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GA based Internal Model Controller Design for Load Frequency Control in Power System via Reduced Order Model

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ABSTRACT: *In the conventional two degree freedom (TDF)-internal model controller (IMC) design, obtaining suitable value of tuning parameter is much more complex and difficult. In this paper, the approach of genetic algorithm (GA) is proposed to obtain optimized value of tuning parameter used in TDF-IMC controller design. For TDF-IMC controller design, 2nd order reduced-model is obtained using the Routh approximation. The results obtained are quite encouraging and shows the preservation of stability and other dominant/essential characteristics with improved response of load frequency control (LFC) during load disturbances and parameter variations. The applicability of the proposed algorithm is illustrated with the help of a suitable numerical example from literature.*

KEYWORDS: *Internal Model Control, Model Order Reduction, Genetic Algorithm, Load Frequency Control, Disturbance Rejection*

I. INTRODUCTION

Power system is complex interconnected network of generation, transmission, and distribution systems that are installed in various areas through tie-lines. Moreover, with escalation in development of electric power technology power system has become a complex unit. Therefore, in such complex web in 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. The purpose of the load frequency control (LFC) in the power system are: i) maintaining zero steady state errors for frequency deviations, ii) counteracting sudden load disturbances, iii) minimizing unscheduled tie-line power flows between neighboring areas and transient variations in area frequency, iv) coping up with modeling uncertainties and system nonlinearities within a tolerable region, and v) guaranteeing ability to perform well under prescribed overshoot and settling time in frequency and tie-line power deviations [1, 2]. Different 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. However, the mismatches between the assumed (nominal) models and the real-world processes destroy the ability of many control schemes, thereby demanding better approach in the field of robust control to increase the efficiency of the control system during load disturbance. A control strategy, internal model control (IMC) provides an advanced, effective, powerful and simple framework for the analysis and synthesis of control system performance, especially robustness and load disturbance rejection. In a review paper [14] more emphasis is given on the issues in IMC design for single-input-single-output (SISO) systems, like quantitative filter selection and tuning guidelines, modified structures, and related aspects of contemporary research developments.

Recently [15, 26] discussed the robust design and tuning for a modified IMC structure. But no specific method to determine tuning parameter (λ_f) has been suggested in [26], whereas in proposed method genetic algorithm (GA) technique has been used to find the optimal value of the tuning parameter (λ_f). It can further be inferred that the GA based optimized tuning parameter (λ_f)) for TDF-IMC design scheme reflects much better response during disturbances and parameter variations.

II. PROLEM STATEMENT

Practically, there is always a possibility of process-model mismatch, the process model may not be invertible and system can be often affected by unknown disturbances. However, one class of strongly directional control strategy that has received extensive research in electric power components and process engineering is IMC [16-20]. This control technique has less computational burden, exhibit robustness, sub-optimality, and analytical as well as easily understandable approach. In literature, it is reported that, it is also possible to optimize system performance for load disturbance rejection without sacrificing nominal set-point tracking using two degree-of-freedom (TDF) of IMC [21-24]. And designing controller for the power system plants is usually more complex and more numbers of controllers is required with increase in order of the power system plant. Therefore in such areas, model order reduction is an important technique that simplifies higher order system and plays a major role in design and implementation of control system. Moreover, with reduced- model, its computational complexity, size, and cost is minimized.In the year 2010 Tan [25] 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, fulfill the control objectives in a satisfactory manner. Further Liu and Gao [24] has suggested a modified design of the internal model control (IMC) filter which is proposed for improving closed-loop system performance due to load disturbance. Recently Saxena and Hote have used Routh approximated 2nd order reduced-model for designing modified IMC controller for single area LFC, without suggesting any specific approach to determine the tuning parameter (λ_f). In this paper GA has been used to optimize tuning parameter (λ_f), for better control design which can effectively reduce the rise time, overshoot, undershoot, settling time and peak value of the system response. The results obtained using the proposed algorithm is far better than the existing ones.

