designed.

The IMC design procedure goes as follows [29].

1) Decompose the plant model $\tilde{P}$ into two parts:

$$\tilde{P}(s) = P_M(s)P_A(s) \tag{1}$$

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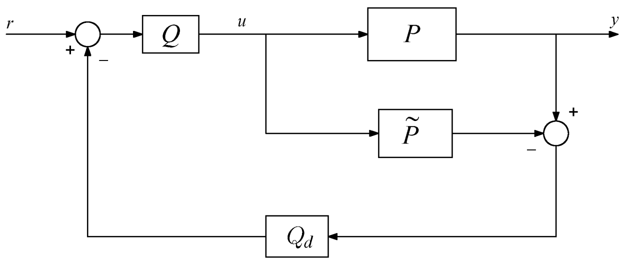

Fig. 2. TDF-IMC configuration.

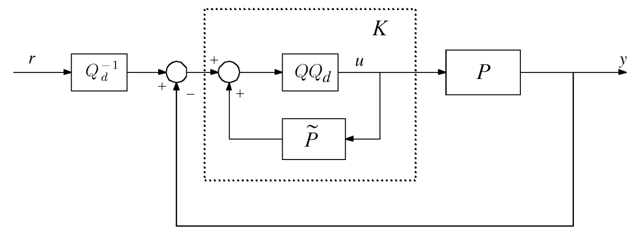

Fig. 3. Equivalent conventional feedback configuration.

where $P_M(s)$ is the minimum-phase (invertible) part and $P_A(s)$ is the allpass (nonminimum-phase with unity magnitude) part.

2) Design a setpoint-tracking IMC controller

$$Q(s) = P_M^{-1}(s)\frac{1}{(\lambda s+1)^r} \tag{2}$$

where λ is a tuning parameter such that the desired setpoint response is $1/(\lambda s + 1)^r$, and r is the relative degree of $P_M(s)$.

It is shown that IMC control can achieve very good tracking performance. However, the load disturbance rejection performance sometimes is not satisfactory. So a second controller is added to improve the disturbance-rejection performance. The TDF-IMC structure is shown in Fig. 2, and the design of Q_d goes as follows:

Design a disturbance-rejecting IMC controller of the form

$$Q_d(s) = \frac{\alpha_m s^m + \cdots + \alpha_1 s + 1}{(\lambda_d s + 1)^m} \tag{3}$$

where λ_d is a tuning parameter for disturbance rejection, m is the number of poles of $\tilde{P}(s)$ such that the $Q_d(s)$ needs to cancel. Suppose $p_1, \cdots, p_m$ are the poles to be canceled, then $\alpha_1, \cdots, \alpha_m$ should satisfy

$$\left(1 - \tilde{P}(s)Q(s)Q_d(s)\right)\Big|_{s=p_1,\cdots,p_m} = 0. \tag{4}$$

It can be shown that the TDF-IMC structure is equivalent to the conventional TDF feedback structure shown in Fig. 3, where the feedback controller K equals

$$K = \frac{QQ_d}{1 - \tilde{P}QQ_d}. \tag{5}$$

Direct implementation of IMC structure requires high-order transfer function understanding if the plant model $\tilde{P}$ is of high-order, which is the case in load frequency control for power systems as we will discuss in next section. So we would like to transfer the structure to conventional PID control structure, since PID control is easy to implement and maintain in practice.

The standard procedure for obtaining PID parameters from IMC controllers is to expand the final controller (5) into Maclaurin series and get the coefficients of the first three terms. The procedure can be obtained from the IMCTUNE package [30]. We have proposed a new method to approximate any high-order controller with PID in the frequency domain [31]. The procedure goes as follows.

1) Given any controller $K(s)$, get a frequency range of interest, compute the frequency response of $K(s)$.
2) Find the frequency ω_z such that the magnitude of $K(j\omega)$ achieves its minimum value.
3) Then the approximated PID is

$$K_{\mathrm{PID}}(s) = K_p + \frac{K_i}{s} + K_d s \tag{6}$$

with

$$\begin{aligned} K_p &= \text{Real part of } K(j\omega_z) \\ K_i &= |K(j\omega_s)|\,\omega_s \\ K_d &= K(j\omega_z) - K_i/(j\omega_z) \end{aligned} \tag{7}$$

where ω_s is any frequency that is small (say $\omega_s = 0.001$). The procedure amounts to approximating $K(s)$ by a PID controller with the same integral action and the lowest turning point, and the resulted PID controller retains the magnitude of the IMC controller at low to medium frequency range, thus the load-rejecting performance will be guaranteed close to that of the TDF-IMC controller.

From the design practice, it is noted that the above approximation procedure works well for stable processes, however, for lightly-damped and unstable processes, an additional lead compensator may be needed to cascade with the PID controller to retain the performance of the high-order controller, i.e., the final controller should be in the form

$$K_{\mathrm{PIDm}}(s) = \left(K_p + \frac{K_i}{s} + K_d s\right)\frac{\alpha s + 1}{\beta s + 1}. \tag{8}$$

The parameters of the lead compensator $(\alpha s+1)/(\beta s+1)$ are determined by approximating the phase of the $K_{\mathrm{PIDm}}(s)$ with that of the original controller at a certain frequency. We find that the frequency where the original controller achieve its maximum phase is a proper choice, so the procedure to determine α and β goes as follows (continue from the above procedure):

4) Find the frequency ω_p such that the phase of $K(j\omega)$ achieves its maximum value.

