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Research Article

Fractional adaptive control for an automatic voltage regulator

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ABSTRACT

This paper presents the application of a direct Fractional Order Model Reference Adaptive Controller (FOMRAC) to an Automatic Voltage Regulator (AVR). A direct FOMRAC is a direct Model Reference Adaptive Control (MRAC), whose controller parameters are adjusted using fractional order differential equations. Four realizations of the FOMRAC were designed in this work, each one considering different orders for the plant model. The design procedure consisted of determining the optimal values of the fractional order and the adaptive gains for each adaptive law, using Genetic algorithm optimization. Comparisons were made among the four FOMRAC designs, a fractional order PID (FOPID), a classical PID, and four Integer Order Model Reference Adaptive Controllers (IOMRAC), showing that the FOMRAC can improve the controlled system behavior and its robustness with respect to model uncertainties. Finally, some performance indices are presented here for the controlled schemes, in order to show the advantages and disadvantages of the FOMRAC.

1. Introduction

Adaptive control refers to the control of partially known systems. This uncertainty may be caused by unknown (fixed or time-varying) system parameters, and/or the plant being only partially modeled or subjected to external disturbances. In these cases, conventional control theory does not achieve satisfactory performance, whereas adaptive control has been a very useful tool, given its ability to adjust parameters automatically by means of adaptive laws, which allow dealing with uncertainty while achieving the desired system behavior.

One of the most popular adaptive control schemes is Model Reference Adaptive Control (MRAC), where the aim is to find a suitable control signal such that the controlled system output follows the reference model output, while at the same time the stability of the closed loop system is preserved [14].

The subject of fractional calculus (calculus of integrals and derivatives of arbitrary real or complex order) has gained considerable interest and importance during recent years, mainly due to its demonstrated applicability in numerous seemingly diverse and widespread fields of science and engineering [10].

There has been growing interest in combining classical MRAC schemes and fractional calculus in recent years. Some MRAC schemes have been proposed, in which the model of the plant to be controlled, the reference model and/or the adaptive laws for adjusting the parameters are defined by fractional order differential equations [20,12,13,22,18].

The lifestyle of modern society is deeply linked to the use of electricity. Most of the equipment used today operates on the basis of electrical energy, and is sensitive to both the continuity of the power supply, and its quality (voltage and frequency levels).

The power demand is never constant in power generation systems, and this affects the output voltage and frequency levels of the generators. For this reason, any power generation system should have a control scheme, in order to maintain the voltage and frequency levels within desired values, regardless of the demand.

The Automatic Voltage Regulator (AVR) is the controller whose main purpose is to maintain the voltage level in an electric generator at acceptable values by adjusting the generator exciter voltage.

Many control schemes have been proposed for AVR. PID controllers are the most reported control scheme for the AVR, and the difference between these works lies in the technique used to select the PID parameters. It can be cited for example PID controllers whose parameters have been adjusted using Particle Swarm Optimization (PSO) [7,16], using third order PSO [8], using Quantum-behaved PSO [2], using optimization method based in Continuous Action Reinforcement Learning Automata (CARLA) [9], using Adaptive Tabu Search algorithm [15], and using combined genetic algorithm and fuzzy logic approach [3].

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Other control schemes have been proposed, different from PIDs, such as Fuzzy Gain Scheduled PI Controllers (FGSPIC) [17], Brain Emotional Learning Intelligent Controllers (BELBIC) [19], Nonlinear adaptive controllers [6] and Fractional order PID controllers [23]. This last one is a fractional PID, whose parameters are adjusted using PSO. However, given the importance of the control problem, this topic is still open to control solutions that would improve the performance of the controlled system, for example minimizing the overshoot and the convergence time of the control error to zero.

This paper presents a direct Fractional Order Model Reference Adaptive Controller (direct FOMRAC) for an AVR, where the parameters of the controller are adjusted using adaptive laws defined by fractional order differential equations. This FOMRAC shows an improvement in characteristics of the response of the controlled system and in robustness with respect to model uncertainties.

The paper is organized as follows: Section 2 introduces general concepts of direct FOMRAC, fractional calculus and Genetic algorithm optimization. In Section 3 the model of the plant to be controlled is presented, and the proposed fractional adaptive control scheme is introduced. Section 4 contains the results obtained through simulations of the proposed control scheme, and its comparison with other control schemes proposed in the control literature. Section 5 contains the evaluation of the system behavior for the different control schemes studied, making use of various performance indices. Finally, Section 6 presents the conclusions of the work.

2. General concepts

This section introduces some general concepts, which are used throughout the work, in order to ease the understanding of the proposed schemes.

2.1. Fractional calculus

In fractional calculus, the traditional definitions of the integral and derivative of a function are generalized from integer orders to real orders.

In the time domain, the fractional order derivative and fractional order integral operators are defined by a convolution operation.