III. INTERNAL MODEL CONTROL THEORY

IMC forms the basis of development in control system for control strategy scheme that has the potential to achieve perfect control. The schematic representation of IMC structure is shown Fig.1.It is characterized by a control device consisting of 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 are as follows:

[1] Factor the model in two parts:

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

such that $G_{M+}(s)$ contains all non-minimal phase part and $G_{M-}(s)$ is 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

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

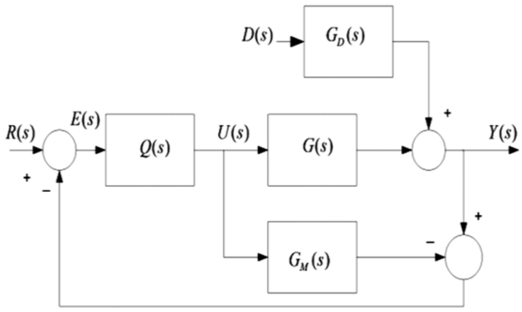

Fig.1. Basic IMC Structure

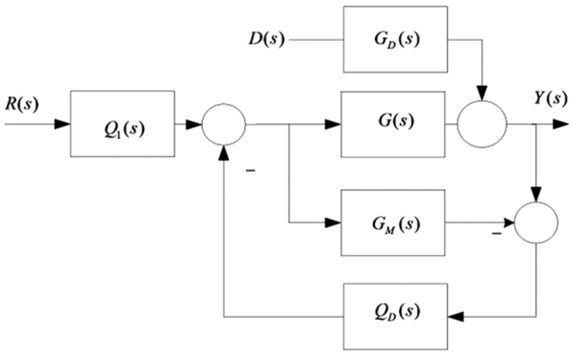

Fig.2. TDF-IMC structure

where the order *n* is an integer selected large enough to make $Q(s)$ proper/semi-proper for physical realization of the plant, while λ, is a tuning parameter, which determines 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.

3.1 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. Therefore to eliminate 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. Let us 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 $T(s)$ function and multiplicative error $\varepsilon(s)$ which is a 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 2nd order internal-model of a system, therefore conventional IMC filter $F(s)$ of the form (3) is replaced by a modified filter $F'(s)$ which is defined by

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

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

$$\lim (1 - T(s)) = 0,\ \forall i = 1,2. \tag{8}$$

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

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

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

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., $G_{M+}(s) = \frac{(1-as)}{(1+as)}$, then put, x = 3,and by substituting (9) into (8), we get (12) and (13).

$$\psi = \frac{\begin{array}{l} a^2\lambda_f p_1 p_2 (p_1 + p_2)(a\lambda_f^3 + 3a^3\lambda_f^2) p_1 p_2 \\ + a\lambda_f (p_1^2 + p_2^2 + p_1 p_2) \\ + (\lambda_f^3 + 3a\lambda_f^2)(p_1 + p_2) + 3\lambda_f^2 \end{array}}{p_1 p_2 (p_1 - p_2)} \tag{12}$$

$$\theta = \frac{\begin{array}{l} a^2\lambda_f^2 p_1^2 p_2^2 (3a\lambda_f^2 + 3a^2\lambda_f) p_1 p_2 \\ - 3a\lambda_f (p_1 + p_2) + a\lambda_f p_1 p_2 (p_1 + p_2) \\ + (\lambda_f^3 + 3a\lambda_f) - 3\lambda_f \end{array}}{a^2\lambda_f p_1 p_2 (p_1 + p_2 + 1)} \tag{13}$$

3) Case III: When $G_{M+}(s)$ contains neither 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 σ = 0, in (10) and (11), brings

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

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

IV. LFC MODEL FOR SINGLE AREA POWER PLANT

4.1 Plant Description

Generally, Power systems are the large-scale system with complex network with non-linear dynamics. Here, a single area power system is considered [1] and basically, this plant consist of a governor $G_g(s)$, a non-reheated turbine $G_t(s)$, load and a generator $G_p(s)$ with feedback of regulation constant R, and droop characteristic $1/R$. System also includes step load change input $\Delta P_d(s)$ to the generator. Simple block diagram of a power plant is shown in Fig. 3.

