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Fault Tolerant Design for Permanent Magnet Synchronous Motor using Fuzzy Speed Controller

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Abstract: In recent years, permanent magnet synchronous motors (PMSM) are making significant inroads because of robustness, high efficiency and widely used in industrial applications. However, the un-modeled dynamics, the eventual mistakes and the strong nonlinearity diminish the motor performance quality. Indeed, since its synthesis is based on heuristic knowledge, linguistic description to perform a task and does not require a system model, the fuzzy logic control (FLC) idea is successfully applied to motor systems. Despite these advantages, the occurrence of failure may dramatically degrade the system performance and may even result in catastrophic system collapse. Therefore, in order to overcome with the above drawbacks in this study a new fault tolerant control (FTC) structure based FLC is designed to improve PMSM drives currents and speed controls during healthy and faulty conditions. Numerical results are given to highlight and validate the proposed control strategies.

Keywords: Fault tolerant systems, fuzzy logic control, failure, mathematical models, permanent magnet synchronous motors.

1. INTRODUCTION

PMSM has been increasingly used in many automation control fields as actuators, due to its advantages of superior power density, high-performance motion control with fast speed and better accuracy (Chou *et al.,* 2013). Indeed, since its synthesis is based on simple well known control methods and offers good satisfactory steady state as well as transient response, i.e. vector control is one of the most conventional controllers used for motor systems. However, in industrial applications, there are many uncertainties, such as system parameter variations, external load disturbance and un-modeled uncertainty, which diminish the performance quality of the PMSM and make the vector controller unable to deal with all those difficulties, (Lokriti *et al.,* 2013). To cope with these problems, many intelligent control techniques (Jung *et al.,* 2011), (Ozturk and Celik, 2012), (Chou *et al.,* 2013) have been developed.

In fact, Fuzzy Logic Controllers (FLCs), which is based on heuristic knowledge and linguistic description to perform a task and need no accurate mathematical models of uncertain nonlinear systems (Jung *et al.,* 2011), (Ozturk and Celik, 2012) have been successfully applied in many control applications, especially for speed control of servo motor drives such as induction motors speed drive (Benbouzid *et al.,* 2007), (Lokriti *et al.,* 2013), (Gdaim *et al.,* 2015) and PMSM, (Jung *et al.,* 2011), (Mishra *et al.,* 2012). However, the events of faults associated with actuator, sensor and/or component subsystem, achieve graceful degradation in the system performance (Mekki *et al.*, 2014). Thus, in the last recent years, the fault tolerant control (FTC) idea has been proposed.

As a response to high requirement for system safety, and survivability, fault tolerant control (FTC) for motor systems have received considerable attention during the past few decades (Patton, 1997), (Benbouzid *et al.,* 2007), (Zhang and Jiang, 2008), (Akrad *et al.,* 2011), (Guo *et al.*, 2015), (Prashant *et al.*, 2013), (Mekki *et al.*, 2014). In general, fault tolerance is no longer limited to high-end systems but also to spacecraft systems and automobile applications. It becomes an important means to increase the reliability, availability, and continuous operation of electro-mechanical systems among the automotive ones (Mekki *et al.*, 2015). In this field, survey papers and review can be found in the literature (Patton, 1997), (Zhang and Jiang, 2008), (Prashant *et al.*, 2013) and the references therein.

The FTC problems for PMSM systems have been received considerable attention, and important works have been addressed. Compared to the existing works

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in the literature (Benbouzid *et al.,* 2007), (Mishra *et al.,* 2012), (Akrad *et al.,* 2011), (Guo *et al*., 2015), (Mekki *et al*., 2014), the contributions of this paper are highlighted in the following aspects: In the framework of tracking control, mostly works (Mishra *et al.,* 2012), (Lokriti *et al.,* 2013) have been developed with fuzzy speed controller and PI currents controllers. Starting from the above works, this paper not only employed the FLC as speed controller but investigated it in FTC design. The FTC scheme proposed in this paper (based fuzzy logic) has certain advantages compared to (Akrad *et al.,* 2011), (Guo *et al*., 2015) and (Mekki *et al*., 2014), which are based observers, optimal torque control and internal model. The last one focuses of the combination between complex internal model (need compensation term) and backstepping controller. Moreover, in (Benbouzid *et al.,* 2007) authors propose a very complex FTC structure based projection method this later needs a switching block (to switch between two controls strategies). However, in this paper a simple FTC structure (needn't switching block and uses only one controller) is proposed. In fact, the FTC problem design based FLC scheme is still in its early stage of development, and a few results have been reported in the literature.

