Load Frequency Control in Power Systems via Internal Model Control Scheme and Model-Order Reduction

Sahaj Saxena, *Student Member, IEEE*, and Yogesh V. Hote, *Member, IEEE*

***Abstract*—The large-scale power systems are liable to performance deterioration due to the presence of sudden small load perturbations, parameter uncertainties, structural variations, etc. Due to this, modern control aspects are extremely important in load frequency control (LFC) design of power systems. In this paper, the LFC problem is illustrated as a typical disturbance rejection as well as large-scale system control problem. For this purpose, simple approach to LFC design for the power systems having parameter uncertainty and load disturbance is proposed. The approach is based on two-degree-of-freedom, internal model control (IMC) scheme, which unifies the concept of model-order reduction like Routh and Padé approximations, and modified IMC filter design, recently developed by Liu and Gao [24]. The beauty of this paper is that in place of taking the full-order system for internal-model of IMC, a lower-order, i.e., second-order reduced system model, has been considered. This scheme achieves improved closed-loop system performance to counteract load disturbances. The proposed approach is simulated in MATLAB environment for a single-area power system consisting of single generating unit with a non-reheated turbine to highlight the efficiency and efficacy in terms of robustness and optimality.**

***Index Terms*—Internal model control (IMC), load frequency control (LFC), model-order reduction, robustness.**

Nomenclature of Power System Parameters

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).
$\Delta f(t)$	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.

Manuscript received May 21, 2012; revised June 07, 2012, August 31, 2012, November 27, 2012, and January 29, 2013; accepted January 30, 2013. Date of publication March 07, 2013; date of current version July 18, 2013. Paper no. TPWRS-00543-2012.

The authors are with the Indian Institute of Technology Roorkee, Roorkee, Uttarakhand, India (e-mail: sahajsaxena11@gmail.com; yhotefee@iitr.ernet.in).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TPWRS.2013.2245349

I. Introduction

With the rapid progress in electric power technology, the whole power system has become a complex unit. Generation, transmission, and distribution systems are installed in various areas which are generally interconnected to their neighboring areas through transmission lines called tie-lines. In such web of interconnected power systems, both area frequency and tie-line power interchange fluctuations occur frequently just because of randomness in power load demand, system parameter uncertainties, modeling errors, and disturbance due to varying environmental conditions. So, the stability of power system is essential to maintain synchronism and prescribed voltage levels, in case of any transient disturbances like faults, line trips, or any overload. In this context, load frequency control (LFC) is responsible for providing efficient and reliable power generation in an electrical energy system and tie-line power interchange. The principle roles of LFC for power systems are: 1) maintaining zero steady state errors for frequency deviations, 2) counteracting sudden load disturbances, 3) minimizing unscheduled tie-line power flows between neighboring areas and transient variations in area frequency, 4) coping up with modeling uncertainties and system nonlinearities within a tolerable region, and 5) guaranteeing ability to perform well under prescribed overshoot and settling time in frequency and tie-line power deviations [1], [2]. Thus, LFC can be considered as an objective optimization and robust control problem.

Many control strategies like integral control [3], discrete time sliding mode control [4], optimal control [5], intelligent control [6], [7], adaptive and self-tuning control [8], [9], PI/PID control [10], IP control [11], and robust control [12], [13] have been reported in the literature as an existing LFC solution. It is observed in power systems that the parameter values in the various power generating units like governors, turbines, generators, etc., fluctuate depending on system and power flow conditions which change almost every minute. Therefore, parameter uncertainty is an important issue for the choice of control technique. Hence, a robust strategy for LFC is required which takes care of both the uncertainties in system parameters and disturbance rejection.

II. Motivation and Problem Statement

In order to design a robust controller for LFC problem, various control strategies as mentioned in the introduction section are useful. However, one class of strongly directional control strategy that has received extensive research in electric power components and process engineering is internal model control (IMC) [14]–[18]. This class of control technique is known to exhibit robustness, sub-optimality, less computational burden, and analytical as well as easily understandable approach. However, IMC has a little edge in comparison to aforementioned techniques with reference to command following and disturbance rejection. In literature, it is reported that it is also possible to optimise system performance for load disturbance rejection without sacrificing nominal set-point tracking using two-degree-of-freedom (TDF) IMC [19]–[21].

As far as power system is concerned, one issue is that the inter connection of power systems result in huge increase in both the order of the system and number of controllers. With the ever-growing complexity of power systems in the electricity generation industry, formation of reduced-order models of these large-scale systems are extremely important. So in such cases, model-order reduction plays an important role in simplifying the design and implementation of the control systems. Moreover, as the size of model reduces, its computational complexity, size, and cost reduces. In [22], [23], Tan has proposed a robust IMC based PID controller for LFC in single-area power systems, and reported that a third-order single-area power plant when approximated by second-order plus dead-time (SOPDT) model, can also fulfil the control objectives in a satisfactory manner. So, this work motivated us to propose the IMC based controller using model-order reduction scheme for internal-model of a plant. Therefore, in present study, a new control strategy for LFC is proposed which is a combination of modified IMC filter design and model-order reduction technique. Such designed controller is capable of handling plant/model mismatches and parameter uncertainties. The main advantage of this approach is that the proposed controller provides faster disturbance rejection, and brings robust and optimal performance.

More specifically, we aim to accomplish the following research objectives:

1) Reduce the order of single-area power system having non-reheated type turbine. For simplicity, model-order reduction scheme of Padé [25] and Routh approximations [26] are applied. These reduced order models are treated as internal (predictive) models for IMC structure.
2) Consider TDF-IMC structure to optimize the performance of system for load disturbance rejection. The structure and proposed controller synthesis scheme is employed to demonstrate the effectiveness of utilizing reduced order models.
3) Conduct a robust study by inserting 50% perturbation uncertainty in each parameter, simultaneously. Evaluate optimal performance and robustness of the control systems in terms of integral error criterion and closed-loop complementary sensitivity function with process multiplicative uncertainty (error), respectively.

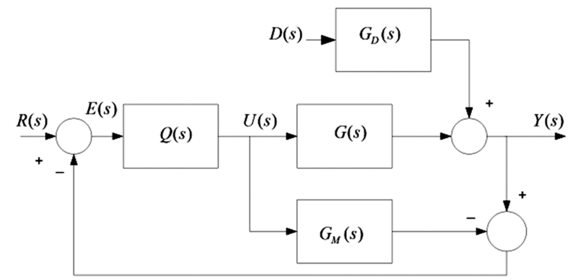

Fig. 1. Basic IMC structure.

