Design FOPID Control of an Automatic Voltage Regulator (AVR) System
Imperialist Competitive Algorithm

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Abstract

This paper addresses a robust method for optimal Fractional order PID (FOPID) control of automatic Voltage Regulation (AVR) system to damp terminal voltage oscillation following disturbances in power systems. The optimization is carried out by the Imperialist Competitive algorithm Optimization (ICA) to improve their situation. The optimal tuning problem of the FOPID gains to control of AVR system against parametric uncertainties is formulated as an optimization problem according to time domain based objective function. It is carried out under multiple operation conditions to achieve the desired level of terminal voltage regulation. The results analysis reveals that the ICA based FOPID type AVR control system is effective and provides good terminal voltage oscillations damping ability.

Keywords: ICA Algorithm; Fractional order PID; fractional calculus; PID control; Automatic Voltage Regulator

1. Introduction

In recent years, the scale of power systems has been expanded, and with that stability and constancy of nominal voltage level in an electric power grid is becoming more important. One of method for increasing stability and achieving nominal voltage level in an electric power grid is raising the voltage or employing series capacitors in power transmission lines, but controlling of generator exciter by using of Automatic Voltage Regulator (AVR) is attracting attention because of its inherent cost advantage [1]. The generator excitation system maintains generator voltage and controls the reactive power flow using an automatic voltage regulator [4]. The task of an AVR system is to hold the terminal voltage magnitude of a synchronous generator at a specified level. Thus, the stability of the AVR system would seriously affect the security of the power system. Despite the potential of the modern control techniques with different structure, Proportional Integral Derivative (PID) type controller is still widely used for AVR system [2]. This is because it performs well for a wide class of process. Also, they give robust performance for a wide range of operating conditions and easy to implement. On the other hand, Mukherjee and Ghoshal [3] have presented a comprehensive analysis of the effects of the different PID controller parameters on the overall dynamic performance of the AVR system. It is shown that the appropriate selection of PID
controller parameters results in satisfactory performance during system upsets. Thus, the optimal tuning of a PID gains is required to get the desired level of robust performance. Since optimal setting of PID controller gains is a multimodal optimization problem (i.e., there exists more than one local optimum) and more complex due to nonlinearity, complexity and time-variability of the real world power systems operation. Hence, local optimization techniques, which are well elaborated upon, are not suitable for such a problem [5].

In this study, the problem of robustly FOPID gains tuning is formulated as an optimization problem based on time domain based objective function. The optimization is carried out under multiple operation points by Genetic algorithm such that the relative stability is guaranteed and the time domain specifications concurrently secured.

Results evaluation show that the proposed method is effective and alternative to FOPID fixed gain controller design as it retains the simplicity of the controller and still guarantees a robust acceptable performance over a wide range of operating and system conditions.

2. Fractional-Order Derivative and Its Approximation

Definition

The differ integral operator, represented by $0^{\alpha}_{t}D$, is a combined differentiation-integration operator commonly used in fractional calculus and general calculus operator, including fractional-order and integer is defined as:

$$0^{\alpha}_{t}D = \begin{cases} \frac{d^{\alpha}}{dt^{\alpha}} & \alpha > 0 \\ 1 & \alpha = 0 \\ \int_{0}^{t} (dt)^{-\alpha} & \alpha < 0 \end{cases}$$  \hspace{1cm} (1)

There are several definitions of fractional derivatives [7]. The best-known one is the Riemann-Liouville definition, which is given by

$$\frac{d^{\alpha}f(t)}{dt^{\alpha}} = \frac{1}{\Gamma(n)} \frac{d^{n}}{dt^{n}} \int_{0}^{t} f(\tau) (t-\tau)^{\alpha-n+1} d\tau$$  \hspace{1cm} (2)

Where $n$ is an integer such that $n - 1 < \alpha < n$, $\Gamma(0)$ is the Gamma function. The geometric and physical interpretation of the fractional derivatives was given as follows

$$\Gamma(z) = \int_{0}^{\infty} e^{-t} t^{z-1} dt$$  \hspace{1cm} (3)