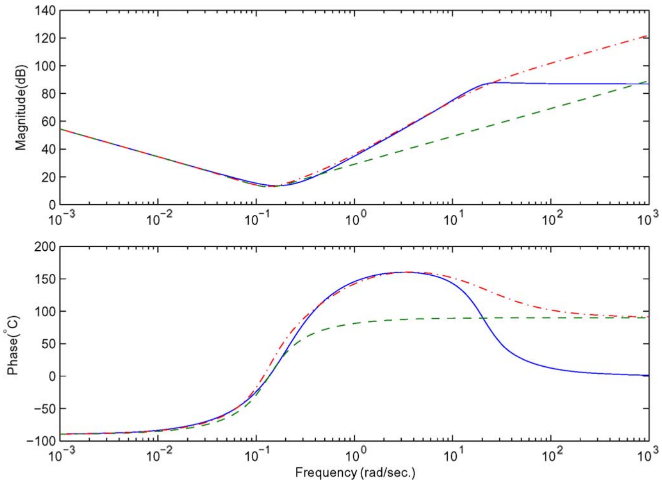

Fig. 4. Magnitude of IMC controller and PID controller (solid: IMC; dashed: PID; dashdotted: PID+lead).

5) Let

$$\phi_m = \angle K(j\omega_p) - \angle K_{\mathrm{PID}}(j\omega_p). \tag{9}$$

So ϕ_m is the phase advance between the original controller and the approximated PID controller at ω_p.

6) If $\phi_m < 0$, then it is not necessary to add the lead compensator (i.e., $\alpha = 0$, $\beta = 0$); otherwise, let

$$a = \frac{1 + \sin(\phi_m)}{1 - \sin(\phi_m)} \tag{10}$$

and set

$$\begin{aligned} \beta &= \frac{1}{\omega_p \sqrt{a}} \\ \alpha &= a\beta. \end{aligned} \tag{11}$$

The procedure is just a modification of the design of a lead compensator in frequency domain in classical control theory, which can be found in any undergraduate textbook, e.g., [32]. The Bode plot of a TDF-IMC controller for a lightly-damped, unstable plant and its PID approximations by the above procedure are shown in Fig. 4. It is observed that the magnitude and phase of a pure PID approximation are indeed close to the IMC controller at low frequency. However, the frequency range is too small (0.3 rad/s) compared with a modified PID approximation, which extends the range to 5 rad/s. So better performance can be retained.

III. LFC-PID Design

We consider the case of a single generator supplying power to a single service area, and consider three types of turbine used in generation. We are interested in tuning PID controllers to improve the performance of load frequency control system, i.e., find a control law $u = -K(s)\Delta f$, where $K(s)$ takes the form

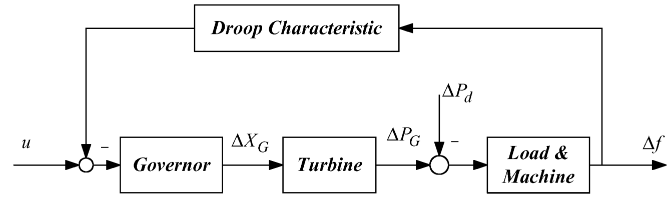

Fig. 5. Linear model of a single-area power system.

$$K(s) = K_p\left(1 + \frac{1}{T_i s} + T_d s\right). \tag{12}$$

In practice, to reduce the effect of noise, the PID controller should be implemented as a practical one

$$K(s) = K_p\left(1 + \frac{1}{T_i s} + \frac{T_d s}{N s + 1}\right) \tag{13}$$

where N is the filter constant, or implemented as suggested in [25]

$$K(s) = K_p\left(1 + \frac{1}{T_i s} + T_d \frac{1 - e^{-Ts}}{T}\right) \tag{14}$$

where T is a small sampling rate.

Since for the load-frequency control problem the power system under consideration is expressed only to relatively small changes in load, it can be adequately represented by the linear model shown in Fig. 5 (obtained by linearizing the plant around the operating point [1]).

The droop characteristic is a feedback gain to improve the damping properties of the power system, and it is generally set to $1/R$ before load frequency control design. So there are two alternatives for LFC design, i.e.,

1) Design controller $\tilde{K}(s)$ for the power system without droop characteristic, and then subtract $1/R$ from $\tilde{K}(s)$, i.e., the final controller will be

$$K(s) = \tilde{K}(s) - 1/R. \tag{15}$$

If $\tilde{K}(s)$ is of PID type, then the final proportional gain of the PID controller just needs to be decreased by $1/R$.

2) Design controller $K(s)$ directly for the power system with droop characteristic.

The model dynamics for the two cases are different so the final result might be different if the tuning parameters are not carefully chosen. We will discuss the two alternatives in detail.

