Frequency Design Approach for FPID controller of Model Reduction AVR

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Keywords

AVR system;
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optimization methods;
FPID controller;
frequency domain;
FOMCON

Abstract

A very important concept with regard to power system control is automatic voltage regulator (AVR). The task of (AVR) is to hold the terminal voltage magnitude of a synchronous generator at a specified level. The mathematical model of AVR is nonlinear and very complex in order, so for simplicity, it needs to reduce the order. Fractional proportional-Integral-Derivative controller (FOPID) is proposed and executed on AVR utilizing frequency design approach. The FPID controller showed strong execution in transient exhibitions, robust performance in transient performances, less settling time, maximum overshoot and steady-state error. The FPID controller displays an iso-damping property (flat reaction). The design is done in frequency domain and hence stability and robustness of the design is automatically guaranteed unlike the other time domain optimization-based controller design methods. The proposed method compared with, TID controller (Tilt-Integral-Derivative) and FOLLC (Fractional Order Lead-Lag Compensator. MATLAB tool box for Fractional order system (FOMCON) is used for transient response analysis. The results show that the FPID controller tuned with settled PID parameters gives acceptable execution regarding set point following when compared with classical TID and FOLLC.

1-Introduction

Large power distribution networks must keep the overall voltage profiles at an acceptable level at all time. The AVR system maintains the terminal voltage of the alternator in the generating station and also helps in suitable distribution of the reactive power amongst the parallel connected generators (Neal and Mark 1994) [1]. Classical PID controller has been used in the AVR loop due to its simplicity and ease of implementation (Flynn et al.1996) [2]. However, recently the fractional order PID (FOPID) controller have been used in the design of AVR systems and have been shown to outperform the PID in many cases [3,4]. In (Zamani et al.2009) [5], the FOPID has been tuned for an AVR system using the Particle Swarm Optimization (PSO) algorithm employing time domain criterion like the Integral of Absolute Error (IAE), percentage overshoot, rise time, settling time, steady state error, and controller effort.

(Dong-Li et al.2014) [6], the optimal parameters of the FOPID controller for the AVR system, has been found using a chaotic ant swarm algorithm. A customized objective function has been designed using the peak overshoot, steady state error, rise time and the settling time. However, the optimization is done in the time domain and the obtained controller values are checked for robustness against gain variation by varying different parameters of the control loop. All these mentioned literatures which employ time domain optimization techniques cannot guarantee a certain degree of gain or phase margins which are important for the plant operator (Patrick et al.2014) [7]. These margins are useful from a control practitioner's view point as they can give an estimate of how much uncertainty the system can tolerate before it becomes unstable. Hence frequency domain designs are mostly preferred over time domain design from the implementation and operation point of view of a control system. Several tuning strategies have been proposed by many contemporary researchers to tune FOPID controllers in both frequency domain and time domain. It has been found that the frequency domain design technique requires a reduced order template of the original higher

order process (Karl and Hagglund 1995) [8]. In present day (Aidan.2006), most of the industrial controllers are tuned with a few set of design specifications, either in time domain (e.g. error index, rise time, percentage of overshoot, settling time, overshoot-undershoot ratio etc.) or frequency domain (e.g. gain margin, phase margin, cross-over frequencies, maximum sensitivity and complementary sensitivity magnitudes etc.).

An optimization-based frequency domain tuning method for controller has been proposed by [10,11] which takes two extra specifications on maximum value of the magnitude of sensitivity and complementary sensitivity function along with the specifications presented in [12,13].

Tuning of the controller using the frequency-domain approaches is studied in many papers. For example, (Barbosa et al. (2004) [14] propose a method based on optimization strategies. Tuning of H_∞ controllers for fractional single input single-output (SISO) system was suggested in (Petrás and Hyslopova 2002) [15]. In (Yeroglu and Tan 2011) [16], tuning method for based on Ziegler-Nichols and Astrom-Hagglund tuning rules is presented.

In this study, a controller has been designed for a model reduction AVR using frequency-domain approach, and Differential Evolution Algorithm (DE) has been used for obtaining the parameters (K_p , K_i , K_d , λ , μ). This work is organized as follows: Section 2 covers AVR mathematical model, Section 3 covers AVR model reduction, Section 4 presents FOPID controller design, Section 5, presents study comparison with other fractional order controller and discussion, finally the conclusion is provided in Section 6.