According to Kilbas et al. [10], the Riemann–Liouville fractional integral of order $\alpha \in \mathbb{R}$, with $\alpha \geq 0$ and denoted as ${}^{R}I_0^{\alpha}$, is defined as

$$ {}^{R}I_0^{\alpha} f(t) = \frac{1}{\Gamma(\alpha)} \int_0^t \frac{f(\tau)}{(t-\tau)^{1-\alpha}}\, d\tau, \quad t > 0 \tag{1} $$

where $\Gamma(\alpha)$ is the Gamma function, defined as

$$ \Gamma(\alpha) = \int_0^{\infty} t^{\alpha-1} e^{-t}\, dt $$

Several definitions exist regarding the fractional derivative of order $\alpha \geq 0$, but the Caputo definition defined in (2) is used the most in engineering applications, since this definition incorporates initial conditions for $f(\cdot)$ and its integer order derivatives, i.e., initial conditions that are physically appealing in the traditional way:

$$ {}^{C}D_0^{\alpha} f(t) = \frac{1}{\Gamma(n-\alpha)} \int_0^t \frac{f^{n}(\tau)}{(t-\tau)^{\alpha-n+1}}\, d\tau, \quad n-1 < \alpha < n, \ \ n \in \mathbb{Z}^{+} \tag{2} $$

One of the most common ways of using fractional integrals and derivatives in simulations and practical implementations is by means of numerical approximations of these operators. The idea is to obtain integer-order transfer functions whose behavior approximates the fractional order Laplace operator:

$$ C(s) = ks^{\alpha} \tag{3} $$

Oustaloup's method is one of the available frequency-domain methods for making this approximation, which uses a recursive distribution of N poles and N zeros [21] of the form

$$ C(s) = k' \prod_{n=1}^{N} \frac{1 + s/\omega_{zn}}{1 + s/\omega_{pn}} \tag{4} $$

The gain k' is adjusted so that if $k=1$ then $|C(s)| = 0$ dB at 1 rad/s. Zeros and poles are placed inside a frequency interval $[\omega_l, \omega_h]$.

This approximation is available in the fractional derivative block of the Ninteger Toolbox for Matlab [4], and is the one used in this work.

2.2. Fractional model reference adaptive control

According to Narendra and Annaswamy [14], the Model Reference Adaptive Control (MRAC) problem can be stated qualitatively as follows: let a linear time-invariant (LTI) plant P be defined by input–output pairs $\{u(\cdot), y_p(\cdot)\}$. Let a stable LTI reference model M be defined by its input–output pair $\{r(\cdot), y_m(\cdot)\}$ where $r : \mathbb{R}^{+} \rightarrow \mathbb{R}$ is a bounded piecewise-continuous function. The aim of the MRAC is to determine the control input $u(t)$ for all $t \geq t_0$ so that

$$ \lim_{t \to \infty} |y_p(t) - y_m(t)| = 0 $$

In the case of direct MRAC, the parameters of the controller are directly adjusted; that is to say, no identification of the plant parameters is attempted.

For the classical direct MRAC, the controller parameters are adjusted by using a differential equation of integer order (adaptive law). In the case of direct FOMRAC, the controller parameters are adjusted using a differential equation of fractional order (fractional adaptive law), with the same structure of the adaptive laws used in the integer order MRAC [14], but the derivative order is fractional. Details of the fractional adaptive law are given in Table 1.

In this work, a direct FOMRAC has been implemented for the AVR. In general terms, the control scheme is defined as follows.

Given a known reference model, defined by the transfer function $G_m(s)$, a reference signal $r(t)$ is applied to obtain the measurable output $y_m(t)$. This output is compared with the AVR output voltage $y_p(t)$ to compute the control error defined as $e(t) = y_p(t) - y_m(t)$.

Using this control error and other available signals in the control scheme, the controller parameters are adjusted, using a fractional

Table 1
Fractional MRAC implementations details.

Reference model	$G_m(s) = \dfrac{1.2}{s^3 + 5.2s^2 + 7s + 1.2}$
Control law	$u(t) = \theta(t)^T \omega(t)$
	$\theta^T(t) = [k(t) \quad \theta_1 T(t) \quad \theta_0(t) \quad \theta_2^T(t)] \in \mathbb{R}^{10}$
	$\omega(t) = [r(t) \quad \omega_1^T(t) \quad y_p(t) \quad \omega_2^T(t)]^T \in \mathbb{R}^{10}$
Auxiliary signals	$\dot{\omega}_1(t) = \Lambda \omega_1(t) + lu(t)$
	$\dot{\omega}_2(t) = \Lambda \omega_2(t) + ly_p(t)$
	$\Lambda = \begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & -2 & 0 & 0 \\ 0 & 0 & -3 & 0 \\ 0 & 0 & 0 & -4 \end{bmatrix}$
	$l = [-1\ 1\ 3\ 4^T$
Errors	$e_1(t) = y_p(t) - y_m(t)$
	$e_2(t) = \theta^T(t)\overline{\omega}(t) - \overline{u}(t)$
	$\varepsilon(t) = e_1(t) + k_1(t) e_2(t)$
	$\overline{u}(t) = G_m(s) u(t)$
Adaptive law	$D^{\alpha} k_1(t) = -\gamma \dfrac{\varepsilon(t) e_2(t)}{1 + \overline{\omega}(t)\overline{\omega}^T(t)}$
	$D^{\alpha} \theta(t) = -\gamma \dfrac{\varepsilon(t)\overline{\omega}(t)}{1 + \overline{\omega}(t)\overline{\omega}^T(t)}$
	$\overline{\omega}(t) = G_m(s)\omega(t)$