III. IMC Theory and Model Order Reduction

The schematic representation of IMC structure is presented in Fig. 1. The structure is characterized by a control device consisting of the feedback controller $Q(s)$, the real plant to be controlled $G(s)$, and a predictive model of the plant, i.e., the internal-model $G_M(s)$. The internal-model loop uses the difference between the outputs of $G(s)$ and $G_M(s)$. This difference commonly known as an error, represents the effect of disturbances $D(s)$ and plant/model mismatch if exists.

The two-step procedure for designing IMC controller is

1) Factor the model as

$$G_M(s) = G_{M+}(s)G_{M-}(s) \tag{1}$$

such that $G_{M+}(s)$ is a non-minimum phase part and $G_{M-}(s)$ is a minimum phase.

2) Define the IMC controller as

$$Q(s) = G_{M-}^{-1}(s)F(s) \tag{2}$$

where $F(s)$ is a low-pass filter, commonly of the form

$$F(s) = (1+\lambda s)^{-n}. \tag{3}$$

In (3), λ is a tuning parameter, which adjusts the speed of response of a closed-loop system, and also removes plant/model mismatch which generally occurs at high frequency, thus responsible for robustness. n is an integer, chosen such that $Q(s)$ becomes proper/semi-proper for physical realization.

A. Two-Degree-of-Freedom IMC Controller

IMC scheme is based on pole-zero cancellation. It can achieve very good tracking ability; however, the response to disturbance rejection may be sluggish. So, a trade-off is required, where the performance for load disturbance rejection occurs by sacrificing set-point tracking. To avoid this problem, two different controllers $Q_D(s)$ and $Q_1(s)$, as shown in Fig. 2, are introduced in basic IMC structure [24]. Now, the set-point response and disturbance response of the modified IMC structure namely TDF-IMC, can be improved, and each controller can be tuned independently.

In this presented work, we have considered the TDF-IMC structure as shown in Fig. 2, and applied the design scheme recently developed by Liu and Gao [24]. In Fig. 2, we can define $Q_D(s)$ as a disturbance rejection filter (feedback controller) and $Q_1(s)$ as a set-point filter. The closed-loop complementary sensitivity function $T(s)$ and multiplicative error $\varepsilon(s)$ which is a

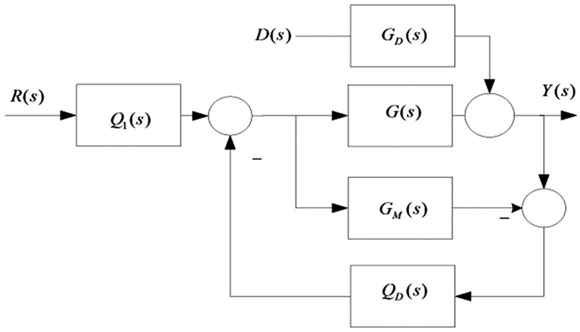

Fig. 2. TDF-IMC structure.

measure of plant/model mismatch can be defined, respectively, by

$$T(s) = Q_D(s)G_M(s) \tag{4}$$

and

$$\varepsilon(s) = \frac{(G(s) - G_M(s))}{G_M(s)}. \tag{5}$$

Since an effective IMC filter suggested in [24] is adopted to design IMC based controller for second-order internal-model of a system, therefore, $F(s)$ of the form (3) is replaced by a modified filter $F'(s)$ such that

$$F'(s) = \frac{(\psi s^2 + \theta s + 1)}{(\lambda_f s + 1)^x} \tag{6}$$

where $x = 3$ or 4, depending upon the requirement to make controller proper. On substituting (6) into (2), the TDF-IMC controller can be derived as

$$Q_D(s) = \frac{G_{M-}^{-1}(s)(\psi s^2 + \theta s + 1)}{(\lambda_f s + 1)^x} \tag{7}$$

where ψ, θ should satisfy the following condition for each pole, p_1 and p_2 of the second-order system:

$$\lim_{s \to -p_i} (1 - T(s)) = 0, \quad \forall i = 1, 2. \tag{8}$$

Substituting (1) and (7) in (4), we get

$$T(s) = \frac{G_{M+}(s)(\psi s^2 + \theta s + 1)}{(\lambda_f s + 1)^x}. \tag{9}$$

Now, from (9), three cases arises for $G_{M+}(s)$:

1) *Case I*: When $G_{M+}(s)$ contains delay term only, i.e., $G_{M+}(s) = e^{-\sigma s}$, then put $x = 4$, and by substituting (9) into (8), we get

$$\psi = \frac{p_1 e^{-\sigma p_2}(p_2\lambda_f - 1)^4 - p_2 e^{-\sigma p_1}(p_1\lambda_f - 1)^4 - p_1 + p_2}{p_1 p_2 (p_2 - p_1)} \tag{10}$$

$$\theta = \frac{p_1^2 e^{-\sigma p_2}(p_2\lambda_f - 1)^4 - p_2^2 e^{-\sigma p_1}(p_1\lambda_f - 1)^4 - p_1^2 + p_2^2}{p_1 p_2 (p_2 - p_1)}. \tag{11}$$

2) *Case II*: When $G_{M+}(s)$ contains non-minimum phase term, then factorize $G_M(s)$ such that $G_{M+}(s)$ has only all-pass term, i.e., $G_{M+}(s) = (1 - as)/(1 + as)$, then put $x = 3$, and by substituting (9) into (8), we get (12) and (13) at the bottom of the page.
3) *Case III*: When $G_{M+}(s)$ neither contains non-minimum phase term nor delay term, i.e., $G_{M+}(s) = 1$, then it can be considered as a special case of above mentioned *case I*. Therefore, on substituting $\sigma = 0$, in (10) and (11), brings

$$\psi = \frac{p_1(p_2\lambda_f - 1)^4 - p_2(p_1\lambda_f - 1)^4 - p_1 + p_2}{p_1 p_2 (p_2 - p_1)} \tag{14}$$

$$\theta = \frac{p_1^2(p_2\lambda_f - 1)^4 - p_2^2(p_1\lambda_f - 1)^4 - p_1^2 + p_2^2}{p_1 p_2 (p_2 - p_1)}. \tag{15}$$

Thus, it is clear that controller $Q_D(s)$ expressed by (7) does not require heavy computational burden. Hence, controller's simplicity and easy practical implementation are the major advantage of this design scheme. Here, we are only concerned with disturbance rejection problem, i.e., effect of $D(s)$ on $Y(s)$, we need not to evaluate set-point filter $Q_1(s)$ since $R(s) = 0$ is assumed.