2-AVR mathematical model

(AVR) is the main controller in the excitation scheme that retains a synchronous generator terminal voltage at a given rate. Different kinds of excitation systems exist, depending on the technique of providing DC power (Fusco and Russo 2008) [17]. In this work, it

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linearized the AVR plant and linearized parts to study this system (Sadat 2005) [18]. The AVR consists of four subsystems' descriptions are as follows:

A-Amplifier Model

In excitation system, using an electronic device called amplifier, the amplitude of a signal waveform can be increased. The amplifier is represented by a gain (K_a) and a time constant (τ_a) and the transfer function is [5, 19];

$$G_a(s) = \frac{K_a}{1 + \tau_a s} \quad (1)$$

Where $K_a = [10, 400]$, $\tau_a = [0.02, 0.1]$ sec

B-Exciter Model

There is a variety of different excitation types. However, modern excitation systems use ac power source through solid-state rectifiers such as SCR. In the simplest form, the transfer function of a modern exciter may be represented by a single time constant (τ_e) and a gain (K_e), i.e. [5, 19].

$$G_e(s) = \frac{K_e}{1 + \tau_e s} \quad (2)$$

Where, $K_e = [0.8, 1]$, $\tau_e = [0.5, 1.0]$ sec.

C-Generator Model

For AVR, we have considered a simplified linearized model as shown in Fig. 1. The transfer function of generator model can be expressed as [5, 18, 19].

$$G_{OL}(s) = \frac{2HK_3K_6S^2 + K_3K_6K_D S + K_3\omega_0(K_1K_6 - K_2K_5)}{2HK_3S^3 + (2H + K_D T_3)S^2 + (K_D + \omega_0 T_3)S + \omega_0(K_1 - K_2K_3K_4)} \quad (3)$$

Figure1. The generator mode

$$H_s(s) = \frac{K_s}{1 + \tau_s s} \quad (4)$$

Where, $K_s = [0.1, 1]$ and $\tau_s = [0.01, 0.7]$. The open-loop transfer function of AVR, can be represented as [5, 19]:

$$G_{AVR} = G_a * G_e * G_{OL} \quad (5)$$

Or can be written as:

$$G_{AVR} = \frac{a_2 s^2 + a_1 s + a_0}{b_5 s^5 + b_4 s^4 + b_3 s^3 + b_2 s^2 + b_1 s + b_0} \quad (6)$$

Where

$$\begin{aligned} a_0 &= K_a K_3 \omega_0 (K_1 K_6 - K_2 K_5) \\ a_1 &= K_a K_e K_6 K_D \\ b_0 &= \omega_0 (K_1 - K_2 K_3 K_4) \\ b_1 &= K_D + \omega_0 T_3 + \omega_0 K_1 \tau_e - \omega_0 \tau_e K_2 K_3 K_4 + \omega_0 \tau_e K_1 \\ &\quad + \omega_0 \tau_e K_2 K_3 K_4 \\ b_2 &= 2H + K_D T_3 + K_D \tau_e + \omega_0 T_3 \tau_e + K_D \tau_a + \omega_0 T_3 \tau_a + \omega_0 \tau_e K_1 \tau_a \\ &\quad - \omega_0 \tau_e K_2 K_3 K_4 \tau_a \\ b_3 &= 2HT_3 + 2H\tau_e + K_D T_3 \tau_e + 2H\tau_a + K_D T_3 \tau_a + K_D \tau_e \tau_a \end{aligned}$$

$$\begin{aligned} b_4 &= 2HT_3 \tau_e + 2HT_3 \tau_a + 2H\tau_e \tau_a + K_D T_3 \tau_e \tau_a \\ b_5 &= 2H\tau_a T_3 \tau_e \end{aligned}$$

Refer to (Fusco and Russso 2008) [17], Where:

$$K_1 = 1.591, K_2 = 1.5, K_3 = 0.333, K_4 = 1.8, K_5 = 0.12, K_6 = 0.3, T_3 = 1.91, H = 3, K_D = 0, \omega_0 = 377.$$

The open-loop transfer function of AVR as:

$$G_{AVR} = \frac{5.994 s^2 + 825.2}{0.573s^5 + 7.176s^4 + 51.06s^3 + 451.1s^2 + 876.6s + 260.8} \quad (7)$$

Equation (7) shows the open-loop transfer function of AVR, it is necessary to dealing with closed-loop system to measure the dynamic transient response parameters (max overshoot, settling and rise times, etc), so that it must be insert the feedback measurement sensor.