The Laplace transform of the Riemann-Liouville fractional derivative is

$$L\left\{ \frac{d^{\alpha}f(t)}{dt^{\alpha}} \right\} = s^{\alpha} L\{f(t)\} - \sum_{k=0}^{n-1} s^{k} \left[ \frac{d^{\alpha-k-1}f(t)}{dt^{\alpha-k-1}} \right]$$  \hspace{1cm} (4)

Where, $L$ means Laplace transform, and $s$ is a complex variable. Upon considering the initial conditions to zero, this formula reduces to
\[ L\left\{ \frac{d^\alpha f(t)}{dt^\alpha} \right\} = s^\alpha L\{f(t)\} \quad (5) \]

The Caputo fractional derivative of order \( \alpha \) of a continuous function \( f: \mathbb{R}^+ \to \mathbb{R} \) is defined as follows

\[
\frac{d^\alpha f(t)}{dt^\alpha} = \begin{cases} 
\frac{1}{\Gamma(m-\alpha)} \int_0^t \frac{f^{(m)}(\tau)}{(t-\tau)^{\alpha-m+1}} d\tau & m-1 < \alpha < m \\
d^m \frac{d^m f(t)}{dt^m} & \alpha = m 
\end{cases}
\quad (6)
\]

Thus, the fractional integral operator of order \( \alpha \) can be represented by the transfer function \( H(s) = \frac{1}{s^\alpha} \) in the frequency domain.

The standard definition of fractional-order calculus does not allow direct implementation of the fractional operators in time-domain simulations. An efficient method to circumvent this problem is to approximate fractional operators by using standard integer-order operators. In Ref [10], an effective algorithm is developed to approximate fractional-order transfer functions, which has been adopted in [11] and has sufficient accuracy for time-domain implementations. In Table 1 of Ref [12] approximations for \( \frac{1}{s^\alpha} \) with \( \alpha \) from 0.1 to 0.9 in step 0.1 were given with errors of approximately 2 dB. We will use the \( \frac{1}{s^{0.95}} \) approximation formula [11] in the following simulation examples.

\[
\frac{1}{s^{0.95}} \approx \frac{1.2831s^2 + 18.6004s + 2.0833}{1.2831s^3 + 18.4738s^2 + 2.6574s + 0.003} \quad (7)
\]

In the simulation of this paper, we use approximation method to solve the fractional-order differential equations.

3. Fractional order controllers

The differential equation of fractional order controller \( PI^\alpha D^\beta \) is described by:

\[
u(t) = K_p e(t) + K_i \tau^{-\lambda} e(t) + K_d \tau^{-\delta} e(t).
\quad (8)
\]

The continuous transfer function of FOPID is obtained through Laplace transform, which is given by:

\[
G_c(s) = K_p + K_i s^{-\lambda} + K_d s^{-\delta} \quad (9)
\]
It is obvious that the FOPID controller not only need design three parameters, $K_p, K_i$ and, $K_d$ but also design two orders, $\lambda, \delta$ of integral and derivative controllers. The orders $\lambda, \delta$ are not necessarily integer, but any real numbers. As shown in Figure 3 the FOPID controller generalizes the conventional integer order PID controller and expands it from point to plane. This expansion could provide much more flexibility in PID control design [13].
4. Imperialist Competitive Algorithm (ICA)

Imperialist Competitive Algorithm is a new evolutionary optimization method which is inspired by imperialistic competition and has been applied in some different fields [14]. Like other evolutionary algorithms, it starts with an initial population which is called country and is divided into two types of colonies and imperialists which together form empires. Imperialistic competition among these empires forms the proposed evolutionary algorithm. During this competition, weak empires collapse and powerful ones take possession of their colonies [15]. Imperialistic competition converges to a state in which there exists only one empire and colonies have the same cost function value as the imperialist. After dividing all colonies among imperialists and creating the initial empires, these colonies start moving toward their relevant imperialist state which is based on assimilation policy. Figure 6 shows the movement of a colony towards the imperialist. In this movement, θ and x are random numbers with uniform distribution as illustrated in Equation 10 and d is the distance between colony and the imperialist [16]

\[ X \sim U(0, \beta \times d), \theta \sim U(-\gamma, \gamma) \] (10)

Where β and γ are parameters that modify the area that colonies randomly search around the Imperialist.

