Research article

Robust sensorless vector control of an induction machine using Multiobjective Adaptive Fuzzy Luenberger Observer

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Abstract

This paper presents an inherent speed estimation scheme associated to the Indirect Field Oriented Control in case of Induction motor sensorless control. Indeed, through the design of a Multiobjective Adaptive Fuzzy Luenberger Observer, the speed sensorless control issue even at low speed, the observer poles’ assignment issues and the speed estimation’s sensitivity to rotor resistance uncertainties issue are treated concurrently. First of all, the structure of the proposed Takagi-Sugeno adaptive observer is described. Secondly, based on Lyapunov theory, observer gains are designed and a fuzzy speed estimation scheme is provided. The design’s objectives consist of minimizing the sensitivity of the proposed observer to rotor resistance uncertainties (using the $L_2$ techniques) and to guarantee a specified observer dynamic performance through a D-stability analysis. The design conditions are formulated into Linear Matrix Inequalities terms. Finally, experiments are conducted to demonstrate the effectiveness of the proposed results regardless of uncertainties in the rotor resistance.

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1. Introduction

In spite of the fact that the Induction Motor (IM) was the subject of many researches, it still presents a lot of challenges for engineering applications due to the increasing demand on the industry to a high level of performances. Within the development and implementation of Indirect Rotor Field Oriented Control (IRFOC) [1–3], the IMs were able to compete with DC machines in high performance applications. This method, based on flux and magnetic torque control of the machine, is now the most adopted one in the industry, either in the railway’s field traction, machine tool or robotics.

One of the main challenges for IRFOC is the speed estimation. It is worth to note that the use of sensors increases the weight, the cost and the electrical sensitivity as well as undesirable effects on the system reliability. To overcome this problem, many studies have focused, since the early nineties on speed estimation schemes development using different methods. Their development started by the use of classical approaches [4,5], then step by step they were associated with sophisticated and intelligent tools such as Neural Networks (NN) [6] or Fuzzy Logic (FL) [7,8].

In addition, another challenge is still facing the IRFOC which consists on its sensitivity to IM parameter uncertainties. It is worth noticing that these uncertainties are caused by modeling errors or instantaneous variations which depends on temperature, saturation or slip frequency. This problem influences either conventional appli-
Ref. [15] in order to estimate IM’s resistances in case of sensorless control. Indeed, a NN-based algorithm was proposed in first one is based on the simultaneous estimation of both IM parameters and rotor speed. This is due to a poor dynamics, lack of robustness regarding the parameters mismatches or noises, observability issue, detectability problem [13,14] etc.

To deal with this shortcoming, two strategies were proposed. The first one is based on the simultaneous estimation of both IM parameters and rotor speed. Indeed, a NN-based algorithm was proposed in Ref. [15] in order to estimate IM’s resistances in case of sensorless application. In Refs. [16,17], the authors described a sliding mode observer to concurrently estimate the rotor time constant and the rotor speed. Vicente et al. [18], Zaky [11], and Marino et al. [19,20] are based on the technique of adaptive observers to estimate resistances in case of sensorless control. In Ref. [21], a Model Reference Adaptive System (MRAS) tuning algorithm of the stator inductance in case of sensorless control was developed. A Kalman Filtering (KF) approach was presented in Ref. [22] to the simultaneous estimation of the rotor resistance, the stator resistances and the rotor speed. In Ref. [23], the authors described a signal injection method in order to estimate the rotor resistance in case of sensorless application. However, it is worth to note that the simultaneous estimation of speed and one or more of the parameters of the IM is a sensitive, tricky and tactful process which requires a heavy computing effort and a so sophisticated hardware. Moreover, in some cases, it can be an origin of instability problem [24]. Recently a novel strategy is being developed. This latest approach is based on computing the speed estimator from accurate information of IM states regardless of the IM parameters’ uncertainties. In Refs. [25–27], different sliding mode observers are proposed. The authors were based on the robustness property of sliding mode against parameters’ uncertainties to generate robust observers. Then, the speed estimation is deducted using these accurate information. However, the chattering phenomenon remains the main drawback of such approach. In Ref. [28], another method is proposed. The authors propose a two steps-algorithm, through which they estimate firstly, rotor flux using a robust Kalman Filter considering uncertainties of the machine parameters. Secondly, the rotor speed is computed via a Recursive Least Squares (RLS) algorithm. Although the robustness of this method against IM parameters’ variations, it requires a high computational load due to the simultaneous use of both the descriptor Kalman Filter and the RLS algorithm.

Recently, significant researches have been devoted to the subject of the Takagi-Sugeno (TS) fuzzy approach [29,30] and its applications within the power systems and IM drive [7,31–34]. This method overcomes the problem of local linearization in different operating points due to its simplicity and its capacity to describe a large class of nonlinear systems by fuzzy blending of all linear local models [30]. Different TS models of the IM were described [31–34] and some TS fuzzy sensorless drive schemes were recently carried out [7,8,33]. However, the proposed speed sensorless approaches were tested while considering only the nominal model of the IM and didn’t investigate the impact of parameters mismatch on the control performances.

The main objective of this actual study is to design a speed estimation scheme considering the rotor resistance uncertainties. The choice of this parameter was made due to its high influence on IRFOC control [35,36]. To this regard, a Multiobjective Adaptive Fuzzy Luenberg Observer (MAFLO) is being investigated in this paper. Based on the fourth order IM model, an uncertain TS model of the machine is proposed. Thanks to this method, the rotor resistance uncertainties are formulated into uncertainties in the state matrix, the rotor speed is considered as the only premise variable and the mechanical equation is not considered. Then, an adaptive Luenerberg TS observer is introduced while considering the rotor speed as an immeasurable premise variable. Afterwards, \( L_2 \) observer gains are synthesized, whilst a pole placement study is introduced through a D-stability analysis in order to guarantee dynamic performances of estimation errors. The bounded lemma and the real lemma are being used to design sufficient conditions into Linear Matrix Inequalities (LMI) formalism [37] which are easily solvable using as LMI Toolbox of Matlab software. Based on accurate outputs of the proposed observer, a TS-based rotor speed estimation scheme is described. The stability analysis of the global algorithm (including IM states robust observer and rotor speed estimator) is investigated using the Lyapunov theory. The proposed approach allows minimizing the impact of the rotor resistance variation on the sensorless control’s performances, and permits to avoid the complexity issue of the simultaneous estimation of rotor resistance and mechanical speed. Thus, it doesn’t require a heavy computing effort which makes it suitable for a real implementation. Moreover, it overcomes the chattering problem caused by the sliding mode method [17,26].

The layout of this paper is organized as follows: in Section 2, the problem is formulated and the TS fuzzy IM model is introduced. In section 3, the MAFLO is presented in the first step. In the second step, the design of observer gains is formulated to ensure the stability, the MAFLO local poles’ assignment and \( L_2 \) norm regardless to the rotor resistance uncertainties. In the same time, a high efficiency adaptive speed estimation scheme, based on an accurate knowledge of IM states (rotor flux and stator currents), is computed. Finally, in section 4, experiments are carried out to show the effectiveness of the proposed approach.

2. Modeling of the induction machine

2.1. State space dynamic model of induction machine

In practice, the IM drive system is designed based on the nominal parameters of the machine. However, these parameters are generally affected. Beyond the modeling error, the rotor resistance is one of the most parameters affected by both temperature and slip. Moreover, it is not accessible for measurement. Thus, a considerable attention should be given to this problem taking into account its high influence.
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