Fig.2 shows the arrangement of the AVR system parts as a closed loop. The generator's terminal voltage $V_t(s)$ is constantly detected by the sensor and compared to the required reference voltage $V_{ref}(t)$. The distinction between the reference and the sensed terminal voltages (e.g. error voltage) is amplified by the amplifier and used by the exciter to excite the generator.

Figure 2. Simplified AVR block diagram

Finally, the closed-loop transfer function (after connecting the sensor feedback element) is:

$$\frac{V_t(s)}{V_{ref}(s)} = \frac{G_{AVR}}{1 + G_{AVR}H_s} \quad (8)$$

$$\frac{V_t(s)}{V_{ref}(s)} = G_O(s) = \frac{0.0599s^3 + 5.994s^2 + 8.252s + 825.2}{0.00573s^6 + 0.644s^5 + 7.686s^4 + 55.571s^3 + 465.86s^2 + 879.208s + 1086} \quad (9)$$

The transfer function of AVR as appear in Equation (9) is sixth order, so we've tried to approximate it to second order.

3-AVR model reduction

There are many methods for model order reduction (Antoulas 2001) [20], but in this work an optimization method is used. Biogeography-based optimization (BBO) is an evolutionary algorithm that optimizes a function by stochastically and iteratively improving candidate. The BBO algorithm consists of two main operators: migration and mutation. This algorithm utilizes migration operator as a powerful tool to share information between habitats in the solution space. So, it can be considered as an exploitation mechanism during the optimization process. The migration operator shares information between habitats based on immigration (δ) and emigration (σ) rates, probabilistically. Each habitat has its own immigration (δ) and emigration (σ) rates which are the functions of species in the habitat. For a given habitat, the immigration (δ) rate is inversely proportional to the J (fitness) value, while the emigration (σ) rate is directly proportional to J value. The habitats with high immigration rates (poor solutions) are more likely to accept information from the other habitats with high J values, while the habitats with low immigration rates (good solutions) share their information with other poor habitats with a high probability. The fitness (J) is calculated as (Nazar and Hadidi 2012) [21]:

$$J = \sum_{i=0}^k [y(t_i) - y_k(t_i)] \quad (10)$$

While, the immigration and emigration rates are calculated for each habitat as follows:

$$\delta = l * (1 - \frac{s}{s_{max}}) \quad (11)$$

$$\sigma = \frac{E * S}{s_{max}} \quad (12)$$

Where:

S= maximum number of species

E =maximum emigration rate

l=maximum immigration rate

The parameters of BBO algorithm in this work are, Generation count limit =150, Population size=50, Mutation Probability = 0.06, Number of Elites = 2, Lower bound of each element= [0 0 0 0], Upper bound of each element= [1 5 5 5].

Refer to equation (9), of original system and using steps of (BBO) algorithm, by MATLAB program, it is found that the reduced transfer function is:

$$G_r = \frac{0.0003217s+2.401}{1.2775s^2+2.386s+3.171} \quad (13)$$

The step responses of the reduced order model and the original system are compared in Fig.3.

Figure 3. Step Response Comparison of Original and Reduced Order systems

Finally, table.1, shows the performance comparison between original and reduced order systems.

Table 1. shows the performance comparison between original and reduced systems

Property	Original	Reduced system(BBO)
Rise time (sec)	1.03	1.07
Settling time (sec)	4.5	3.55
Overshoot %	10.9	9.71
peak	0.843	0.832
Peak time (sec)	2.42	2.38

4- FPI controller design

Oustaloup who initially presented the the fractional-order Controllers (FOC). He urbanized the three different form of the CRONE controller with the end goal that first, second and third generation controllers were developed (Yangquan et al. 2009) [22]. (I. Podlubny1999) [23] exhibited the primary report on fractional order PID controller. He authored an idea of fractional order PID controller which is the expansion of the old style PID controllers, where a PID controller structure with an integrator of order λ and a differentiator of order μ was presented (Lu and Shuo2015) [25].