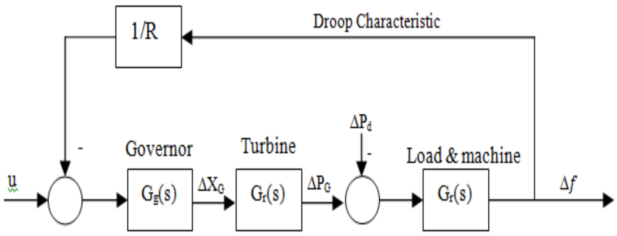

Fig.3. Model of a Single-Area Power System

Table 1

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

The subsystem dynamics can be represented as:

$$G_g(s) = (T_g(s) + 1)^{-1}$$

$$G_t(s) = (T_t(s) + 1)^{-1}$$

$$G_p(s) = K_p(T_p(s) + 1)^{-1} \tag{16}$$

The system model is shown as:

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

$$G(s) = \frac{G_p(s)G_t(s)G_g(s)}{1 + \frac{G_p(s)G_t(s)G_g(s)}{R}} \tag{18}$$

and

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

The control law: $u(s) = -K(s)\Delta f(s)$, where, $K(s)$ the IMC is based compensator to control the power plant $G(s)$ and minimize the effect on $\Delta f(s)$ in the environment of small load disturbance $\Delta P_d(s)$ [27].

V. MODEL ORDER REDUCTION

Model order reduction (MOR) is basically a technique in which the original system is reduced to a lower order model while retaining all the dominant characteristics of the given system. In order to implement MOR technique it is always required to formulate mathematical model of the physical system. From (18), it is evident that even the single-area power system containing only one generator, is of 3rd order, and thus the designed IMC controller will be obviously of higher order if the full-order model is considered. Hence, we obtain the 2nd order reduced-model of the single-area power system using Routh approximation.

5.1 Routh Approximated Model

In order to obtain the reduced-order model of the original higher order system, the coefficient of the original system is approximated using Routh table (see Table 1) in this method. A 2nd order reduced-model is considered as $G_{MRA}^{Routh}(s) = Z_2(s)/P_2(s)$ where $Z_2(s)$ and $P_2(s)$ is numerator and denominator, respectively. Computation of the Routh approximation is presented in following steps.

Firstly, we apply reciprocal transformation to $G(s)$ [28] using relation $\hat{G}(s) = \frac{1}{s}G\left(\frac{1}{s}\right)$. Thus, $G(s)$ becomes

$$G(s) = \frac{K_p s^2}{(Ds^2 + Cs + Bs + A)} \tag{20}$$

where,

$$A = T_p T_t T_g,\ B = T_p T_t + T_t T_g + T_p T_g$$
$$C = T_p + T_t + g,\ D = 1 + \frac{K_p}{R}$$

And, on expanding [28] $\hat{G}(s)$, we have

$$G(s) = \frac{Z_i(s)}{P_i(s)} = \sum_{i=1}^{n} \beta_i \prod_{j=1}^{l} F_j(s) \tag{21}$$

where $\beta_i (i = 1,2)$ are constant and $F_j(s)(i = 1,2)$ contains α_i terms and are constant.

