Chapter 7

Sensor less Induction Motor drives for electrical actuators

Chapter 7:
Sensor less Induction Motor drives for electrical actuators

For a decade, induction motor drive-based electrical actuators have been under investigation as potential replacement for the conventional hydraulic and pneumatic actuators in aircraft. Advantages of electric actuator include lower weight and size, reduced maintenance and operating costs, improved safety due to the elimination of hazardous fluids and high pressure hydraulic and pneumatic actuators, and increased efficiency.

Recently, the emphasis of research on induction motor drives has been on sensorless vector control which eliminates flux and speed sensors mounted on the motor. Also, the development of effective speed and flux estimators has allowed good rotor flux-oriented (RFO) performance at all speeds except those close to zero. Sensorless control has improved the motor performance, compared to the Volts/Hertz (or constant flux) controls.

Chapter presents the documented schemes for speed sensor less drives. These schemes combine the attributes of the direct and indirect field-oriented control (FOC) or use model adaptive reference systems (MRAS) with a speed-dependent current model for flux estimation which tracks the voltage model-based flux estimator.

7.1. INTRODUCTION

The induction motor has been the workhorse of industry for many years. In particular, the squirrel cage motor is one of the most important ac machines because of its low cost, high reliability, low inertia and high transient torque capacity. Significant advances in power electronics have permitted the implementation of sophisticated methods for control of induction motors, using FOC which allows decoupling and separate control of the torque and flux components of the stator currents. Two types of field-oriented control are available. One is the direct field-oriented control which regulates the rotor flux using direct measurements of rotor flux magnitude and position. The other is the indirect field-orientation in which the rotor flux is regulated by the slip frequency, the stator currents and the rotor speed.

There are a number of trends and tradeoffs involved in implementing the different forms of field-oriented control. First, most of the field orientation methods require precise estimation of either the rotor position or speed. This implies the need for speed sensors such as shaft-mounted tacho-generators, resolvers or digital shaft encoders. The speed sensors lower the system reliability and, also, require special attention to measurement noise. Second, the direct field-oriented scheme requires the rotor flux which is measured using Hall effect sensors or search coils. The Hall effect sensors degrade the performance and reliability of the drive system. Third, the implementation of direct field orientation uses an open-loop integration of the machine voltage to estimate the flux, which gives problems at low speeds. Finally, although the indirect field-oriented control scheme is simple and preferred, its performance is highly dependent on an accurate knowledge of the machine parameters.

Research in induction motor drives, for the past fifteen years, has focused on improving the different field- oriented schemes to remedy the above problems. In particular, much work has been done in decreasing the sensitivity of the control system to the motor parameter estimates, and estimating, rather than measuring, the rotor flux or speed from the terminal voltages and currents. This eliminates the flux or speed sensor, thereby achieving sensorless control. The estimators are, also, known as observers. Another control scheme, known as direct self control (DSC) or direct torque control (DTC), requires only stator parameters, and has been developed as an alternative sensor-less drive.

Signals representing the terminal voltages and currents are fed to observers for estimating the rotor flux magnitude, angle and speed. The estimated quantities are compared with their respective command values. The errors are fed into the controllers which feed the power electronic converters.

A number of developed approaches for flux and speed observers are documented in the
Literature A rotor flux observer has been developed, however, the observer requires the motor rotor speed and a shaft encoder for speed sensor. Speed Identification Schemes reported are described in following sections.

7.1.1 Kalman Filter Schemes

The Kalman filter algorithm and its extension are robust and efficient observers for linear and nonlinear systems, respectively. The observers use knowledge about the system dynamics and statistical properties of the system, and measurement noise sources to produce an optimal state estimation. A continuous time model is used in case of the Kalman filter, whereas the extended Kalman filter requires a discrete statespace model. A major advantage of the Kalman filtering approach is its fault tolerance which permits system parameter drifts. Therefore, exact models are not required. The application of full- and reduced-order versions of Kalman and Extended-Kalman filters to speed estimation in induction motor and drives has been investigated [1], [2] and [3].