The structure of FPID controller is in the parallel form:

$$C(s) = Kp + \frac{K_i}{s^\lambda} + Kds^\mu \quad (14)$$

A- Tuning Of FPID Controller

There are several methods for tuning FPID controller in literature. According to (Valerio and Costa 2010) [26], tuning methods can be divided into three different categories as follow:

1-Rule-based methods

The auto-tuning and internal model control (IMC) methods are also used for tuning of fractional order controllers (Concepcion et al.2008) [10]. Ziegler Nichols type rules for FPID controller were proposed in (Valerio and Costa 2006) [27]. This method is only applicable, where plant response is similar to S-shaped behavior for a step input.

2-Analytical methods

A tuning method for the fractional order system based on analytical method was proposed in (Chunna and Dingyu 2005) [24]. Parameters of the FPID controller were obtained by solving equations that were obtained from the desired specifications. The tuning method based on the specifications as well as the proposed auto-tuning method for FPID controller based on the relay test was described in [10,28].

3-Numerical (optimization) methods

The tuning of fractional order controllers based on numerical methods has been proposed by many researchers. Based on a genetic algorithm (Cao et al. 2005)[29]proposed tuning of FPID using integral of time-weighted absolute error (ITAE) and control input as a performance index. In (Chang and Chen 2009) [30] also suggested tuning of FPID using an adaptive genetic algorithm for the active magnetic bearing system. Based on the genetic algorithm (Das et al.2012) [31], tuning rules have been developed using time domain performance index.

In this work using an optimization method in frequency domain to design FPID controller for AVR.

B- Proposed Method of FPID Controller Design

The concept of frequency domain design of $PI^\lambda D^\mu$ controllers was first proposed by (Concepcion et al.2008) [10]. If $G(s)$ is the transfer function of the process, then the objective is to find out a controller $C(s)$, so that the open loop system $G(s)C(s)$ meets the following design specifications [27,32].

1. Phase Margin Specification

Consider:

$$Arg(G(j\omega_{gc})C(j\omega_{gc})) = -\pi + \varphi_m \quad (15)$$

Where φ_m the desired phase is margin and ω_{gc} is the desired gain crossover frequency.

2. Gain Crossover Frequency Specification

Consider:

$$|G(j\omega_{gc})C(j\omega_{gc})| = 1 \quad (16)$$

3. Robustness against System's Gain Variation

Consider:

$$\left(\frac{d}{d\omega} (Arg[G(j\omega)C(j\omega)]) \right)_{\omega=\omega_{gc}} \quad (17)$$

4. Complementary Sensitivity Specification

Consider:

$$|T(j\omega)|_{dB} = \left| \frac{G(j\omega)C(j\omega)}{1+G(j\omega)C(j\omega)} \right|_{dB} \leq AdB$$

$$\forall \omega \geq \omega_t \text{ (rad/s)} \Rightarrow |T(j\omega)|_{dB} = AdB \quad (18)$$

Where A is the specified magnitude of the complementary sensitivity function or noise attenuation for frequencies for all $\omega \geq \omega_t$ (rad/s).

5. Sensitivity Specification

Consider:

$$|S(j\omega)|_{dB} = \left| \frac{1}{1+G(j\omega)C(j\omega)} \right|_{dB} \leq BdB$$

$$\forall \omega \geq \omega_s(\text{rad/s}) \Rightarrow |S(j\omega)|_{dB} = BdB \quad (19)$$

Where B is the specified magnitude of the sensitivity function or load disturbance rejection for frequencies for all $\omega \geq \omega_t$ (rad/s).

Now five specifications (15)-(19) have been solved using optimization algorithm to obtain the $PI^{\lambda}D^{\mu}$ controller parameters.

