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Adaptive sliding-mode type-2 neuro-fuzzy control of an induction motor

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ABSTRACT

An innovative adaptive control method for speed control of induction motor based on field oriented control is presented in this paper. The fusion of sliding-mode and type-2 neuro fuzzy systems is used to control this system. An online learning algorithm based on sliding-mode training algorithm, and type-2 fuzzy systems is employed to deal with parametric uncertainties and disturbances, by adjusting the control parameters. The sliding-mode adaptive mechanism tune the parameters of type-2 membership functions (antecedent part) and the consequent part parameters, according to the inputs: speed error and its derivative, in structure of type-2 neuro fuzzy system. Since the parameters of the induction motor may vary, and the information that is used to construct the membership functions and the rules of fuzzy logic system is uncertain, type-2 neuro fuzzy structure is selected as the controller. The results obtained by using this approach are compared with those of type-1 counterpart. The proposed adaptive sliding-mode type-2 neuro-fuzzy controller can control the induction motor with higher performance as it is compared with type-1 neuro-fuzzy systems while it shows more robustness to variations in the parameters and measurement noise.

1. Introduction

Induction motors have been used widely for the industrial application like in which variable speed, low cost, high reliability and high performance are needed. There is a lot of control application for induction motors, like speed and torque control, energy optimization, flux control and monitoring, etc. (Chakraborty, Nakamura, & Okabe, 2015; Seera, Lim, Nahavandi, & Loo, 2014). The dynamical model of induction motors (IMs) is complex and nonlinear (Finch & Giaouris, 2008). The field oriented control of an IM is a practical method which results in high performance system response and simplifies the speed control of an IM (Kang & Nam, 2005). The simplification, this method makes to the control of IM makes it dynamics similar to a separately excited DC motor (Pucci, 2012). This method can also be used in sensorless control of IM because it needs the feedback from the flux and the state variable of IM (Kang & Nam, 2005; Mondal, Bose, & Oleschuk, 2003).

Classical control systems such as PI are used along with field oriented control methods for the speed control of IM (Ho & Sen, 1990). However, the design of these controllers needs to have an exact mathematical model of the motor and its accurate parameter values, Hence these controllers are sensitive to motor parameters and load variations (Kowalska, Szabat, & Jaszczak, 2002; Ustun & Metin, 2008). To overcome with these problems, variable structure control methods such as sliding mode control (SMC) (Wai, 2000), fuzzy logic based control (Fan & Zhang, 2011) and the combination of fuzzy and neural network control (Dandil, 2009; Yousef & Wahba, 2009) may be used.

SMC is a class of variable structure controllers which shows high robustness with respect to modeling uncertainties and external disturbances (Panchade, Chile, & Patre, 2013). The main advantage of SMC is that it benefits from a switching control law which makes it possible to guarantee the stability of the system (Toledo, Gennaro, Loukianov, & Rivera, 2008). However, the switching control law injects chattering into the system. Fuzzy control methods are robust, less model dependent. They can be easily used to model linguistic rules (Cerman, 2013). Fuzzy sliding mode control is an effective method that it uses the expert knowledge, without need to knowing the parameters and structure of the control system (Rehman & Dhaouadi, 2008). On the other hand, this method has a major disadvantage which is the lack of methodical design techniques for the fuzzy rules and its membership functions (Gadoue, Giaouris, & Finch, 2010). To deal with this problem, adaptive fuzzy sliding-mode control systems have been introduced (Barrero, Gonzales, Torralba, Galvan, & Franquelo, 2003).

A number of adaptive fuzzy sliding mode control algorithms have been proposed in the recent years for control of IM based

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on field oriented control (Huang, Hsu, Chiang, Kou, & Lee, 2012; Kowalska, Dybkowski, & Szabat, 2010; Wai, 2006). The adaptation laws in these algorithms are designed based on Lyapunov stability theory. This method is mainly proposed for nonlinear system. It provides the fuzzy rules to automatically adjust with respect to Lyapunov stability conditions. Adaptive fuzzy sliding mode control benefits from the robustness feature of traditional sliding-mode control and the online tuning characteristic of an adaptive fuzzy controller. Adaptive fuzzy sliding mode control has been applied to many fields of industries such as control of electrical drives, robotics, etc. (Cerman & Husek, 2012; Kung & Su, 2005; Oentayo, Er, Linn, & Li, 2014; Shahnazi, Shanechi, & Pariz, 2008).

In recent years, tremendous concentration has been paid to another type of fuzzy system called type-2 fuzzy logic system. This type of fuzzy systems benefit from a new type of membership function which is itself a type-1 fuzzy number. It is widely shown to be a more promising method to deal with uncertainties in the system in terms of external disturbances, noisy measurements, and different meanings of words for different people. Type-1 fuzzy methods use crisp membership functions. Although it can deal with some levels of uncertainties and noise in the system, they are not capable of perform well in the presence of high levels of noise and uncertainties. Many recent researches use adaptive fuzzy sliding-mode control method to benefit from the capability of SMC to cope with uncertainties, modeling errors and external disturbance and the flexibility and general function approximation property of fuzzy systems. Furthermore, it is sometimes difficult to exactly determine the parameters of the membership functions of type-1 fuzzy systems. The use of type-2 membership functions makes it possible to cover a wider range of membership functions and handle some uncertainties in the antecedent part. (Chiang, Hsu, & Li, 2015; Kheireddine, 2007; Mendel, 2007; Naik & Nsingh, 2012; Saghafinia & et al., 2014).