A. LFC Design Without Droop Characteristic

1) Non-Reheated Turbine: The plant for a power system with a non-reheated turbine consists of three parts:

- Governor with dynamics:

$$G_g(s) = \frac{1}{T_G s + 1}. \tag{16}$$

- Turbine with dynamics:

$$G_t(s) = \frac{1}{T_T s + 1}. \tag{17}$$

- Load and machine with dynamics:

$$G_p(s) = \frac{K_P}{T_P s + 1}. \tag{18}$$

Now the open-loop transfer function without droop characteristic for load frequency control is

$$\begin{aligned}\tilde{P}(s) &= G_p G_t G_g \\ &= \frac{K_P}{(T_P s + 1)(T_T s + 1)(T_G s + 1)}.\end{aligned} \tag{19}$$

From the TDF-IMC-PID design procedure, since $\tilde{P}$ is minimum-phase, the setpoint-tracking IMC controller takes the form

$$\begin{aligned}Q(s) &= \tilde{P}^{-1}(s)\frac{1}{(\lambda s + 1)^3} \\ &= \frac{(T_P s + 1)(T_T s + 1)(T_G s + 1)}{K_P(\lambda s + 1)^3}.\end{aligned} \tag{20}$$

To improve the disturbance response another degree-of-freedom $Q_d(s)$ is used. From Fig. 5, we observe that the load demand $\Delta P_d(s)$ must pass through $K_P/(T_P s + 1)$ to affect the frequency deviation $\Delta f(s)$, in order to have a fast disturbance rejection, we choose $Q_d(s)$ to cancel the pole $s = -(1/T_p)$. Let

$$Q_d(s) = \frac{\alpha_1 s + 1}{\lambda_d s + 1} \tag{21}$$

then α_1 should satisfy

$$\begin{aligned}&\left(1 - \tilde{P}(s)Q(s)Q_d(s)\right)\Big|_{s=-\frac{1}{T_P}} \\ &= \left(1 - \frac{\alpha_1 s + 1}{(\lambda s + 1)^3(\lambda_d s + 1)}\right)\Bigg|_{s=-\frac{1}{T_P}} = 0\end{aligned} \tag{22}$$

that is

$$\alpha_1 = T_P\left(1 - \left(1 - \frac{\lambda}{T_P}\right)^3\left(1 - \frac{\lambda_d}{T_P}\right)\right). \tag{23}$$

By choosing suitable parameters λ and λ_d, TDF-IMC controllers $Q(s)$ and $Q_d(s)$ can be obtained from (20) and (21), and the corresponding PID controller can be obtained by the procedure described in the previous section.

2) Reheated Turbine: For reheated turbines, the turbine dynamics becomes

$$G_t(s) = \frac{cT_r s + 1}{(T_r s + 1)(T_T s + 1)} \tag{24}$$

where T_r is a constant and c is the portion (percentage) of the power generated by the reheat process in the total generated power. In such case the open-loop transfer function without droop characteristic becomes

$$\begin{aligned}\tilde{P}(s) &= G_p G_t G_g \\ &= \frac{K_P(cT_r s + 1)}{(T_P s + 1)(T_T s + 1)(T_r s + 1)(T_G s + 1)}\end{aligned} \tag{25}$$

and the setpoint-tracking IMC takes the form

$$Q(s) = \frac{(T_P s + 1)(T_T s + 1)(T_r s + 1)(T_G s + 1)}{K_P(cT_r s + 1)(\lambda s + 1)^3}. \tag{26}$$

The disturbance-rejecting IMC Q_d has the same structure (21) as the non-reheat turbine case, and α_1 can be computed in the same way as in (23).

3) Hydro Turbine: For hydro turbines, the turbine dynamics is

$$G_t(s) = \frac{1 - T_w s}{1 + 0.5T_w s} \tag{27}$$

where T_w is a constant. In this case the open-loop transfer function without droop characteristic becomes

$$\begin{aligned}\tilde{P}(s) &= G_p G_t G_g \\ &= \frac{K_P(1 - T_w s)}{(T_P s + 1)(0.5T_w s + 1)(T_G s + 1)}.\end{aligned} \tag{28}$$

Now the transfer function contains a right-half-plane zero, so the setpoint-tracking IMC takes the form

$$Q(s) = \frac{(T_P s + 1)(0.5T_w s + 1)(T_G s + 1)}{K_P(T_w s + 1)(\lambda s + 1)^2}. \tag{29}$$

The disturbance-rejecting IMC has the same structure (21) as the non-reheat turbine case, however, in this case the parameter α_1 must satisfy

$$\alpha_1 = T_P\left(1 - \left(1 - \frac{\lambda}{T_P}\right)^2\left(1 - \frac{\lambda_d}{T_P}\right) / \left(1 + \frac{T_w}{T_P}\right)\right). \tag{30}$$

B. LFC Design With Droop Characteristic

In this case the plant model used in LFC design is

$$P(s) = \frac{G_g G_t G_p}{1 + G_g G_t G_p / R} \tag{31}$$

where G_g is the governor dynamics (16), G_p is the load and machine dynamics (18), and G_t is the turbine dynamics [(17) for non-reheated turbines, (24) for reheated turbines, and (27) for hydro turbines].

Unlike $\tilde{P}(s)$ discussed in the previous subsection, which has a non-oscillatory step response for all kinds of turbines, the step response of $P(s)$ is generally oscillatory, even unstable in some cases for hydro turbines, so the LFC design is more complicated. In [31], it was shown that for LFC tuning purpose, the transfer function of the power systems can be approximated with a second-order oscillatory model, and a PID tuning procedure can be done based on the TDF-IMC method. We note that the approximation to a second-order model is not necessary, and the process only works well for power systems with non-reheated turbine.

Here we can directly apply the TDF-IMC design method to the plant model (31). To achieve good disturbance rejection performance, we need to use Q_d to cancel the undesirable poles (e.g, oscillatory and unstable poles) of $P(s)$. MATLAB-based programs for general TDF-IMC design and PID reduction as discussed in Section II are available for such purpose.