To formulate the objective function (also known as fitness function), equation (15) and equation (16) can be combined as in [48].

$$J_1 = \text{Re}\{G(j\omega_{gc})C(j\omega_{gc})\} + \cos(\varphi_m)$$

$$J_2 = \text{Im}\{G(j\omega_{gc})C(j\omega_{gc})\} + \sin(\varphi_m) \quad (20)$$

From equations (17), (18) and (19) let:

$$J_3 = \left(\frac{d}{d\omega} (\text{Arg}[G(j\omega)C(j\omega)]) \right)_{\omega=\omega_{gc}} \quad (21)$$

$$J_4 = \{|T(j\omega_t) - 10^{A/20}|\} \quad (22)$$

$$J_5 = \{|S(j\omega_{gc}) - 10^{10/20}|\} \quad (23)$$

Now, the objective function J which is minimized to satisfy specifications (20)-(23) is given as.

$$J = \omega_1 \times |J_1| + \omega_2 \times |J_2| + \omega_3 \times |J_3| + \omega_4 \times |J_4| + \omega_5 \times |J_5| \quad (24)$$

where $|J_1|$, $|J_2|$, $|J_3|$, $|J_4|$, and $|J_5|$ are the magnitudes of J_1, J_2, J_3, J_4 , and J_5 , respectively. $\omega_1, \omega_2, \omega_3, \omega_4$ and ω_5 are corresponding weights assigned to J_1, J_2, J_3, J_4 , and J_5 .

In this work, (DE) is used to minimize the object function in equation (24). In (Storn and Price 1997)[33] proposed a new floating point encoded evolutionary algorithm for global optimization and named it DE owing to a special kind of differential operator, which they invoked to create new offspring from parent chromosomes instead of classical crossover or mutation. Easy methods of implementation and negligible parameter tuning made the algorithm quite popular very soon. This algorithm is similar to Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) but DE has some advantages. Fig.4 shows the flow graph of DE algorithm.

Figure 4. Flow graph of differential evolution algorithm

Steps of DE are given as in (Trias et al. 2013) [34]. In this study, the selections of the DE algorithm parameters are:

Maximum Number of Iterations= 150, Population Size =10, $\beta_{min} = 0.2$, $\beta_{max} = 0.8$, Crossover Probability = 0.2, VarMin= [0 0 0 0], VarMax= [10 10 1.5 10 1.5].

The values of all weights are considered as $\omega_1=\omega_2=\omega_3=\omega_4=\omega_5=1$. After tuning is done, the value of FOPID parameters K_p, K_i, K_d, λ and μ comes out to be 3.0323, 2.2977, 0.71934, 1.0034 and 1.3385 respectively. The Bode diagram of open loop system is given in Fig.5. As it can be seen, the gain crossover frequency specification, $\omega_{gc} = 2$ rad/sec, and the phase margin specification, $\varphi_m = 79.2681$ deg, are fulfilled. Besides, the phase of the system is forced to be flat at ω_{gc} and so, to be almost constant within an interval around ω_{gc} . It means that the systems is more robust to gain changes and the overshoot of the response is almost constant within this interval. The magnitudes of the functions T(s) and S(s) are shown in Figs.6, 7, respectively. As it can be observed,

$|T(j\omega)|_{dB} = -20dB$ for $\omega \geq \omega_t = 100$ rad/ sec, and $|S(j\omega)|_{dB} = -20dB$ for $\omega \leq \omega_s = 0.1$ rad/ sec, fulfilling the specifications. Fig.8 shows the step response of FOPID controller using DE algorithm with frequency domain parameters. Where the $M_p=0\%$, $T_s=4.1$ sec, $T_r=1.021$ sec and $ess=0$.

Figure 5. Bode plots of the open-loop system controller with AVR system

Figure 6. Magnitude of T(s)

Figure 7. Magnitude of S(s)

Figure 8. Step response of FOPID Controller using DE algorithm of proposed method

To show the robustness properties of the controlled system, by applying a disturbance signal of (-0.2), (0.2) at time=2sec and 4sec which are applied to the system, as shown in Fig.9.it is clearly that the

controller (DE) can reject the disturbance and achieve a suitable performance.

Figure 9. Disturbance rejection effects of AVR system response using DE-PI^λD^μ for dynamic object function.