B. Model Order Reduction

By model-order reduction we mean roughly that the large-scale system (higher-order or full-order) is approximated by small-scale system (lower-order or reduced-order), such that the inherent behavior of the original system does not deteriorate. In terms of control perspective, the basic concept behind the model-order reduction technique is to preserve the dominant poles of the full-order model of the plant while rejecting the non-dominant poles. Until now, many model reduction techniques have been developed [25]–[34]. These methods can be utilized for SISO/MIMO systems to obtain lower-order models which further can be used to design IMC based controller. As an example of utilizing reduced order modeling, only two methods: Padé and Routh approximations [25], [26] are considered in the present study. The application of these techniques to LFC is elaborated in Section V.

$$\psi = \frac{a^2\lambda_f p_1 p_2(p_1 + p_2) + \left(a\lambda_f^3 + 3a^2\lambda_f^2\right) p_1 p_2 + a\lambda_f \left(p_1^2 + p_2^2 + p_1 p_2\right) + \left(\lambda_f^3 + 3a\lambda_f^2\right)(p_1 + p_2) + 3\lambda_f^2}{a^2 p_1 p_2 + a(p_1 + p_2 + 1)} \tag{12}$$

$$\theta = \frac{a\lambda_f^2 p_1^2 p_2^2 + \left(3a\lambda_f^2 + 3a^2\lambda_f\right) p_1 p_2 - 3a\lambda_f(p_1 + p_2) + a\lambda_f p_1 p_2(p_1 + p_2) + \left(\lambda_f^3 + 3a\lambda_f\right) p_1 p_2 - 3\lambda_f}{a^2 p_1 p_2 + a(p_1 + p_2 + 1)} \tag{13}$$

IV. Proposed IMC Strategy

As discussed earlier in order to apply IMC design scheme, a perfect model is required. Furthermore, the controller must be able to invert the model perfectly. However, in real time applications, it is difficult to get a perfect model. So, generally the process is approximated as first-order or second-order plus dead time (FOPDT or SOPDT) model. This results in addition of delay terms in the transfer function. Since the IMC controller needs inverse plant model, and the inversion of delay terms for controller design leads to predictor action. Moreover, most often the obtained transfer function is of higher-order which sometimes leads to unrealizable controller and results into slower response, and more complex computation. Thus, there is a need of model-order reduction techniques to develop causal, realizable, and lower-order process models. So, based on Sections III, the proposed IMC design involves following two steps:

1) Approximate the model of a system using Padé or Routh approximation techniques.
2) Evaluate the TDF-IMC controller $Q_D(s)$ for this approximated (reduced) model.

V. LFC For Single-Area Power Plant

A. Plant Description

Usually, the power systems are large-scale systems with complex nonlinear dynamics [1]. However, for relatively load disturbance, they can be linearized around the operating point. Here, a single-area power system supplying power to a single service-area through single generator is considered. This power plant for LFC design consists of governor $G_g(s)$, non-reheated turbine $G_t(s)$, load and machine $G_p(s)$, and $1/R$ is the droop characteristics, a kind of feedback gain to improve the damping properties of the power system. The linear model of plant is shown in Fig. 3. The dynamics of these subsystems are

$$\begin{aligned} G_g(s) &= (T_G s+1)^{-1} \\ G_t(s) &= (T_T s+1)^{-1} \\ G_p(s) &= K_P(T_P s+1)^{-1}. \end{aligned} \tag{16}$$

The whole system model can be illustrated by

$$\Delta f(s) = G(s)u(s) + G_d(s)\Delta P_d(s) \tag{17}$$

where we see (18) at the bottom of the page, and

$$G_d(s) = \frac{G_p(s)}{1+G_g(s)G_t(s)G_p(s)/R}. \tag{19}$$

Equation (17) clearly explains that LFC is basically a disturbance rejection (regulator) problem in which the objective is to

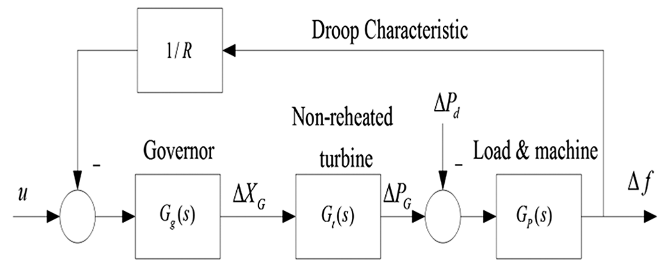

Fig. 3. Linear model of a single-area power system.

evaluate the control law: $u(s) = -K(s)\Delta f(s)$, where $K(s)$ is IMC based compensator to control the power plant $G(s)$ and minimize effect on $\Delta f(s)$ in the environment of small load disturbance $\Delta P_d(s)$ [35].

B. Model-Order Reduction of Plant

It is clear from (18) that even the single-area power system containing only one generator, still, it is of third-order, and thus IMC control design is obviously of higher order if the full-order model is used. So, we obtain the second-order reduced-model of the single-area power system using following methods.