IV. Parameter Tuning

The TDF-IMC design needs to tune two parameters (λ and λ_d) to achieve desired performance. Generally speaking, a large $\lambda(\lambda_d)$ will result a sluggish closed-loop response and good robustness against uncertainties in plant model, and a small $\lambda(\lambda_d)$ will result a fast closed-loop response and bad robustness. The tuning procedure is just a compromise between closed-loop response and robustness. The final PID controller is directly related to the two parameters, so a guideline for choosing the two parameters is of practical importance.

A. Robustness Against Plant Parameter Variation

The PID controller is tuned for the nominal systems parameters. Note that in reality the exact values of the system parameters are unknown. Instead, they are known to belong to a certain interval. We would like to tune the PID controller so that it can retain the robust stability under the specified range of parameter variation.

For example, for a power system with a non-reheated turbine, suppose the uncertain parameters are

$$\begin{aligned} &\delta_1 := 1/T_P, \quad \delta_2 := K_P/T_P, \quad \delta_3 := 1/T_T, \\ &\delta_4 := 1/RT_G, \quad \delta_5 := 1/T_G. \end{aligned} \tag{32}$$

Define the uncertainty structure "Δ" as

$$\Delta = \begin{bmatrix} \delta_1 & & & & \\ & \delta_2 & & & \\ & & \delta_3 & & \\ & & & \delta_4 & \\ & & & & \delta_5 \end{bmatrix}. \tag{33}$$

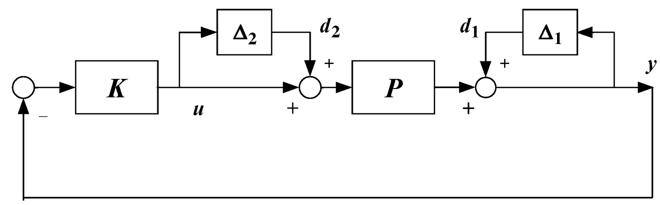

Fig. 6. Uncertainty structure of a unity feedback configuration.

By the structured singular value (SSV) theory [33], robustness against parameter variation amounts to checking whether the following condition holds:

$$\mu_\Delta(M) < 1 \tag{34}$$

where M is a suitable transfer matrix. For details, refer to [15].

The robustness analysis for power systems with reheated turbines and hydro turbines can be also done using the SSV technique. If the turbine is reheated, then the turbine model is $(cT_r s + 1)/((T_r s + 1)(T_T s + 1))$, so two other parameter (c and T_r) must be taken into account to have a detailed SSV analysis; if the turbine a hydro-turbine [with model $(1 - T_w s)/(1 + 0.5 T_w s)$], the plant model structure is different from a power system with non-reheated turbine, and the SSV analysis should take this structure information into account.

B. Robustness for General Uncertainty

It is noted that the SSV analysis procedure involves finding the detailed uncertainty structure of the plant model, it is very complex and problem-specific. To alleviate the burden, a robustness measure is proposed to evaluate the robustness of a feedback control system with a general uncertainty in [34].

The uncertainty structure is described as

$$\begin{aligned} &P_\Delta = (1 - \Delta_1)^{-1} P (1 + \Delta_2), \text{ with } \Delta_1, \Delta_2 \in H_\infty \\ &\Delta := \begin{bmatrix} \Delta_1 & 0 \\ 0 & \Delta_2 \end{bmatrix}. \end{aligned} \tag{35}$$

It represents simultaneous input multiplicative and inverse output multiplicative uncertainty. A unity feedback control system with the uncertain plant P_Δ is shown in Fig. 6.

For the uncertainty structure, robustness measure ε_m is defined as

$$\varepsilon_m := \mu_\Delta \left(\begin{bmatrix} (I + PK)^{-1} & (I + PK)^{-1} \\ -K(I + PK)^{-1} & -K(I + PK)^{-1} P \end{bmatrix} \right) \tag{36}$$

and the smaller it is, the better robustness the closed-loop can achieve. Generally speaking, the robustness measure should be less than 5. For load frequency control, since there are uncertainties in the plant model and constraints in the governor and turbine generator, large robustness is required to put the PID controller in practice. In the examples below, iterative tuning of the PID controllers is done: step responses are simulated to check if the parameters can achieve certain dynamic performance, and the robustness measure is computed to make sure that it is less than 3.

The proposed robustness measure assumes a simple and general uncertainty structure, so the measure gives a simple and good measure of robustness of the PID controllers [35].

V. Numerical Studies

A. Non-Reheated Turbine

Consider a power system with a non-reheated turbine. The model parameters are given by

$$K_P = 120,\ T_P = 20,\ T_T = 0.3,\ T_G = 0.08,\ R = 2.4. \quad (37)$$

The plant model without droop characteristic is

$$\tilde{P} = \frac{120}{(0.8s+1)(0.3s+1)(20s+1)}. \quad (38)$$

By the LFC-PID design procedure discussed in Section III, with $\lambda = 0.1$ and $\lambda_d = 0.8$, we get the following PID controller:

$$K(s) = 0.4461 + \frac{0.6202}{s} + 0.1905s. \quad (39)$$

LFC-PID can also be tuned for the plant model with droop characteristic, which is

$$P(s) = \frac{250}{s^3 + 15.88s^2 + 42.46s + 106.2}. \quad (40)$$

The model has a pair of complex poles at $-1.30 \pm 2.51j$ with damping ratio 0.459. So the response is oscillatory. The additional degree-of-freedom Q_d is used to cancel the effect of the oscillatory poles. With $\lambda = 0.1$ and $\lambda_d = 0.5$, we get the following PID controller:

$$K(s) = 0.4036 + \frac{0.6356}{s} + 0.1832s. \quad (41)$$

The responses for the tuned PID controllers with a load demand $\Delta P_d = 0.01$ are shown in Fig. 7(a). They are very close and achieve good damping performance.