Second step that follows is to compute α and β that corresponds to $\hat{G}(s)$, which is tabulated in **Table 1**. Much detail illustration is reported in [28].From the table reciprocated reduced-order numerator $\hat{Z}_2(s)$ and denominator $\hat{P}_2(s)$ for 2nd order reduced model is expressed as

$$Z_2(s) = \beta_2 + \alpha_2 \beta_1 s$$

$$P_i(s) = 1 + \alpha_2 s + \alpha_1 \alpha_2 s^2 \tag{22}$$

On substituting values of α and β in (21), we have

$$Z_2(s) = \frac{CK_p s}{BC - AD} \tag{23}$$

$$P_i(s) = 1 + C^2 s/(BC - AD) + CDs^2/(BC - AD)$$

Eventually, the required reduced order system is obtain by reciprocating the terms of (22) as

$$G_{MRA}^{Routh}(s) = \frac{CK_p}{((BC - AD)s^2 + C^2 s + CD)} \tag{24}$$

VI. GENETIC ALGORITHM

Genetic algorithm is a natural selection process. It always provides high quality solutions because it is independent of the choice of the initial configurations. The flow chart of genetic algorithm is shown in Fig. 4.

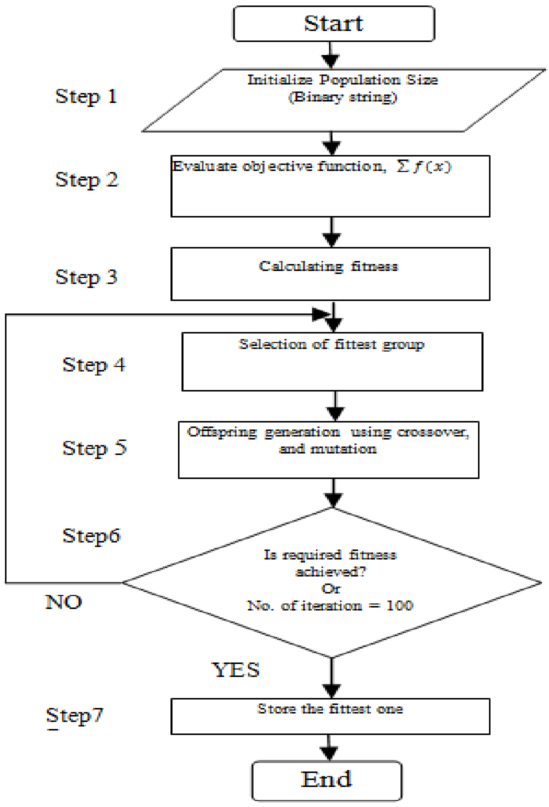

Fig. 4. Flow Chart for Proposed Genetic Algorithm

Moreover, it is computationally simple and effective with easier implementation [29, 30].The goal of optimization is to find the best solution or optimal value of tuning parameter (λ_f), so that the TDF-IMC controller gives better response during load perturbation.

The procedure of applied genetic algorithm for the tested system in this work is given below:

a) Generate randomly a population of parameter string in binary form.
b) Calculate the fitness function as given in **Table 1** for each individual in the population.
c) Choose fittest group of the individuals.
d) Choose parents and applying crossover function to create next generation.
e) Choose next fittest group of the individuals.
f) Choose parents and applying mutation function on new population.
g) Compute the children and parents finesses.
h) If the iteration criteria reaches to the maximum value it will go ahead, otherwise; return to step (c)
i) Plot the performance graph, store fittest individual and stop.

VII. SIMULATION RESULTS

7.1 Application of Genetic Algorithm to find λ_f

Parameter used for the genetic algorithm solution is shown in Table 2 and the response of the fitness function is shown in Fig. 5. Fitness function $\Sigma f(x1, x2)$ includes the settling time and the peak value of response.

7.2 Plant parameters

The values of system parameter are taken from [25] as:

$$K_p = 120,\ T_p = 20,\ T_t = 0.3,\ T_g = 0.08,\ R = 2.4 \quad (25)$$

On substituting the values of (25) in (18), we have

$$G(s) = \frac{250}{(s^3 + 15.88s^2 + 42.46s + 106.2)} \quad (26)$$

Table 2

The number of population	10
The maximum iteration	20
fitness function	$\sum f(x1, x2)$