1) Padé Approximation Method: This reduction method is based on matching of few coefficients of Taylor series expansion, about $s = 0$ of the reduced-order model with the corresponding coefficients of the original model. In order to convert higher-order system $G(s)$ into second-order reduced model $G_{MR}^{Padé}(s)$, we first define $G_{MR}^{Padé}(s)$ as

$$G_{MR}^{Padé}(s) = \frac{(a_0+a_1 s)}{(b_0+b_1 s+s^2)}. \tag{20}$$

Equation (18) can be rewritten as

$$G(s) = \frac{K_P/A}{s^3+\left(\frac{B}{A}\right)s^2+\left(\frac{C}{A}\right)s+\left(\frac{D}{A}\right)} \tag{21}$$

where

$$\begin{aligned} A &= T_P T_T T_G, \quad B = T_P T_T + T_T T_G + T_P T_G \\ C &= T_P + T_T + T_G, \quad D = 1+\left(\frac{K_P}{R}\right). \end{aligned} \tag{22}$$

The coefficients of the power series expansion $G(s)$ can be expressed as $G(s) = c_0 + c_1 s + c_2 s^2 + c_3 s^3 + \ldots$, which yields

$$\begin{aligned} C_0 &= \frac{K_P}{D}, \quad c_1 = \frac{-CK_p}{D^2}, \quad c_2 = \frac{(C^2-BD)K_P}{D^3} \\ C_3 &= \frac{(2BCD-AD^2-C^3)K_P}{D^4}. \end{aligned} \tag{23}$$

$$\begin{aligned} G(s) &= \frac{G_g(s)G_t(s)G_p(s)}{1+G_g(s)G_t(s)G_p(s)/R} \\ &= \frac{K_P}{T_P T_T T_G s^3 + (T_P T_T + T_T T_G + T_P T_G)s^2 + (T_P+T_T+T_G)s + (1+K_P/R)} \end{aligned} \tag{18}$$

TABLE I
$\alpha-\beta$ TABLE FOR ROUTH APPROXIMATION

α Table			β Table		
	D	B		K_p	0
$\alpha_1=\dfrac{D}{C}$	C	A	$\beta_1=\dfrac{K_P}{C}$	0	
$\alpha_2=\dfrac{C^2}{BC-AD}$	$B-\dfrac{AD}{C}$		$\beta_2=0$	0	

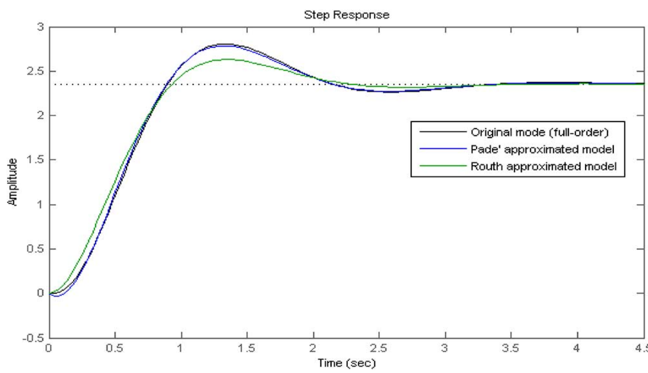

Fig. 4. Comparison between step responses of original model and that of reduced order model.

Now, to obtain second-order reduced model, $G_{MR}^{Padé}(s)$ of the form described in (20), the parameters a_i and b_i ($i=0,1$) can be evaluated by simplifying

$$\begin{pmatrix} c_2 & c_1 \\ c_3 & c_2 \end{pmatrix}\begin{pmatrix} b_0 \\ b_1 \end{pmatrix}=\begin{pmatrix} -c_0 \\ -c_1 \end{pmatrix}, \quad \begin{pmatrix} a_0 \\ a_1 \end{pmatrix}=\begin{pmatrix} c_0 & 0 \\ c_1 & c_0 \end{pmatrix}\begin{pmatrix} b_0 \\ b_1 \end{pmatrix}. \tag{24}$$

2) Routh Approximation Method: In this method, the reduced order model can be obtained by approximating the coefficients of Routh table. Consider a second-order reduced-model $G_{MR}^{Routh}(s)$ as $G_{MR}^{Routh}(s)=P_2(s)/Q_2(s)$ where $P_2(s)$ and $Q_2(s)$ are numerator and denominator, respectively. We first reciprocate $G_{MR}^{Routh}(s)$ using relation $\tilde{L}(s)=(1/s)L(1/s)$ Thus, the reciprocated model of $G(s)$ becomes

$$\tilde{G}(s)=\frac{K_P s^2}{(Ds^3+Cs^2+Bs+A)} \tag{25}$$

and then, expand $\tilde{G}(s)$, namely

$$\tilde{G}(s)=\frac{\tilde{P}_i(s)}{\tilde{Q}_i(s)}=\sum_{t=1}^{n}\beta_t\prod_{j=1}^{l}F_j(s) \tag{26}$$

where $\beta_i(i=1,2)$ are constants, and $F_i(s)(i=1,2)$ contains α_i terms. Next, we need to compute α and β tables corresponding to $\tilde{G}(s)$, which is shown in Table I. The detailed study and evaluation of α and β tables are reported in [26]. These α and β terms gives reciprocated reduced-order numerator $\tilde{P}_2(s)$ and denominator $\tilde{Q}_2(s)$ for second-order reduced model as

$$\begin{aligned}\tilde{P}_2(s)&=\beta_2+\alpha_2\beta_1 s\\ \tilde{Q}_2(s)&=1+\alpha_2 s+\alpha_1\alpha_2 s^2.\end{aligned} \tag{27}$$

On substituting values of α and β in (27), we get

$$\begin{aligned}\tilde{P}_2(s)&=\frac{CK_p s}{(BC-AD)},\\ \tilde{Q}_2(s)&=1+C^2 s/(BC-AD)+CDs^2/(BC-AD).\end{aligned} \tag{28}$$

Finally, the required reduced order model is obtained by again reciprocating the terms of (28), which gives

$$G_{MR}^{Routh}(s)=\frac{CK_p}{((BC-AD)s^2+C^2 s+CD)}. \tag{29}$$

VI. SIMULATION STUDIES

Consider the typical values of parameters for single-area power system as expressed in [22]:

$$K_P=120,\ T_P=20,\ T_T=0.3,\ T_G=0.08,\ R=2.4. \tag{30}$$

Using (30), $G(s)$ is evaluated as

$$G(s)=\frac{250}{(s^3+15.88s^2+42.46s+106.2)} \tag{31}$$

which is a third-order under-damped system. Since IMC requires a plant model in its control structure, so, before applying the proposed scheme as mentioned in Section IV, consider the predictive model $G_M(s)$ for IMC structure same as the original full-order power plant, i.e., $G_M(s)=G(s)$. The various steps to provide the proposed design scheme are as follows.