For the tuned PID settings, the robustness measure ε_m's of the closed-loop systems are 2.2. They are very small which mean that the closed-loop systems with the tuned PID controllers are quite robust. To verify this, suppose the parameters of the system vary by 50%, i.e.,

$$\begin{aligned} &1/T_T \in [2.564, 4.762], \quad 1/T_G \in [9.615, 17.857] \\ &1/T_P \in [0.033, 0.1], \quad K_P/T_P \in [4, 12] \\ &1/RT_G \in [3.081, 10.639]. \end{aligned} \quad (42)$$

The robust stability chart $(\mu_\Delta(M))$ for the tuned PID controllers is shown in Fig. 8. The maximum values are less than 0.71, meaning that the closed-loop systems remain stable for the range of each parameter given in (42), and in fact at least 1/0.71 (140%) larger than the specified range, so the PID controllers are very robust against parameter variation. The responses of the system for the worst case of the parameter variations are shown in Fig. 7(b) and (c) for the tuned PID controllers. Both guarantee stability and performance of the closed-loop system under parameter variations.

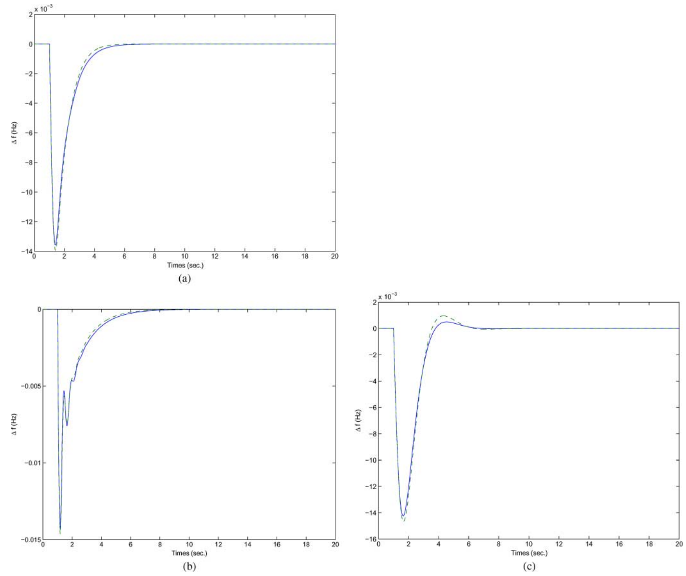

Fig. 7. Responses of a power system with non-reheat turbine [solid: PID setting (39); dashed: PID setting (41)]. (a) Nominal parameters; (b) upper bound; (c) lower bound.

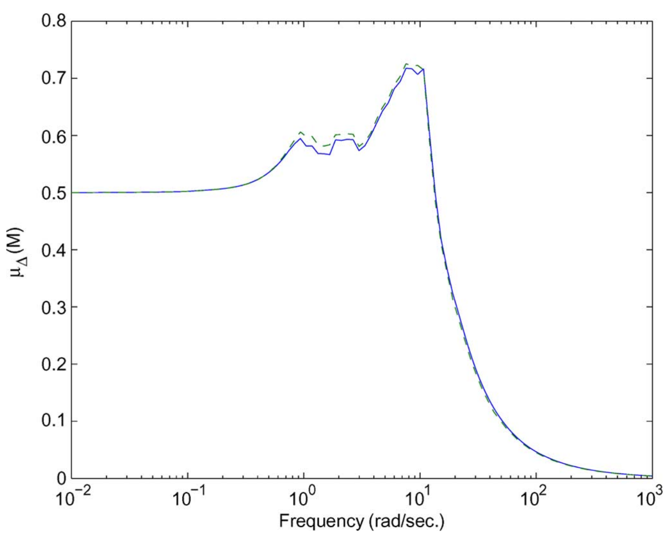

Fig. 8. SSV plot for parameter variations [solid: PID setting (39); dashed: PID setting (41)].

B. Reheated Turbine

Consider a power system with a reheated turbine. The model parameters are given by

$$\begin{aligned} &K_P = 120,\ T_P = 20,\ T_T = 0.3,\ T_G = 0.08,\ R = 2.4 \\ &T_r = 4.2,\ c = 0.35. \end{aligned} \quad (43)$$

The plant model without droop characteristic is

$$\tilde{P} = \frac{120(1.47s+1)}{(0.8s+1)(0.3s+1)(20s+1)(4.2s+1)}. \quad (44)$$

By the LFC-PID design procedure discussed in Section III, with $\lambda = 0.1$ and $\lambda_d = 0.5$, we get the following PID controller:

$$K(s) = 2.3380 + \frac{0.9301}{s} + 0.4454s. \quad (45)$$

LFC-PID can also be tuned for the plant model with droop characteristic, which is

$$P(s) = \frac{87.5s + 59.52}{s^4 + 16.12s^2 + 46.24s^2 + 48.65s + 25.3}. \quad (46)$$

The model has a pair of complex poles at $-0.665 \pm 0.739j$ with damping ratio 0.669. Again the response is oscillatory. The additional degree-of-freedom Q_d is used to cancel the effect of the oscillatory poles. With $\lambda = 0.05$ and $\lambda_d = 1.5$, we get the following PID controller:

$$K(s) = 2.7935 + \frac{1.2735}{s} + 0.7866s. \quad (47)$$

The responses for the tuned PID controllers with a load demand $\Delta P_d = 0.01$ are shown in Fig. 9(a). For the tuned PID setting, the robustness measures ε_m for PID setting (45) is 2.4, while it is 1.85 for PID setting (47), so the closed-loop systems are robust. Suppose the parameters of the system vary by 50% as in (42), the responses of the system for the tuned PID controllers are shown in Fig. 9(b) and (c). Both guarantee stability and performance of the closed-loop system under parameter variations. It is observed that due to the large constant T_r of the reheat turbine, the performance of the PID controller tuned without droop characteristic has a smaller integral action than the PID controller tuned with droop characteristic.