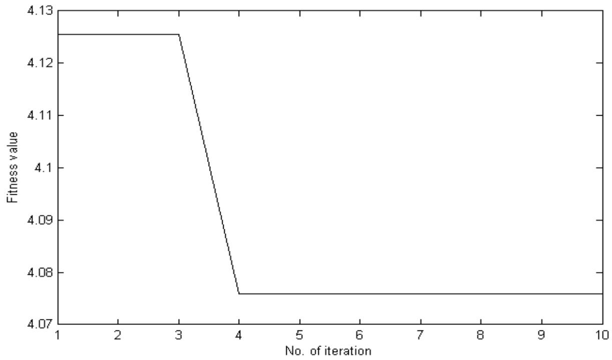

Fig. 5. Performance Graph of Genetic Algorithm

G(s) in (26) is a third order under damped system. The predictive model $G_M(s)$ for IMC structure is same as full order model system, i.e., $G_M(s) = G(s)$.

7.3 Routh Approximated Model

Using Routh approximation method, the 2nd order reduced-model of $G(s)$ is obtained as:

$$G_{MRA}^{Routh}(s) = \frac{18.68}{(s^2 + 3.173s + 7.94)} \tag{27}$$

The step response of original system and 2nd order reduced model is shown in Fig. 6. This response clearly shows that the reduced model obtained by Routh approximation is in good approximation with the response of original system.

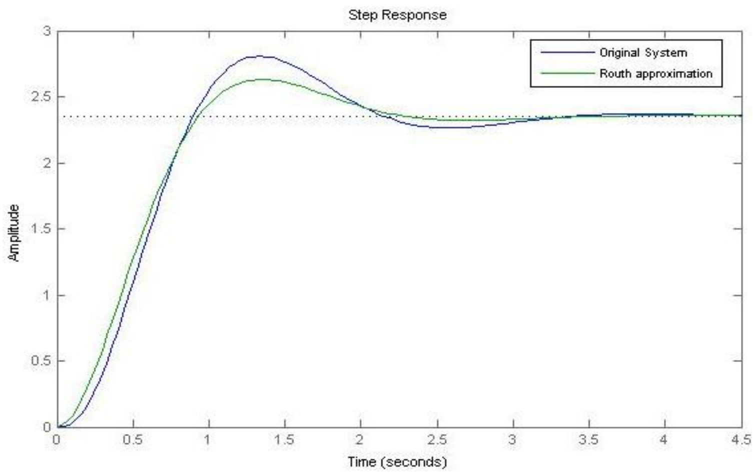

Fig. 6. Step Response of Original and Reduced Model

7.4 Controller for Routh Approximated Model

As (27) is used for designing TDF-IMC controller and (27) does not contain any RHP zero or delay factor, thus factorization of (27) is not required. The TDF-IMC controller suggested by Saxena and Hote [26] is given as:

$$Q_D^{Routh}(s) = \frac{(s^2 + 3.173s + 7.94)(0.1419s^2 + 0.5362s + 1)}{18.68(0.2s + 1)^4} \tag{28}$$

where, λ_f, φ, θ and x are 0.2, 0.1419, 0.5862 and 4, respectively.

The proposed GA based TDF-IMC controller is given by

$$Q_{DGA}^{Routh}(s) = \frac{\frac{(s^2 + 3.173s + 7.94)}{(0.1250s^2 + 0.4561s + 1)}}{18.68(0.13s + 1)^4} \qquad (29)$$

where λ_f, φ, θ and x are 0.13, 0.1250, 0.4561 and 4, respectively.