A. Application of Model-Order Reduction

Using Padé approximation and Routh approximation method, the second-order reduced models of (31) are

$$G_{MR}^{Padé}(s)=\frac{(-1.191s+18.92)}{(s^2+2.708s+8.043)} \tag{32}$$

$$G_{MR}^{Routh}(s)=\frac{18.68}{(s^2+3.173s+7.94)}. \tag{33}$$

The step responses of the original model, i.e., full-order model $G(s)$ and reduced order models expressed in (32) and (33), respectively, are shown in Fig. 4. From this figure, it is evident that the response of the original third-order model is almost equal to that of reduced second-order models. Thus, we can say that two models are in good approximation.

B. Application of Proposed Controller Design

1) Controller for Padé Approximation Model: Since (32) has RHP zero at $s=15.89$, and therefore in order to factorize (32), $G_{MR}^{Padé}(s)$ can be written as $G_{MR}^{Padé}(s)=G_{MR-}^{Padé}(s)G_{MR+}^{Padé}(s)$. Rearrange $G_{MR}^{Padé}(s)$ as

$$G_{MR}^{Padé}(s)=\left(\frac{1.191s+18.92}{s^2+2.708s+8.043}\right)\left(\frac{-1.191s+18.92}{1.191s+18.92}\right) \tag{34}$$

where $G_{MR-}^{Padé}(s)$ is a minimum phase part:

$$G_{MR-}^{Padé}(s)=\frac{(1.191s+18.92)}{(s^2+2.708s+8.043)} \tag{35}$$

and $G_{MR+}^{Padé}(s)$ is a non-minimum phase part:

$$G_{MR+}^{Padé}(s) = \frac{(-1.191s + 18.92)}{(1.191s + 18.92)}. \tag{36}$$

Taking $\lambda_f = 0.08$, and using (12) and (13), the TDF-IMC controller of the form (7) is given by

$$Q_D^{Pad\tilde{e}}(s) = \frac{(s^2+2.708s+8.043)(0.0057s^2+0.1687s+1)}{(1.191s+18.92)(0.08s+1)^3} \tag{37}$$

where φ, θ, λ_f and x are 0.0057, 0.1687, and 3, respectively.

2) Controller for Routh Approximation Model: For evaluating TDF-IMC controller when Routh approximated reduced second-order model expressed in (33) is used, there is no need to factorize (33) because it does not contain any RHP zero or delay factor. So, in this case, $G_{MR}^{Routh}(s) = G_{MR-}^{Routh}(s)$ Now, selecting $\lambda_f = 0.2$, and using (14) and (15), the controller is given by

$$Q_D^{Routh}(s) = \frac{(s^2+3.173s+7.94)(0.1419s^2+0.5862s+1)}{18.68(0.2s+1)^4} \tag{38}$$

where φ, θ and x are 0.1419, 0.5862, and 4, respectively.

As pointed out earlier, the optimal as well as robust controllers are designed for specific type of disturbance (e.g., step load acting at the input of a plant). We have applied a non-periodic load disturbance $\Delta P_D(t) = 0.01$ at $t = 2$ sec., as shown in Fig. 3.

C. Performance Evaluation and Comparative Remarks

The effectiveness of the resulting controller is compared with the TDF-IMC controller developed by Tan [23]. In his reported work, third-order single-area power system described in (18) is approximated with a standard second-order plus dead-time (SOPDT) model using same parameters value expressed in (30). This model is given by $G_{MR}^{SOPDT}(s) = 18.8268e^{-0.0757s}/(s^2+2.6403s + 8.0015)$ [23]. Now, applying our proposed method, $G_{MR}^{SOPDT}(s)$ is obtained by first factorizing $G_{MR}^{SOPDT}(s)$ as $G_{MR}^{SOPDT}(s) = G_{MR-}^{SOPDT}(s)G_{MR+}^{SOPDT}(s)$, where minimum phase part is $G_{MR-}^{SOPDT}(s) = 18.8268/(s^2 + 2.6403s + 8.0015)$ and non-minimum phase part is $G_{MR+}^{SOPDT}(s) = e^{-0.0757s}$. Again using (10) and (11), the corresponding TDF-IMC controller is evaluated as

$$Q_D^{SOPDT}(s) = \frac{(s^2+2.6403s+8.0015)(0.1649s^2+0.5567s+1)}{18.8267(0.2s+1)^4} \tag{39}$$

where φ, θ and x are 0.1649, 0.5567, 0.2, and 4, respectively.

The disturbance rejection response of the power system for nominal case using SOPDT, Padé, and Routh approximation models are illustrated in Fig. 5. The comparison of these three models using proposed method is done with Tan's [23] proposed method. From this Fig. 5, it is observed that the rejections are faster and smoother for the proposed method using Routh and Padé approximation models than that of SOPDT model, and also for SOPDT model using Tan's method. Therefore, it is clear that Routh and Padé approximated models are efficient models to obtain TDF-IMC controllers.

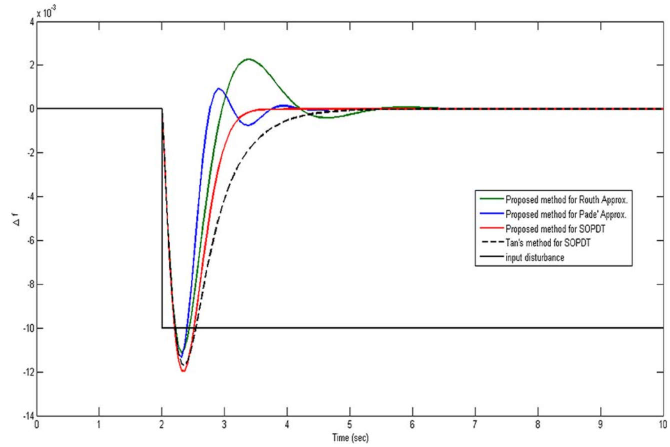

Fig. 5. Responses of a power system using TDF-IMC design with various reduced-order models for nominal parameters.