C. Hydro Turbine

Consider a hydro-turbine power system with the following parameters:

$$K_P = 1,\ T_P = 6,\ T_w = 4,\ T_G = 0.2,\ R = 0.05. \quad (48)$$

The plant model without droop characteristic is

$$\tilde{P} = \frac{(1-4s)}{(0.2s+1)(2s+1)(6s+1)}. \quad (49)$$

By the LFC-PID design procedure discussed in Section III, with $\lambda = 0.1$ and $\lambda_d = 5$, we get the following PID controller:

$$K(s) = -18.9439 + \frac{0.1353}{s} + 1.6855s. \quad (50)$$

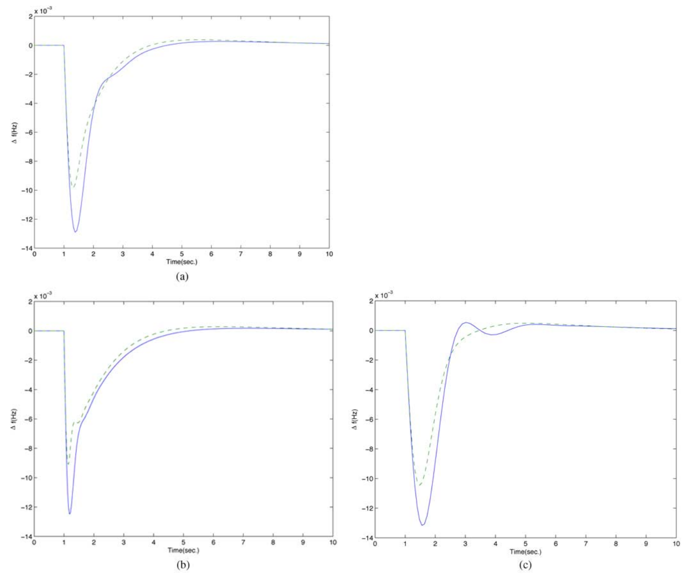

Fig. 9. Responses of power systems with reheat turbine [solid: PID setting (45); dashed: PID setting (47)]. (a) Nominal parameters. (b) Upper bound. (c) Lower bound.

The proportional gain is negative since a large positive proportional gain $1/R = 20$ exists in the feedback loop. The "real" proportional gain for the feedback system is $-18.9439 + 1/R = 1.0561$.

LFC-PID can also be tuned for the plant model with droop characteristic, which is

$$P(s) = \frac{-1.667s + 0.4167}{s^3 + 5.667s^2 - 29.92s + 8.75}. \quad (51)$$

The model has two unstable poles at 0.312 and 3.09. The additional degree-of-freedom Q_d is used to cancel the two unstable poles. With $\lambda = 0.1$ and $\lambda_d = 3$, we get the following PID controller:

$$K(s) = -18.8558 + \frac{0.1523}{s} + 1.8124s. \quad (52)$$

The responses for the tuned PID controllers with a load demand $\Delta P_d = 0.01$ are shown in Fig. 10(a). Also shown are the response of the PID controller ($K_p = -19.017$, $K_i = 0.122$, $K_d = 1.5$) tuned in [14] (the integral gain was manually increased from 0.122 to 0.14 to improve performance). The two tuned PID controllers achieve comparable performance with the one in [14] without a manual re-tuning.

For the tuned PID setting, the robustness measure ε_m's of the closed-loop systems with the tuned PID controllers are less than 3.9, which guarantee that the closed-loop systems are reasonably robust. Suppose the constant T_w of the hydro turbine varies by 50%, the responses of the system for the three controllers are shown in Fig. 10(b) and (c). Stability and performance of the closed-loop system under parameter variation are guaranteed.

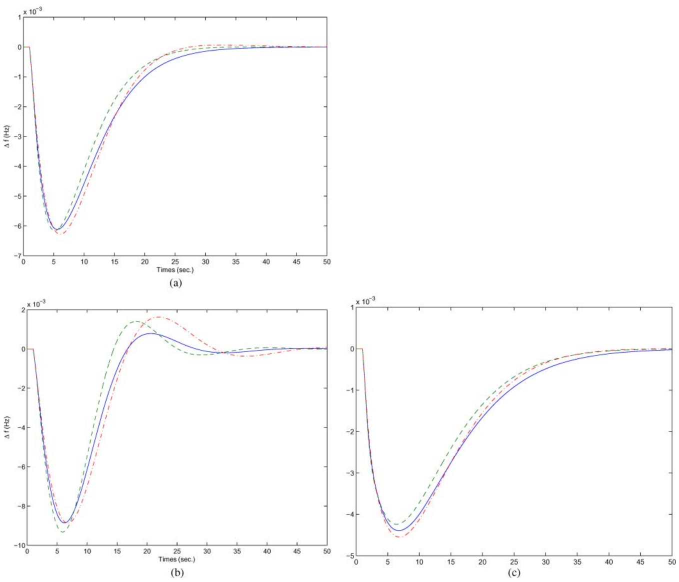

Fig. 10. Responses of a power system with hydro turbine (solid: PID setting (50); dashed: PID setting (52); dashdotted: [14]). (a) Nominal parameters;.(b) $T_w = 6$. (c) $T_w = 2$.