The inputs to the plant are fed into a prediction model. The output of the plant is compared with the output from the model, and the resulting error is fed into a correction Kalman gain stage to reduce the error in the estimated states from the prediction model. Different models of the induction machine for use with Kalman filter have been proposed in Ref. [3]. The results indicate that the operating range of the sensorless drive is not reduced for static, dynamic or field weakening operation. In Refs. [1] and [2] the full- and reduced-order models Extended Kalman filter are used for rotor flux and speed estimation, using direct field orientation. The use of reduced-order model has the advantage of saving computation time, in comparison with the full-order extended Kalman filter. The developments in the real time computational speed of digital signal processing chips make the Kalman filter a powerful approach to sensorless vector control. However, the robustness and sensitivity to parameter variation needs further study [1].

7.1.2 Model Reference Adaptive Schemes

Adaptive control has emerged as a potential solution for implementing high performance control systems, especially when dynamic characteristics of a plant are poorly known, or have large and unpredictable variations. Model reference adaptive system (MRAS) achieves robust and high performance. The main innovation of MRAS is the presence of a reference model which specifies the desired performance. The output of the reference model is compared with an adjustable observer-based model. The error is fed into an adaptation mechanism which is designed to assure the stability of the MRAS.

A number of MRAS-based speed sensorless schemes have been described in the literature for field-oriented induction motor drives [4]-[16] The output of the reference model does not have an explicit dependence on the motor speed. The output of the adjustable model has a speed dependence. For example, the inputs to both the reference and adjustable models can be stator voltages, and the outputs are fluxes or back emf. The difference between the outputs is fed into a speed adaptive scheme the output of which is the estimated speed used to correct the adjustable
model.

Many simplified motor models have been devised to estimate the speed of the induction
motor, using MRAS schemes. The voltage model, shown in Fig. 5, for rotor flux estimation is commonly used as a reference model, since it does not depend on the rotor speed [17]-[18]. The implementation of the two models in different reference frames affects the complexity and robustness of the MRAS scheme [19].

Recently, a number of closed-loop observers that combine the best attributes of the voltage and current models with MRAS and other sensorless approaches have been developed. This has resulted in increased research in direct field orientation, as compared to the standard indirect field orientation employed in induction motor drives [17]-[19].

The speed adaptive algorithm used affects the stability and dynamic performance of the
closed-loop MRAS. In many cases, a proportional integral (PI) controller is found to be satisfactory for the adaptive scheme.

7.1.3 High Frequency Signal Schemes

Recently, new rotor position and speed estimations have been developed, using high
frequency measurements, based on machine saliencies, rotor slotting and irregularities [2024]- [21]. Proper signal processing and filtering of the resulting high frequency stator current are used to detect the induced saliencies present in the stator model of the induction motor. High frequency signals are injected into the stator terminals using the same inverter that supplies the fundamental excitation. Such detection provides continuous estimate of the position and magnitude of flux [20]-[21]. The above

approaches have been shown to have the potential for wide-speed and parameter insensitive sensor less control, particularly during low speed operation, including zero speed. Increased research is expected in this area.

7.1.4 Direct Self Control Schemes

A number of field-orientation methods have been developed. These methods use only
measured stator voltages and currents to implement a sensorless control [22], [23]-[25]. The most promising scheme is the direct self control (DSC), also known as direct torque control (DTC). It is a variation of field oriented control but uses only the stator resistance in its calculations. This makes the DSC less sensitive to parameter changes [22]. Such a control is. In DSC, the flux position and the errors in the torqueand flux are directly used to choose the inverter switching state.

Due to estimation of flux based on integration of a voltage signal, DSC has limitations at low speeds. Also, frequency and temperature variations tend to cause corresponding change in the actual motor resistance, thereby creating an error in the estimate of the stator flux. Tuning the stator resistance used in the controller to track the above changes in the actual motor resistance will improve the DSC scheme, and increase its potential as a simple sensorless control.