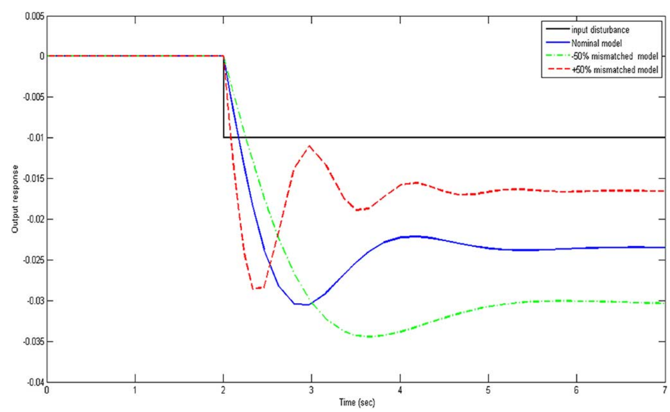

Fig. 6. Effect of disturbance at output for nominal and uncertain models.

The disturbance response of the power system without any control for nominal as well as uncertain models are shown in Fig. 6, which states that the disturbance at output is approximately 50% higher for nominal case, and 100%, 150% more for +50% and −50% uncertain model, respectively, as compared to the input disturbance. In such cases, it is essential to confirm whether the same controller can handle all such parameter uncertainties. In order to study the robust analysis and performance of a power system model, consider a power system model as an uncertain model which is shown in Fig. 7. Here, we have considered 50% additive uncertainty in all the parameters in the same manner as expressed in [22], i.e.,

$$\begin{aligned}
&\delta_1 = \frac{1}{T_P} \in [0.0331, 0.1], \quad \delta_2 = \frac{K_P}{T_P} \in [4, 12] \\
&\delta_3 = \frac{1}{T_T} \in [2.564, 4.762], \quad \delta_4 = \frac{1}{RT_G} \in [3.081, 10.639] \\
&\delta_5 = \frac{1}{T_G} \in [9.615, 17.857].
\end{aligned} \tag{40}$$

Fig. 8(a) and (b) shows the disturbance rejection response for upper and lower bounds uncertain systems. Thus, it is evident that the same controllers, expressed in (37)–(39), for each model are indeed capable of handling parameter variations, and

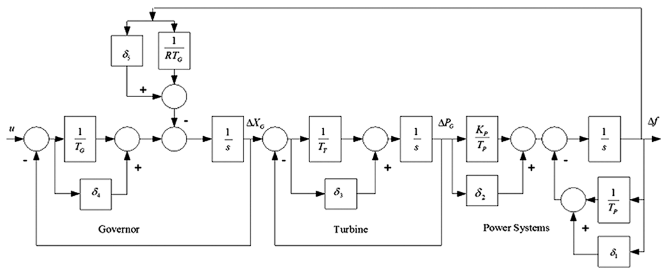

Fig. 7. Linear model of power system with uncertain parameters.

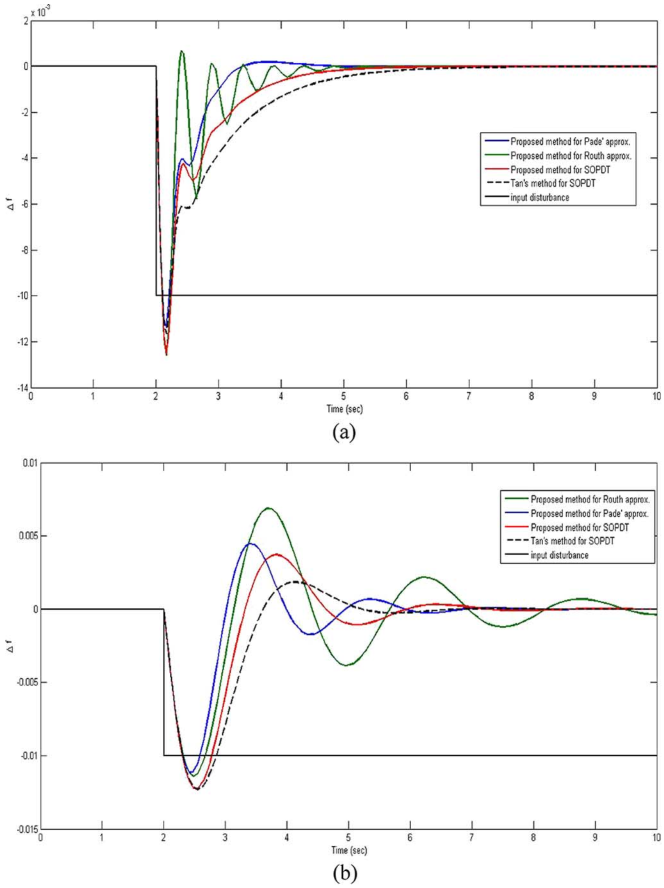

Fig. 8. Responses of a power system using TDF-IMC design with various reduced-order models for (a) lower bound and (b) upper bound uncertainties.

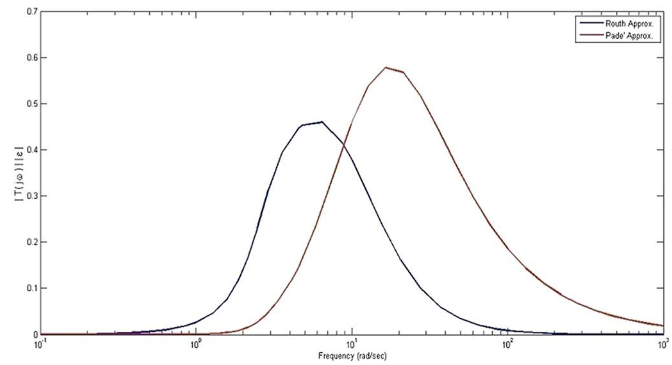

Fig. 9. Robust stability plot for parameter uncertainty.

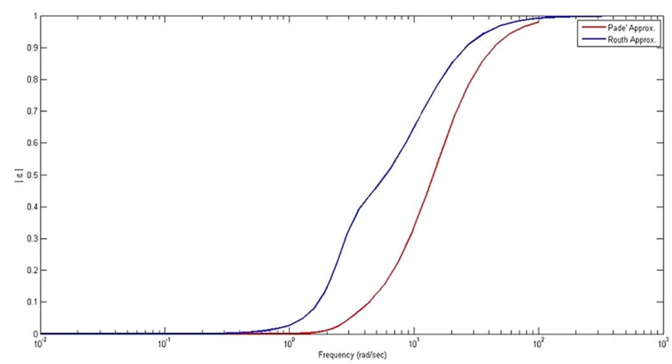

Fig. 10. Variation of multiplicative error with frequency.

achieve superior performance compared to the controller proposed in [23]. Thus, the proposed scheme is robust in nature.