D. Discussions

From the examples above, it is noted that PID tuning can be done with or without first taking the droop characteristic into consideration. Both methods can achieve comparable performances if the tuning parameters are carefully chosen. In fact, the two methods are equivalent in theory, however, due to the PID approximation, the final performance may be different, as in the reheated-turbine case. The method without first considering droop characteristic is simpler in that the open-loop plant model is always stable and non-oscillatory, however, it lacks flexibility if the model is not in the standard form (e.g., there are several different generation units in a single area). On the contrary, the method with considering the droop characteristic first is applicable to all cases, and with careful selection of the tuning parameters, the method can achieve better performance than the method without droop characteristic consideration. Thus it can be a unified PID tuning method, and it is the preferred method in the decentralized PID tuning that will be discussed in the next section.

VI. Decentralized PID Tuning

The tuning of PID load frequency controller can be extended to multi-area case. The difference between LFC of multi-area and that of single area is that not only should the frequency of each area return to its nominal value but 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. For area i, the ACE is defined as (referred to Fig. 11)

$$\mathrm{ACE}_i = \Delta P_{\mathrm{tie}i} + B_i \Delta f_i \tag{53}$$

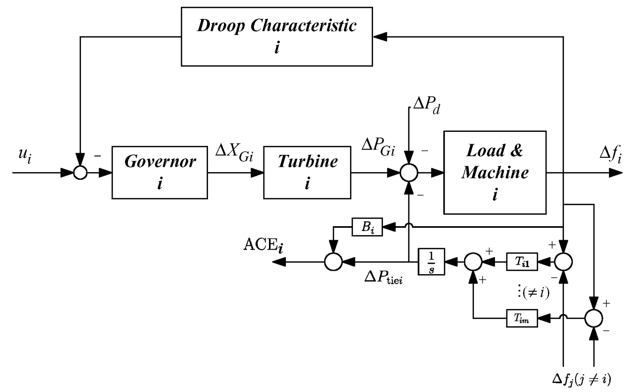

Fig. 11. Block diagram of control area i.

where B_i is the frequency bias setting, and the feedback control for area i takes the form

$$u_i = -K_i(s)\mathrm{ACE}_i. \tag{54}$$

A decentralized controller can be tuned assuming that there is no tie-line exchange power, i.e., $\Delta P_{\mathrm{tie}i} = 0$. In this case the local feedback control will be

$$u_i = -K_i(s) B_i \Delta f_i. \tag{55}$$

So it is clear that to tune a decentralized load frequency controller, one just needs to multiply the plant model (31) by the local bias coefficient B_i, and then follow the same procedure as in single-area LFC-PID tuning, i.e., tune PID controller for

$$P_i(s) = \frac{G_{gi} G_{ti} G_{pi}}{1 + G_{gi} G_{ti} G_{pi}/R_i} B_i. \tag{56}$$

Thus load frequency controller for each area can be tuned independently.

However, since there is coupling among areas, the tuning parameters for each area should take this into consideration. The robustness of the closed-loop system against the tie-line operation can be checked using the SSV technique. The procedure for two-area power system is discussed in detail in [31]. For multi-area case, the procedure is much complex, and further investigation should be made.

To illustrate the decentralized PID tuning method, consider a four-area power system studied in [37] (Fig. 12). Area 1, 2, 3 are identical systems with reheated turbines. The parameters are

$$\begin{aligned} T_{Gi} &= 0.2,\ T_{Ti} = 0.3,\ T_{Pi} = 20,\ K_{Pi} = 120, \\ R_i &= 2.4,\ T_{ri} = 20,\ c_i = 0.333 \quad (i = 1, 2, 3). \end{aligned} \tag{57}$$

Area 4 is a power system with hydro turbine, with the open-loop plant model given by

$$G_g G_t G_p = \frac{1}{48.7s + 1} \frac{0.513s + 1}{10s + 1} \frac{1 - s}{1/2s + 1} \frac{80}{13s + 1} \tag{58}$$

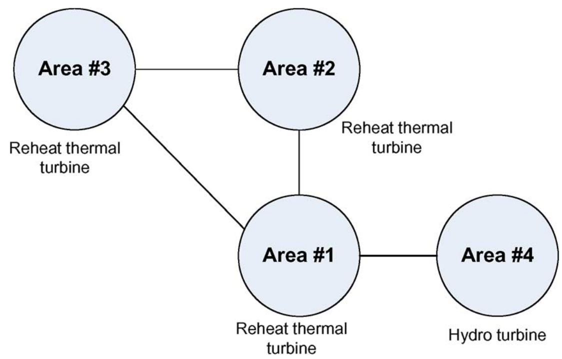

Fig. 12. Simplified diagram of a four-area power system.

and $R = 2.4$. The synchronizing constants are

$$T_{12} = T_{13} = T_{14} = T_{23} = 0.0707 \tag{59}$$

and the frequency bias constants B_i ($i = 1, 2, 3, 4$) are 0.425 for each area.