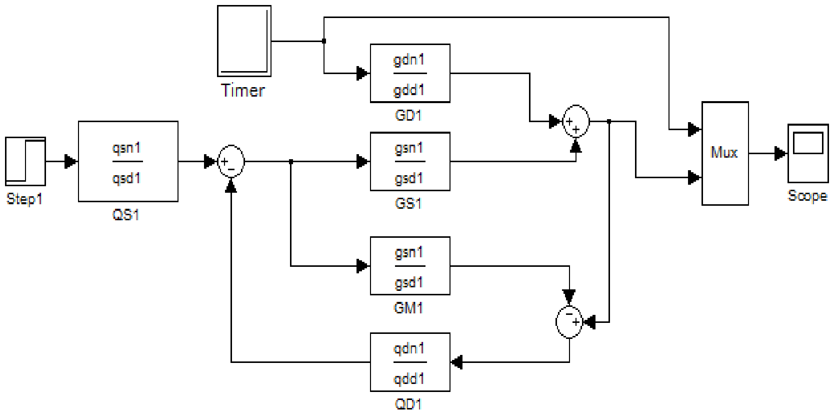

Fig. 7. SIMULINK Model of the TDF-IMC Controller

7.5 Load Disturbance

The input disturbance to the load $\Delta P_d = \pm 1\%$ at time t = 2 sec is taken. Fig.7. shows the MATLAB SIMULINK model of the TDF-IMC controller used in the system with disturbance.

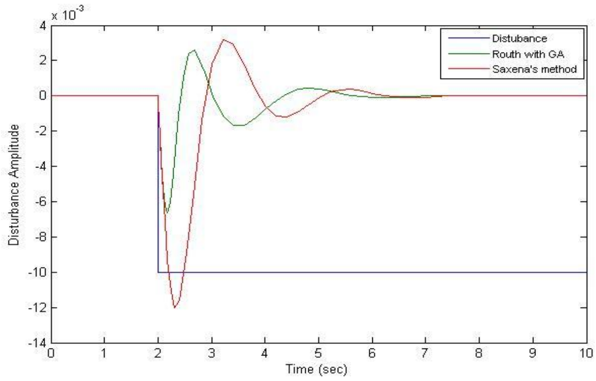

Fig.8. Disturbance Rejection of Sexena'sModel andProposed GA Model (for ΔP_d = -1%)

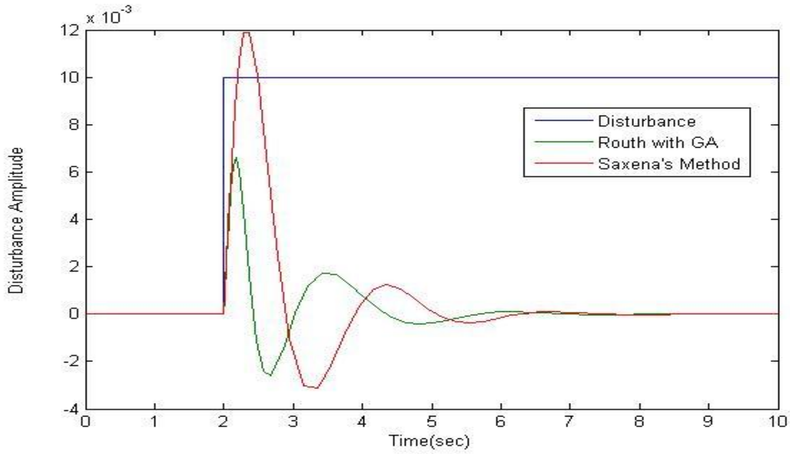

Fig.9. Disturbance Rejection of Sexena'sModel and Proposed GA Model (for ΔP_d =1%)

The disturbance rejection response in single area power system using GA optimized tuned parameter (λ_f) shows significant improvement over Saxena and Hote's approach [26] for ±1% load disturbances to the system at time t = 2 sec., shown in Figs. 8 and 9 respectively. In Tables 3 and 4, the under shoot and overshoot values of the disturbance rejection curve have been compared, which clearly shows the substantial improvement in damping obtained by proposed GA technique over the Saxena and Hote's technique.