Consider the above recent approaches dealing with faults to enhance the robustness of motor systems. The current paper investigates the use of fuzzy controller in order to steer the PMSM speed variable to his desired reference and cope with both parametric and load torque disturbances. This later is combined with simple internal model (doesn't require compensation term) in order to design a FTC strategy.

2. PMSM HEALTHY MODEL

The PMSM healthy model in the synchronous rotating (*d-q*) reference frame is represented as follows (Akrad *et al.,* 2011), (Mekki *et al*., 2014):

$$\begin{aligned} \frac{di_d}{dt} &= a_1 i_d + a_2 i_q \omega_r + b_1 u_d \\ \frac{di_q}{dt} &= a_3 i_q + a_4 \omega_r + a_5 i_d \omega_r + b_2 u_q \\ \frac{d\omega_r}{dt} &= a_6 i_q + a_7 \omega_r + a_8 i_d i_q + dT_l \end{aligned} \tag{1}$$

The PMSM components are expressed according to the motor parameters as follows:

$$\begin{pmatrix} a_1 = -\frac{R_s}{L_d}; a_2 = \frac{L_q}{L_d}; a_3 = -\frac{R_s}{L_q}; a_4 = -\frac{\varphi_f}{L_d}; a_5 = \frac{L_d}{L_q}; a_6 = -\frac{n_p^2 \varphi_f}{J} \\ a_7 = -\frac{f}{J};\ a_8 = \frac{n_p^2 \varphi_f}{J}(L_d - L_q); d = -\frac{n_p}{J};\ b_1 = \frac{1}{L_d}; b_2 = -\frac{1}{L_q} \end{pmatrix}$$

where i_d, i_q stator current; u_d, u_q stator voltage; L_d, L_q stator inductance; R_s stator resistance; φ_f rotor flux; ω_r rotor speed; f viscous friction coefficient; T_l load torque, J Inertia moment. As presented in section 5 in this study a smooth pole PMSM *i.e.* $L_d = L_q = L$ is our interest.

The classical controllers such as proportional integral (PI) controller suffers from overshoot and undershoot of response, when some unknown nonlinearities are present in the system. To overcome these problems, an intelligent controller based FLC will be introduced in the next section.

3. FUZZY LOGIC CONTROL DESIGN

Fuzzy logic provides an approximate effective mean of describing the behavior of some complex system. Unlike traditional logic type, fuzzy logic aims to model the imprecise modes of human reasoning and decision making, which are essential to our ability to make rational decisions in situations of uncertainty and imprecision (Ozturk and Celik, 2012). In general, fuzzy control is a model-free approach; it doesn't depend on model of the system under control. Model-free approaches make the controller design easier, since obtaining a mathematical model of the system is sometimes a very complex task (Oscar *et al.,* 2001).

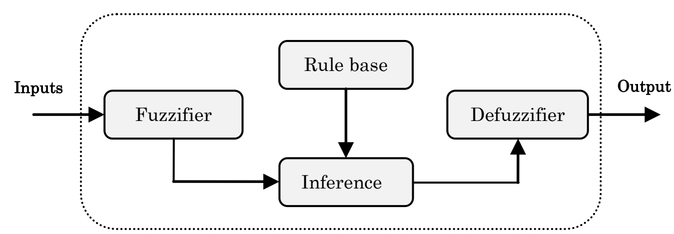

Fig. 1. Structure of fuzzy logic controller

As depicted in Fig. 1, a FLC generally consists of four principal units: 1) a fuzzifier which converts analog inputs into fuzzy variables. These variables are produced by using membership functions (MF); 2) a fuzzy rule base which stores fuzzy rules describing how the fuzzy system performs; 3) a fuzzy inference engine which performs approximate reasoning by associating input variables with fuzzy rules; and 4) a defuzzifier which converts the FLC's fuzzy output to a crisp value for the actual system input over the target. The performance of the FLC is influenced by the shape of the MF, the fuzzy reasoning rules and the defuzzification method (Gdaim *et al.,* 2015). The generic structure of the proposed PMSM speed and currents controllers is shown in Fig. 2.

The FLC in this study uses singleton fuzzifier, triangular and trapezoidal membership function, central gravity defuzzifier method and the universes of discourse of the input and output variables are in the range [-1,+1]. The most significant variables entering the fuzzy controller have been selected as the speed error $e_\omega(t)$ and its time derivative $de_\omega(t)$.