![Figure 4. Motion of colonies toward their relevant imperialist](image)

The total power of an empire depends on both the power of the imperialist country and the power of its colonies which is shown in Equation (11).

\[ T.C.n = \text{Cost (imperialist)} + \zeta \times \text{mean \{Cost (colonies of impiren)\}} \] (11)

Figure 4 shows a big picture of the modeled imperialistic competition. Based on their total power, in this competition, each of the empires will have a likelihood of taking possession of the mentioned colonies. The more powerful an empire, the more likely it will possess the colonies. In other words these colonies will not be certainly possessed by the most powerful empires, but these empires will be more likely to possess them. Any empire that is not able to succeed in imperialist competition and cannot increase its power (or at least prevent decreasing its power) will be eliminated [17].
With the implementation of optimization algorithms, the coefficients of the FOPID controller become optimal. In order to compare, based on cost function or Equation 11, we will display the performance (response) of these algorithm in Figure 8. According to the responses, Rise and Settle Time, easily we can select the ICA Algorithm has better performance and it will be optimized Algorithm in FOPID Controller

5. AVR System Modeling

The task of an AVR system is to hold the terminal voltage magnitude of a synchronous generator at a specified level. Thus, the stability of the AVR system would seriously affect the security of the power system. A simpler AVR system contains five basic components such as amplifier, exciter, generator, sensor and comparator. The real model of such a system is depicted in Figure 6. A unit step response of this system without control has some oscillations which reduce the performance of the regulation. Thus, a control technique must be applied to the AVR system. For this reason, the PID block is connected to amplifier seriously. The A small signal model of this system including PID controller which is constituted through the transfer functions of these components is depicted in Figure 3, and the limits of the parameters used in these transfer functions are presented in Table 1 [3].
Table 1. Parameters of AVR model with transfer function and parameter limits

<table>
<thead>
<tr>
<th>Transfer function</th>
<th>Parameters limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>PID controller</td>
<td>$k_p + \frac{k_i}{s} + k_d \frac{N}{1 + \frac{N}{s}}$</td>
</tr>
<tr>
<td>Amplifier</td>
<td>$TF_{amplifier} = \frac{K_a}{1 + \tau_a s}$</td>
</tr>
<tr>
<td>Exciter</td>
<td>$TF_{exciter} = \frac{K_e}{1 + \tau_e s}$</td>
</tr>
<tr>
<td>Generator</td>
<td>$TF_{generator} = \frac{K_g}{1 + \tau_g s}$</td>
</tr>
<tr>
<td>Sensor</td>
<td>$TF_{sensor} = \frac{K_s}{1 + \tau_s s}$</td>
</tr>
</tbody>
</table>

6. Simulation

We want to design a controller for the AVR system the fitness functions for the system are chosen as follows.

$$F = \min \{ (1 - e^{-\beta})(M_p + E_{ss}) + (e^{-\beta})(T_s + T_r) \}$$

The fitness is to reduce errors and overshoot. $\alpha$ And $\beta$ is the weighted standard error and overshoot.
Figure 9. Fitness convergence in ICA method

Figure 10. Terminal voltage step response of AVR without controller

Figure 11. Terminal voltage step response of AVR system controlled by ICA-FOPID controller
7. Conclusions

This paper presents a novel and effective optimization algorithm to FOPID control design of AVR system using the ICA algorithm in order to improve electromechanical oscillations in a power system. The main feature of ICA is that it converges in the limit to a globally optimal solution with probability one under mild conditions. The problem of optimal tuning of FOPID gains is formulated as an objective optimization problem for a wide range of uncertain plant parameter changes. The results showed that the proposed approach is efficient to tune FOPID controller for AVR system.

References


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