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ORIGINAL ARTICLE

Fractional order nonlinear variable speed and current regulation of a permanent magnet synchronous generator wind turbine system

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Abstract In this paper we derived the fractional order model of the Permanent Magnet Synchronous Generator (PMSG) from its integer model. The PMSG was employing a shaft sensor for the speed sensing and control. But this sensor would increase the hardware complexity as well as the cost of the system. Hence we have developed a Fractional order Nonlinear adaptive control method for speed and current tracking of the PMSG. The objective of an adaptive controller is to first define a virtual control state and force it to become a stabilizing function in accordance with a corresponding error dynamics. In order to study the Lyapunov exponents of the fractional order controller, we proposed a new method which would remove the complexity of finding the sign of the Lyapunov first derivative. The Fractional order control scheme is implemented in LabVIEW for simulation results. The simulation results indicated that the estimated rotor position and speed correspond to their actual values well.

1. Introduction

The renewable nature and their reduced environmental impact of Wind energy plays an important role in the present and future power generation methods. Control mechanism of the Permanent Magnet Synchronous Generators (PMSGs) coupled with the wind turbines is of high complexity. Several control strategies of these control mechanisms are investigated by Robinson and Veers [1]. Most of the Wind Energy Generators operate at fixed speed except the initializing phase [2]. Fixed Speed of operation guarantees a high coefficient of performance and these speeds are often fixed for Wind turbines. To operate turbines at these speeds one has to control the Nonlinearity of the speed components [3].

Permanent Magnet Synchronous Motors (PMSMs) are the most preferred generation systems for Wind energy conversions. The chaotic behavior in the permanent magnet synchronous generator for wind turbine system is investigated, and the Active Disturbance Rejection Control (ADRC) strategy is proposed to suppress chaotic behavior and make operating stably [4]. The use of a predictive control strategy

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which was investigated with a one point controller of PMSG is studied and this control mechanism used Genetic Algorithms to estimate the optimal parameter values of the wind turbine leads to maximization of the power generation [5]. PMSG system controlled by the online-tuned parameters of the novel modified recurrent wavelet neural network (NN)-controlled system is proposed to control output voltages and powers of controllable rectifier and inverter [6].

The performance of the PMSM is sensitive to system parameter and external load disturbance in the plant. Some investigations, for example, by Li et al. [7] and Jing et al. [8] show that with certain parameter values, the PMSM displays chaotic behavior. It is found that with the help of fractional derivatives, many systems in interdisciplinary fields can be elegantly described [7–9]. Furthermore many integer order chaotic systems of fractional order have been studied widely [10–14]. All the physical phenomena in nature exist in the form of fractional order [15], and integer order (classical) differential equation is just a special case of fractional differential equation. The importance of fractional-order models is that they can yield a more accurate description and give a deeper insight into the physical processes underlying a long range memory behavior.

Chaos modeling has applications in many areas in science and engineering [15–17]. Some of the common applications of chaotic systems in science and engineering are chemical reactors, Brusselators, Dynamos, Tokamak systems, biology models, neurology, ecology models, memristive devices, etc. An analysis of saddle-node and Hopf bifurcations in indirect field-oriented control (IFOC) drives due to errors in the estimation of the rotor time constant providing a guideline for setting the gains of PI speed controller in order to avoid Hopf bifurcation [17]. It has been proven the occurrence of either codimension one bifurcation such as saddle node bifurcation and Hopf bifurcation or codimension two such as Bogdanov-Takens or zero-Hopf bifurcation in IFOC induction motors [18–21].

This paper investigates a Fractional order model of the dynamic normalized PMSG [5]. We first derived the dynamic properties of the Fractional order PMSG system, viz. bifurcation, bicoherence, Lyapunov exponents and the equilibria points. We then propose a Fractional order nonlinear adaptive controller for the speed and current control of the PMSG. We considered that all the parameters of the PMSG are unknown and hence derived parameter update laws. The stability of the proposed fractional order controllers is established through Lyapunov stability criterion.