The procedure of PID tuning for Area 1,2,3 is the same as before, except the open-loop plant model must be multiplied by B_i ($i = 1, 2, 3$). With $\lambda = 0.1$, $\lambda_d = 1$, we get the following PID controllers:

$$K_i(s) = 2.4457 + \frac{1.5847}{s} + 1.5261s \quad (i = 1, 2, 3). \tag{60}$$

For Area 4, the open-loop plant model with droop characteristic is

$$P = \frac{-0.00551s^2 - 0.005231s + 0.01074}{s^4 + 2.197s^3 + 0.4008s^2 + 0.01768s + 0.01085}. \tag{61}$$

It has two lightly-damped unstable poles at $0.0294 \pm 0.143j$ with damping ratio -0.202. So besides the PID controller, a lead compensator is cascaded to improve the system performance. With $\lambda = 0.5$, $\lambda_d = 25$, we get the following modified PID controller:

$$K_4(s) = \left(0.1456 + \frac{0.0216}{s} + 18.7715s\right)\frac{3.8787s + 1}{0.03919s + 1}. \tag{62}$$

Fig. 4 given in Section II compares the Bode plot of the IMC controller and its PID approximation with or without the lead compensator. It is clear that the PID with lead compensator is closer to the original IMC controller in a wider frequency range.

To show the performance of the decentralized PID controller, a step load $\Delta P_{d1} = 0.01$ is applied to Area 1 at $t = 0$ and a step load $\Delta P_{d3} = 0.01$ is applied to Area 3 at $t = 100$. The responses of the system are shown in Figs. 13 and 14. It is observed that the PID setting with lead compensator achieves better performance than that without lead compensator.

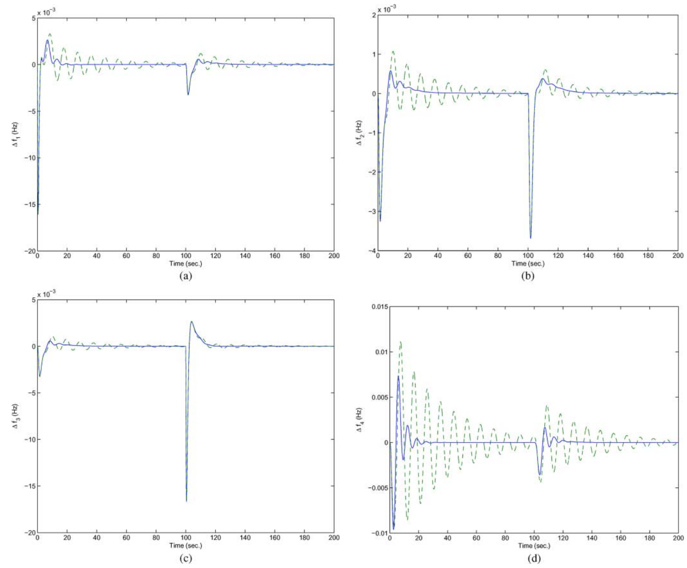

Fig. 13. Frequency deviation of the four-area power system (solid: with lead compensator at Area 4; dashed: without lead compensator at Area 4). (a) Δf_1. (b) Δf_1. (c) Δf_3. (d) Δf_4.

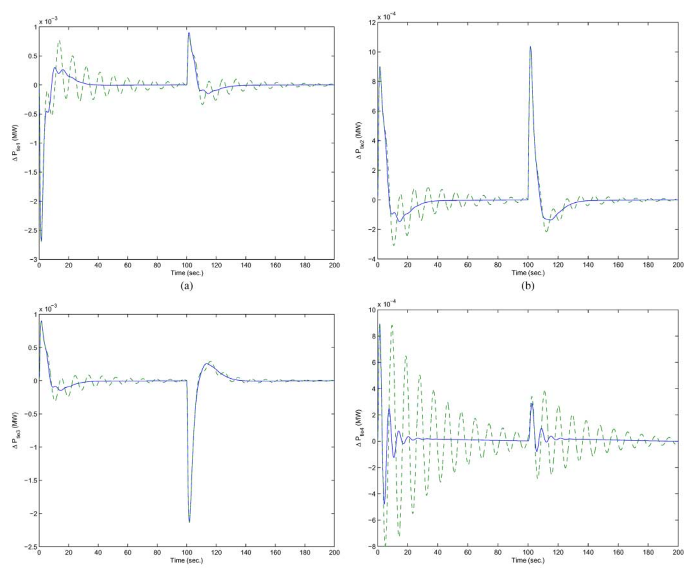

Fig. 14. Tie-line power of the four-area power system (solid: with lead compensator at Area 4; dashed: without lead compensator at Area 4). (a) ΔP_{tie1}. (b) ΔP_{tie2}. (c) ΔP_{tie3}. (d) ΔP_{tie4}.

VII. Conclusions

A unified two-degree-of-freedom IMC design for load frequency control of power systems with non-reheated, reheated, and hydro turbines was studied. The additional degree-of-freedom was set to cancel the effect of the undesired poles of the disturbance, thus the disturbance attenuation performance of the closed-loop system was improved. With the aid of a PID approximation procedure, PID-type load frequency controllers were obtained. Simulation results for single-area and multi-area power systems showed that the PID tuning method is flexible and the performance and robustness of the closed-loop system could be compromised with two tuning parameters. Further research on checking the robustness of multi-area systems and on decentralized PID tuning considering the tie-line interchange power is under progress.

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