6. Controllers study comparison

In this section, fractional-order controllers were introduced, namely:

A- Tilt-Integral-Derivative (TID) controller

It was first proposed by (Lurie1994) [35] and summarized in(Xue,2002) [36].It can be described by the following transfer function :

$$C_{T(s)} = \frac{K_t}{s^n} + \frac{K_i}{s} + K_d s \quad (25)$$

Where $\frac{K_t}{s^n}$ is the Tilt type compensator and $n > 0$.

It can be seen, that the TID controller corresponds to a conventional PID controller with proportional gain replaced by the compensator component.

It is required to find the optimal values of the TID controller gains (K_t, K_i , and K_d), and these, $K_t=8.3237$; $n=3$; $K_i=10$; $K_d= 4.5856$. Where these values are taken from the best optimization of DE with frequency response, and the transient parameters are:

$T_s=4.94\text{sec}$, $M_p =8.19\%$, $Tr=0.39$, and $ess=0$. Fig.10 shows step response of TID Controller.

Figure 10. Step response of TID Controller

B- Fractional Order Lead-Lag Compensator (FOLLC)

Lead compensators are mostly utilized to stabilize the marginally stable systems. Lag compensators are mostly utilized to reduce the magnitude of the system high frequency loop gain. The use of fractional order elements in this lag-lead compensator gives greater flexibility to the designer, to shape the loop frequency responses since the order of the filter can take any real value instead of only integer values the transfer function of (FOLLC) is given by(Xue,2002) [36]:

$$C_{LL} = K_c x^\alpha \left(\frac{\lambda s + 1}{x \lambda s + 1} \right)^\alpha, \quad 0 < x < 1 \quad (26)$$

where α is the fractional order of the controller, λ and x are parameters such that $1/\lambda = \omega_z$ is the zero frequency and $1/x\lambda = \omega_p$ is the pole frequency and K_c is controller gain.

In this paper a method is proposed for the auto-tuning of the fractional lead-lag compensator in equation (26), using relay tests (Xue,2002)[36].The fractional lead compensator is designed with parameters $k_c = 7.83$, $x = 0.05$, $\lambda = 0.364$, $\alpha = 0.5$. Fig.11 shows the step response of (FOLLC).

Figure 11. Step response of FOLLC Controller

The proposed method compared with classical PID controller by using MATLAB pidtuner, the values of this controller $K_p=2.92$, $K_i=2.98$ and $K_d=0.647$. Fig.12 shows the step response of PID Controller. Where $T_s=3.37\text{sec}$, $M_p=6.65\%$, $Tr=0.67\text{sec}$ and $ess=0$.

Figure 12. Step response of PID Controller

Table 2. shows the performance comparison between all controllers, as seen from table the proposed method (FPID controller) appears no overshoot, but sluggish response when compared with classical PID controller, while the worst case in TID controller. It can be concluded from simulations, that the FOPID controller has more robust stability and more efficient for disturbances rejection and change system parameters. Fractional controllers achieve good performances for plants. They often achieve a significant degree of robustness.

Table 2. Shows the performance comparison between all controllers

Controller Types	Mp%	Ts(sec)	Tr(sec)	ess
Classical PID	6.65	3.37	0.67	0
TID	8.19	4.94	0.39	0
FOLLC	26.1	2.1	0.262	0
Proposed method	0	4.1	1.02	0

Conclusion

In this paper, a design method to determine optimal FPID controller's parameters using the frequency response approach is proposed. The regulated voltage of AVR is controlled by FPID-DE controller. The simulation of AVR showed that the proposed controller can perform an efficient search for the optimal FPID controller. The results showed that, when compared to the classical PID, TID and FOLLC controllers- the proposed method improves the dynamic performance of the system. The proposed FPID-DE controller presented better satisfactory performance and possessed good robustness over PID. Moreover, it was found that the proposed FPID-DE controller converged quicker than the PID and TID. The proposed method introduces accuracy as well as convergence speed and simplicity. The results show that the robustness properties of the controlled system are satisfied in phase margin, change parameters and noise rejection.

Declaration of Conflict of Interests

The authors declare that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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