2. Fractional order PMSG model

The mathematical model of a Wind turbine coupled PMSG is given by [5]

$$\begin{aligned}
\dot{w} &= \frac{p}{J}(\phi_f i_q + (L_d - L_q) i_d i_q) - \frac{f}{J} w - \frac{T_L}{J} \\
\dot{i}_q &= -\frac{R_s}{L_q} i_q + \frac{L_d}{L_q} p w i_d - \frac{p\phi_f}{L_q} w + \frac{u_q}{L_d} \\
\dot{i}_d &= -\frac{R_s}{L_d} i_d + \frac{L_q}{L_d} p w i_q + \frac{u_d}{L_d}
\end{aligned} \tag{1}$$

where u_q and u_d are quadrature and direct axis stator control voltages, i_q and i_d are quadrature and direct axis stator control currents, L_q and L_d quadrature and direct axis stator control inductances, p is the number of pole pairs, R_s is the stator resistance, ϕ_f is the rotor flux linkage with stator, T_L is the Load torque, J is the rotor moment of inertia, and f is the friction coefficient.

The fractional-order differential operator is the generalization of integer-order differential operator. There are three commonly used definitions of the fractional-order differential operator, *viz*. Grunwald–Letnikov, Riemann–Liouville and Caputo [23–25].

The fractional order model of PMSG is derived from (1) with the Caputo fractional order definition, which is defined as

$$D_t^\alpha f(t) = \frac{1}{\Gamma(1-\alpha)} \int_{t_0}^{t} \frac{\dot{f}(\tau)}{(t-\tau)^\alpha} d\tau \tag{2}$$

where α is the order of the system, t_0 and t are limits of the fractional order equation, and $\dot{f}(t)$ is integer order calculus of the function.

For numerical calculations we use Caputo via Riemann-Liouville fractional derivative [26] and the above equation is modified as

$$_{(t-L)}D_t^\alpha f(t) = \lim_{h\to 0}\left\{ h^{-\alpha} \sum_{j=0}^{N(t)} b_j (f(t - jh)\right\} \tag{3}$$

Theoretically fractional order differential equations use infinite memory. Hence when we want to numerically calculate or simulate the fractional order equations we have to use finite memory principal, where L is the memory length and h is the time sampling.

$$\begin{aligned}
N(t) &= \min\left\{ \left[\frac{t}{h}\right], \left[\frac{L}{h}\right] \right\} \\
b_j &= \left(1 - \frac{a+\alpha}{j}\right) b_{j-1}
\end{aligned} \tag{4}$$

Applying these fractional order approximations into the integer order model (1) yields the fractional order PMSG described by (5)

$$\begin{aligned}
D_t^{q_1} w &= \frac{p}{J}(\phi_f i_q + (L_d - L_q) i_d i_q) - \frac{f}{J} w - \frac{T_L}{J} \\
D_t^{q_2} i_q &= -\frac{R_s}{L_q} i_q + \frac{L_d}{L_q} p w i_d - \frac{p\phi_f}{L_q} w + \frac{u_q}{L_d} \\
D_t^{q_3} i_d &= -\frac{R_s}{L_d} i_d + \frac{L_q}{L_d} p w i_q + \frac{u_d}{L_d}
\end{aligned} \tag{5}$$

where q_1, q_2 and q_3 are the fractional orders of the respective states.

As the assumption is made that all the parameters of the PMSG model are uncertain, we are defining parameter update laws:

$$\begin{aligned}
&\tau = \frac{T_L}{J};\ e_\tau = \hat{\tau} - \tau;\ e_\tau = D_t^\alpha \hat{\tau},\ b = \frac{f}{J};\ e_b = \hat{b} - b;\ D_t^\alpha e_b = D_t^\alpha \hat{b} \\
&e_{R_s} = \hat{R}_s - R_s;\ D_t^\alpha e_{R_s} = D_t^\alpha \hat{R}_s,\ e_L = \hat{L} - L;\ D_t^\alpha e_L = D_t^\alpha \hat{L} \\
&e_J = \hat{J} - J;\ D_t^\alpha e_J = D_t^\alpha \hat{J}
\end{aligned} \tag{6}$$

3. Dynamics of the fractional order PMSG model

In this section we analyze the fractional order system for various properties of chaotic behavior such as equilibria points, Lyapunov exponents, bifurcation and bicoherence.

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