Chapter 2
Maximum Likelihood-Based Fuzzy Adaptive Kalman Filter Applied to State Estimation of Permanent Magnet Synchronous Motors

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ABSTRACT

In this chapter, a novel fuzzy adaptive Kalman filter for state estimation of a permanent magnet synchronous motor is proposed. The fuzzy set theory is used as a tool to perform on-line modification of the covariance matrices, adjusting the EKF and UKF parameters according to estimation reliability of the currents in the two windings of the rotor, position, and velocity for a two-phase permanent magnet synchronous motor. Also, the methodology uses the maximum likelihood technique, where the difference between the theoretical covariance and the measured covariance is defined as an approximation considering the average of a moving estimation window. This difference is performed continually and used to dynamically update the covariance matrices, aiming to obtain an efficient estimation. The membership functions are optimized to adjust the covariance matrices so that the error variation is minimal. Simulation results illustrate the efficiency and applicability of the proposed methodology.

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INTRODUCTION

For decades, man seeks to understand natural phenomena as a tentative to predict and control them. Such a task, in many cases, is arduous, expensive and challenging to perform due to non-availability of reliable devices, time delays, errors in the measurement system, and high cost devices. With the advance of technology, this became a necessity; studies are carried out in the so-called *systems*. The methods to predict and control the systems are conformed by one or more input signals that perform a function and produce new output signals. If they present random characteristics, then they are called stochastic systems(Haykin, 2002). Systems can be linear or non-linear; these are differentiated by the *Principle of Superposition* that satisfies only the linear systems. Systems can be represented by a *mathematical model*. In other words, there are some observed characteristics of the system which can be modeled through mathematical relationships. Therefore, an essential tool for obtaining an acceptable representation of a system is the estimation, mainly if the indirect variables are difficult to be observed or measured. The state estimators use the measurement of some process variables together with a model to estimate the complex variables to be measured or the complete state, being one of the most common criteria is to minimize the sum of the squares of the error. However, only recently, engineers began the implementation of state estimation algorithms in the computer for complex and fast processing applications(Simon, 2013) (Haykin, 2002).As the research interest has been focused on methods for estimating properties of stochastic dynamic systems, the attention has been devoted to both the input-output models(Vafamand, Mehdi, & Khayatian, 2018) and state-space (SS) models (Dunik, Straka, & Blasch, 2016), as well as recursive and batch processing methods. On the other hand, a growing number of research groups around the world are developing estimation methods related to covariance matrices, where these methods differ in assumptions related to the considered model, the underlying ideas and principles, the properties of the estimates, and the number and essence of the design parameters. Traditionally, covariance matrices estimation methods are divided into four groups: the correlation methods, the maximum-likelihood methods (MLMs), the covariance matching methods (CMMs) and the Bayesian methods(Steven, 1993).

Regarding the models developed for state-space estimation, few have referred to permanent magnet synchronous motors (PMSM). These devices have a wide range of energy-saving applications, including domestic appliances and automotive, due to the inherent high-power factor and the absence of field losses. It is very common the speed and position measurements are performed via an encoder connected to the machine axis.However, this equipment is subject to faults such as cable breakage, noise due to shaft vibrations or electromagnetic interference from the drive. If it is known how to embed the formulation of an estimator into the microcontroller, then it can get rid of the encoder and maybe save a lot of money in the embedded system's product (Silva et al., 2018). There are numerous techniques for estimating the position and speed of rotor in the literature, highlighting those based on sliding modes observers (SMO),(Silva et al., 2018), (Amin, Member, & Aziz, 2017), due to its robustness and reduced computational effort, as well as methods based on sliding super-torsion mode observer(STSMO)(D. Wang et al., 2018) with both static and dynamic performance. Nevertheless, there exist very few developed works using Fuzzy Logic for estimating the position and speed of the PMSM rotor.

Currently, there are several filters used to solve the problem of estimating the position and speed of the PMSM. These filters include the Kalman filter (KF), Extended Kalman filter (EKF)(Parasiliti, Petrella, & Tursini, 2001), (Shi, Chan, Wong, Member, & Ho, 2002),(Simon, 2013),(Tian, Yan, & Jun 2018),Unscented Kalman Filter (UKF)(Kong, 2005),(Chan, Borsje, & Wang, 2009),(Hilairet, Auger, & Berthelot, 2009),(Yin, 2018),Particle filter, among others. Kalman Filter is used only when the system is

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