Table 3 (for -1% disturbance)

System	Undershoot	Overshoot
Saxena'smodel (Red)	-0.012	3.136e-3
Proposed GA model (Green)	-6.624e-3	2.612e-3

Table 4 (for +1% disturbance)

System	Undershoot	Overshoot
Saxena'smodel (Red)	-3.136e-3	0.012
Proposed GA model (Green)	-2.612e-3	6.624e-3

7.6 Parameters Uncertainties

The output response of power system without any kind of controller is illustrated for nominal and uncertain model with ±50% variation in system input. Figs.10 and 11 show the output responses for negative and positive input disturbances respectively.

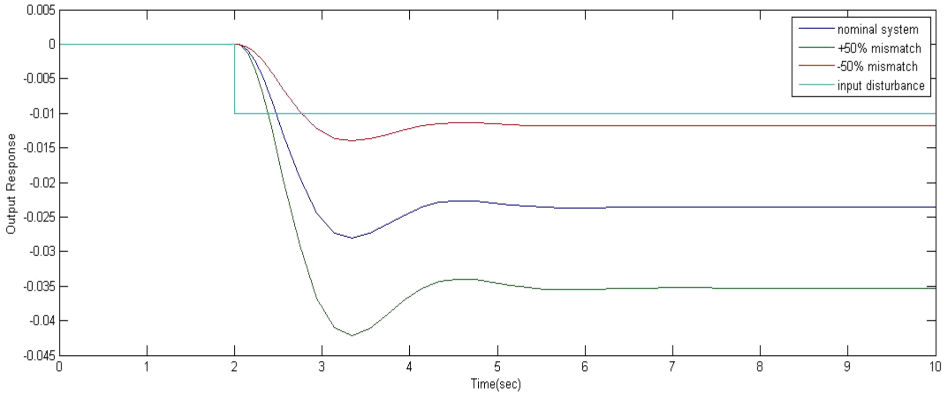

Fig.10.Effect of Disturbances at Output for Nominal and Uncertain Parameters.

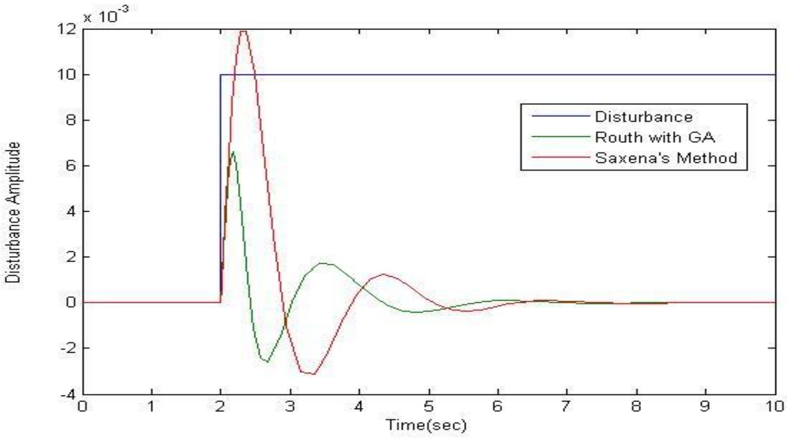

Fig.11. Effect of Disturbance at Output for Nominal and Uncertain Parameters

VIII. CONCLUSIONS

In this study, genetic algorithm has been used for optimising tuning parameter (λ_f) in TDF-IMC controller design whose 2nd order reduced-model is obtained using Routh approximation. It has been shown that the proposed algorithm is effective and provides significant improvement in the system performance over some other existing approach. Also the proposed GA based technique performs robustly during load disturbance and parameter variations as well. In Tables 3 and 4, the under shoot and overshoot values of the disturbance rejection curve have been compared, which clearly shows the substantial improvement in damping obtained by proposed GA technique over the Saxena and Hote's technique. Therefore, the proposed GA optimised TDF-IMC controller design using Routh approximation is recommended to obtain a better LFC control in power systems. Other methods of model order-reduction such as balanced realization and truncation and balanced singular perturbation approximation to design IMC controller for LFC control will be the subject of future work to be applied for multi-input-multi-output plants and multi-area power systems.

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