The main goal of designing a controller is its ability to work well under uncertain environment. In IMC design scheme, the stability of a system is no longer judged by selecting $G(s)$ and $Q(s)$ stable. So, to assure robust stability, the necessary condition can be derived from small gain theorem [36] which states that $\|T\varepsilon\|_\infty = \sup_\omega |T(j\omega)\varepsilon(j\omega)| < 1$ To demonstrate the robust stability, the plot of $\|T\varepsilon\|_\infty$ is shown in Fig. 9. It clearly depicts that the optimum value is less than 1, for both Padé and Routh approximation models.

The previous section clearly illustrates that the IMC design through reduced-order model definitely creates plant/model (full/reduced model) mismatch, which may result into instability, and limit performance of the control system. To achieve this, it is useful to constraint on ε, i.e., (5). Generally, $|\varepsilon|$ approaches or exceeds 1 for higher frequency; so for the robust performance, there must be an upper bound on plant/model mismatch, such that $|\varepsilon| < 1$ Now, to ensure robust performance, Fig. 10 depicts that the multiplicative error for plant/model mismatch in both Padé and Routh approximation models do not exceed 1 for high frequency. Thus, the designed compensator achieves robust performance.

Lastly, Table II summarizes that the designed controllers using model reduction technique, bring optimal performance in terms of integral error criterion, when compared with that of Tan's proposed method for each nominal and uncertain models. For example in case of nominal model, ISE of proposed method for SOPDT, Routh and Padé approximated models is roughly 5 times less than that of method proposed by Tan [23]. Likewise, for uncertain models, IAE and ITAE too are comparatively less, thereby ensuring low cost and computation efficiency.

VII. Conclusion

In electricity power industry, there is an ongoing need for efficient and effective LFC techniques to counter the ever-increasing complexity of large-scale power systems and robustness against parameter uncertainties as well as plant/model mismatch and external load change. In this reported work, two different techniques, namely Padé and Routh approximation model reduction techniques are combined to generate a stable control system for single-area power system consisting single generating unit, and satisfy robust and optimal performance. The method achieves good performance in case of disturbances, eliminates plant/model mismatch and at the

TABLE II
COMPARISON OF PERFORMANCE INDICES FOR VARIOUS REDUCED ORDER MODELS

Reduction technique	IMC design Method	Nominal case			50% Uncertainty case					
					Lower bound			Upper bound		
		ISE	IAE	ITAE	ISE	IAE	ITAE	ISE	IAE	ITAE
SOPDT	Tan [23]	0.004307	0.1841	1.119	0.004631	0.1891	1.135	0.00398	0.1773	1.096
SOPDT	Liu & Gao [24]	0.0008231	0.08061	0.4808	0.0008657	0.08247	0.4857	0.0008095	0.07827	0.4739
Routh		0.0008703	0.08166	0.4832	0.0009178	0.08329	0.4871	0.0008959	0.08118	0.4815
Padé		0.0008499	0.08183	0.4840	0.0009027	0.08336	0.4871	0.0008463	0.07997	0.4793

ISE= Integral Squared Error, IAE=Integral Absolute Error, ITAE=Integral Time-Weighted Absolute Error

same time handle parameter uncertainty. The application of reduced-order model removes any redundant information, and thus improves computational efficiency.

The under-progress work is application to multi-area systems, and to investigate the efficient model-order reduction methods for better approximation to the full-order model.

ACKNOWLEDGMENT

The authors would like to thank the Editor and reviewers for the valuable suggestions which were helpful in improving the manuscript.