This paper presents a new speed controller for direct field-oriented control of IM based on adaptive sliding-mode type-2 neuro-fuzzy controllers. Type-2 neuro-fuzzy controllers are widely known to be resistant to parameter changes and noise, so that they may be a preferable choice to cope with uncertain parameters of IM and its load variations. The cost function used to optimize the parameters of type-2 neuro-fuzzy system is borrowed from SMC theory. The use of SMC makes the controller more robust and more effective. The proposed method is simulated using Matlab/Simulink. The simulation results show that the proposed controller can control the system with high performance. The obtained results are compared with that of type-1 counterpart. The results of this comparison show that the proposed method is more robust to parameter variations and noise when it is compared to type-1 neuro-fuzzy system.

This paper is organized in five sections. In Section 2, the nonlinear model of IM and direct field oriented control of IM are introduced. In Section 3, adaptive sliding-mode type-2 neuro-fuzzy control is described. In Section 4, the simulation results and simulation setup are shown. Moreover the simulation results are compared with an adaptive sliding-mode type-1 neuro-fuzzy (ASMNF-1) controller. Finally the conclusion marks are presented in Section 5.

2. Field oriented control of induction motor

This section includes three parts. In the first part, the dynamic model of induction motor is represented, second part describes the structure of field oriented control that is used in this paper, and in the third part, the propose control method for the direct field oriented control method is described.

2.1. Dynamic model of induction motor

The mathematical model of an IM is expressed in (1–5). As can be seen from these equations, the dynamical model of IM is nonlinear (Finch & Giaouris, 2008; Ouali & Kamoun, 1997; Pucci, 2012).

$$\dot{\lambda}_{dr} = -\frac{1}{\tau_r}\lambda_{dr} + \omega_m\lambda_{qr} + \frac{L_m}{\tau_r}I_{ds} \tag{1}$$

$$\dot{\lambda}_{qr} = -\frac{1}{\tau_r}\dot{\lambda}_{qr} - \omega_m\dot{\lambda}_{dr} + \frac{L_m}{\tau_r}I_{qs} \tag{2}$$

$$\dot{I}_{ds} = \frac{\alpha}{\tau_r L_1}\lambda_{dr} + \frac{\alpha}{L_1}\omega_m\lambda_{qr} - \frac{1}{\tau_1}I_{ds} + \omega_s I_{qs} + \frac{1}{L_1}V_{ds} \tag{3}$$

$$\dot{I}_{qs} = \frac{\alpha}{\tau_r L_1}\lambda_{qr} - \frac{\alpha}{L_1}\omega_m\lambda_{dr} - \frac{1}{\tau_1}I_{qs} - \omega_s I_{ds} + \frac{1}{L_1}V_{qs} \tag{4}$$

$$\dot{\omega}_m = \frac{1}{J}\left[\frac{L_m}{L_m + L_r}\left(\lambda_{dr}I_{qs} - \lambda_{qr}I_{ds}\right) - T_L - B\omega_m\right] \tag{5}$$

In (1–5) the subscripts s and r refer to the stator and rotor, respectively, and subscript d and q denote the mathematical model in a synchronous rotating reference frame for a three phase induction motor. The dots over each variable imply its time derivative; Table 1 shows the name of parameter in dynamic model of induction motor.

Moreover, (5) can be shown as follows.

$$T_e = J\frac{d\omega_m}{dt} + B\omega_m + T_L \tag{6}$$

where, T_e is the electromagnetic torque and B is the viscous friction.

2.2. The structure of field oriented control

In general, torque and speed control of a three-phase induction machine is not as straightforward as that of a dc machine because of the interactions between the stator and rotor field whose orientation are not held spatially at 90° but vary with operating condition. If synchronously rotating qd0 frame was selected, which d-axis is precisely adjusted with the rotor field, the q component of the rotor flux (λ_{qr}) in the chosen reference frame would be zero, where, λ_{qr} is flux rotor. Fig. 1 shows the vector diagram of field oriented control, that is:

$$\lambda_{qr} = 0, \quad \dot{\lambda}_{qr} = 0 \tag{7}$$

Table 1
Parameter of dynamic model of induction motor.

Parameters	Feature
λ_{dr}	Flux linkage of rotor in d axis
λ_{qr}	Flux linkage of rotor in q axis
I_{ds}	Stator current in d axis
I_{qs}	Stator current in q axis
ω_m	Motor speed
J	Inertia
L_s	Self-inductance of stator
L_r	Self-inductance of rotor
L_m	Mutual inductance
V_{qs}	Stator voltage in q axis
V_{ds}	Stator voltage in d axis
R_s	Stator resistance
R_r	Rotor resistance
ω_s	Speed of the stator magnetic field
T_L	Load torque
τ_1	Time constant
$\tau_r = \frac{L_r}{R_r}$	Rotor time constant
$\alpha = \frac{L_m}{L_r}$	Defined
$L_1 = L_s - \alpha L_m$	Defined
$R_1 = R_s + \alpha^2 R_r$	Defined
B	Viscous friction