REFERENCES

[1] P. Kundur, *Power System Stability and Control*. New York, NY, USA: McGraw-Hill, 1994.
[2] H. Shayeghi, H. A. Shayanfar, and A. Jalili, "Load frequency control strategies: A state-of-the-art survey for the researcher," *Energy Convers. Manage.*, vol. 50, no. 2, pp. 344–353, Feb. 2009.
[3] A. Khodabakhshian and N. Golbon, "Unified PID design for load frequency control," in *Proc. IEEE Int. Conf. Control applications (CCA)*, Taipei, Taiwan, 2004, pp. 1627–1632.
[4] K. Vrdoljak, N. Peric, and I. Petrovic, "Sliding mode based load-frequency control in power systems," *Elect. Power Syst. Res.*, vol. 80, no. 5, pp. 514–527, May 2009.
[5] R. K. Cavin, M. C. Budge, and P. Rasmussen, "An optimal linear system approach to load-frequency control," *IEEE Trans. Power App. Syst.*, vol. PAS-90, no. 6, pp. 2472–2482, Nov. 1971.
[6] I. Kocaarslan and E. Cam, "Fuzzy logic controller in interconnected electrical power Systems for load-frequency control," *Int. J. Power Energy Syst.*, vol. 27, no. 8, pp. 542–549, Oct. 2005.
[7] D. Rerkpreedapong, A. Hasanovic, and A. Feliachi, "Robust load frequency control using genetic algorithms and linear matrix inequalities," *IEEE Trans. Power Syst.*, vol. 18, no. 2, pp. 855–861, May 2003.
[8] C. T. Pan and C. M. Liaw, "An adaptive controller for power system load-frequency control," *IEEE Trans. Power Syst.*, vol. 4, no. 1, pp. 122–128, Feb. 1989.
[9] M. A. Sheirah and M. M. Abd-EI-Fattah, "Improved load-frequency self-tuning regulator," *Int. J. Control*, vol. 39, no. 1, pp. 143–158, Jan. 1984.
[10] Y. H. Moon, H. S. Ryu, J. G. Lee, and S. Kim, "Power system load frequency control using noise-tolerable PID feedback," in *Proc. IEEE Int. Symp. Industrial Electronics (ISIE)*, Jun. 2001, vol. 3, pp. 1714–1718.
[11] S. M. S. Boroujeni, B. K. Boroujeni, H. Delafkar, and A. S. Boroujeni, "A new IP type controller for load frequency control problem," *J. Basic. Appl. Sci. Res.*, vol. 1, no. 9, pp. 1078–1083, 2011.
[12] G. Ray, A. N. Prasad, and G. D. Prasad, "A new approach to the design of robust load-frequency controller for large scale power systems," *Elect. Power Syst. Res.*, vol. 51, no. 1, pp. 13–22, Jul. 1999.
[13] A. S. Taher and R. Hematti, "Robust decentralized load frequency control using multi variable QFT method in deregulated power systems," *Amer. J. Appl. Sci.*, vol. 5, no. 7, pp. 818–828, Jul. 2008.
[14] M. Morari and E. Zafiriou, *Robust Process Control*. Englewood Cliffs, NJ, USA: Prentice Hall, 1989.
[15] L. Harnefos and H. Nee, "Model-based current control of AC machines using the internal model control method," *IEEE Trans. Ind. Appl.*, vol. 34, no. 1, pp. 133–141, Jan./Feb. 1998.
[16] A. Petersson, L. Harnefors, and T. Thiringer, "Evaluation of current control methods for wind turbines using doubly-fed induction machines," *IEEE Trans. Power Electron.*, vol. 20, no. 1, pp. 227–235, Jan. 2005.
[17] M. Karimi-Ghartemani and F. Katiraei, "An adaptive internal model control for reactive power compensation," in *Proc. 2005 IEEE Conf. Control Applications*, Toronto, ON, Canada, August 28–31, 2005, pp. 1668–1673.
[18] X. Wei, K. M. Tsang, and W. L. Chan, "DC/DC buck converter using internal model control," *Elect. Power Compon. Syst.*, vol. 37, no. 3, pp. 320–330, Feb. 2009.
[19] Y. Tian and F. Gao, "Double-controller scheme for control of processes with dominant delay," *IEE Proc. Control Theory Appl.*, vol. 145, no. 5, pp. 479–484, 1998.
[20] M. Shamsuzzoha and M. Lee, "Design of robust PID controllers for unstable processes," in *Proc. IEEE 2006 SICE-ICASE Int. Joint Conf.*, pp. 3324–3329.
[21] W. Hu, G. Xiao, and W. Cai, "PID controller based on two-degree-of-freedom direct synthesis," in *Proc. IEEE 2011 Control and Decision Conf. (CCDC)*, pp. 629–634.
[22] W. Tan, "Unified tuning of PID load frequency controller for power systems via IMC," *IEEE Trans. Power Syst.*, vol. 25, no. 1, pp. 341–350, Feb. 2010.
[23] W. Tan, "Tuning of PID load frequency controller for power systems," *Energy Convers. Manage.*, vol. 50, no. 6, pp. 1465–1472, Jun. 2009.
[24] T. Liu and F. Gao, "New insight into internal model control filter design for load disturbance rejection," *IET Control Theory Appl.*, vol. 4, no. 3, pp. 448–460, 2010.
[25] Y. Shamash, "Stable reduced-order models using Padé-type approximations," *IEEE Trans. Autom. Control*, vol. 19, no. 5, pp. 615–616, Oct. 1974.
[26] M. F. Hutton and B. Friedland, "Routh approximations for reducing order of linear, time-invariant systems," *IEEE Trans. Autom. Control*, vol. AC-20, pp. 329–337, Jun. 1975.
[27] Y. Shamash, "Model reduction using Routh stability criterion and the Padé approximation technique," *Int. J. Control*, vol. 21, no. 3, pp. 475–484, Mar. 1975.
[28] W. Krajewski, A. Lepschy, and U. Viaro, "Model reduction by matching Markov parameters, time moments, and impulse-response energies," *IEEE Trans. Autom. Control*, vol. 40, no. 5, pp. 949–953, May 1995.
[29] Y. Shamash, "Truncation method of reduction: A viable alternative," *IEEE Electron. Lett.*, vol. 17, no. 2, pp. 97–98, 1981.
[30] P. Gutman, C. F. Mannerfelt, and P. Molander, "Contribution to model reduction problem," *IEEE Trans. Autom. Control*, vol. 27, no. 2, pp. 454–455, Apr. 1982.
[31] L. S. Shieh and M. J. Goldman, "Continued fraction expansion and inversion of the Cauer third form," *IEEE Trans. Circuits Syst.*, vol. CAS-21, no. 3, pp. 341–345, 1974.
[32] C. T. Chen and C. Y. Chang, "Reduction of transfer functions by the stability-equation method," *J. Franklin Inst.*, vol. 308, no. 4, pp. 389–404, Oct. 1979.
[33] C. T. Chen, *Linear System Theory and Design*. New York, NY, USA: Oxford Univ. Press, 1999.

[34] E. Grimme, “Krylov projection methods for model reduction,” Ph.D. dissertation, Coordinated-Science Lab., Univ. Illinois at Urbana-Champaign, Urbana, IL, USA, 1997.
[35] W. Tan, “Load frequency control: Problems and solutions,” in *Proc. 30th Chinese Control Conf.*, Jul. 22–24, 2011, pp. 6281–6286.
[36] K. Zhou and J. C. Doyle, *Essentials of Robust Control*. Englewood Cliffs, NJ, USA: Prentice Hall, 1998.

Sahaj Saxena (S’12) received the B.Tech. degree in electronics engineering and the M.Tech degree in electrical engineering from Kamla Nehru Institute of Technology, Uttar Pradesh, India, and Indian Institute of Technology Roorkee, India, in 2010 and 2012, respectively. He is currently pursuing the Ph.D. degree in the Department of Electrical Engineering, Indian Institute of Technology Roorkee, India.

His current research interests include automatic control systems, robust control techniques, and intelligent control.

Yogesh V. Hote (M’12) received the B.E. degree in electrical engineering and the M.E. degree in control systems from Govt. College of Engineering, Amravati, India, and Govt. College of Engineering, Pune, India, in 1998 and 2000, respectively, and the Ph.D. degree in instrumentation and control engineering, University of Delhi in 2009.

He is currently working as Assistant Professor in the Department of Electrical Engineering, Indian Institute of Technology Roorkee. From May 31, 2001 to May 30, 2006, he worked as a Lecturer in the Department of Instrumentation and Control Engineering, Netaji Subhas Institute of Technology, New Delhi, and from May 31, 2006 to February 17, 2011 in the same department, he worked as an Assistant Professor. His field of research includes robust control, robotics, numerical analysis, and power electronics.