7.1.5 Intelligent Control Techniques

Neural Networks (NNs) and Fuzzy Logic are gaining potential as estimators and controllers for many industrial applications, due to the fact that they present better properties than the conventional controllers. NNs have learning capability to approximate very complicated nonlinear functions, and therefore considered as universal approximation. Also, they have adaptive capability which makes them very powerful in applications where the dynamics of a plant are time-variant or where the model of the system is partially known. The main advantage of NNs is their inherent fault tolerance.

A fuzzy controller converts a set of linguistic rules, based on expert knowledge, into an automatic control strategy. Such controllers have been found to be superior to conventional controllers, especially when information being processed is inexact or uncertain. In Ref. [34], neural networks are used to estimate feedback signals required for vector control of induction motor drives. In Refs. [26]-[29], NN and fuzzy logic have been used to implement and tune the DSC.

The results obtained showed improvement over the conventional DSC, especially at low speeds. The drawbacks of NN and fuzzy logic include requirement of much training or knowledge base to understand the model of a plant or a process. The training algorithm used has an effect on issues such as learning speed, stability and weight convergence. These issues remain as areas of research and comparison of many training algorithms.

7.2 Classical Techniques

The section describes classical methods used for control of Induction motor drives. It includes methods with and without using observers.

7.2.1 Decoupling Control of Induction Motor Drives

Industrial applications such as robotics, rolling mills, I and machine tools demand fast well damped and precise torque response in all four quadrants of operation. The dc machines have been used for these applications due to their simple control dynamics [30]. However, these machines are inferior to the squirrel-cage induction machines in most other respects, such as cost, power, weight, size, ruggedness, and maximum speed. Furthermore, the induction motor drive allows a maintenance free system. Therefore, it would be advantageous to use induction machines as a basis for electrical to mechanical power conversion.

Acting as an inner loop, the torque controller is the basic building block of a speed or position drive. A fast response torque controller can minimize the effect of load disturbance on speed or position variation. In most applications, it is desirable to decouple the control of torque and flux so that maximum possible torque per ampere of stator current can be obtained under transient and steady-state conditions. This permits a better utilization of the current capability of the power conditioning unit being used. The primary objective of decoupling control is to provide fast dynamic response as well as good steady-state performance (like a separately excited dc machine). In general, decoupling control can be achieved based on stator flux, airgap flux, or rotor flux regulation schemes. These schemes exhibit different behavior on the nature of the control dynamics and static limitation of peak torques. Many researchers have used rotor flux decoupling control of induction machines [31-36]

In [37] attempts have been made to decouple the control of torque in an induction machine with stator flux, airgap flux, and rotor flux field regulation schemes [34]. The control dynamics of each scheme are outlined and investigated. Simulation results are presented to verify that different flux regulation schemes provide decoupling control with excellent dynamic behavior. The transient and steady-state relationships between slip frequency and torque under constant stator flux, airgap flux, and rotor flux operations are simulated and compared. The sensitivity characteristics of the three methods of flux control that are machine fed by impressed currents and voltages are also compared and studied.

The decoupling control of induction machines is investigated in [37]. Three different schemes for decoupling control methods based on stator flux, airgap flux, and rotor flux field regulation are developed. The control dynamics of each scheme are outlined and studied. Simulation results are presented to verify that these schemes provide decoupling control with excellent dynamic behavior. The transient and steady-state relationships between slip frequency and torque under constant stator flux, airgap flux, and rotor flux operations are simulated and compared. The sensitivity characteristics of the three methods of flux control machine fed by impressed currents and voltages are also compared and studied. A prototype torque dnve system is implemented to demonstrate the decoupling control of a squirrel cage induction machine.

Multiple Coupled Circuit Modeling of Induction Machines is presented in [38] for simulation of induction machines with both arbitrary winding layout and/or unbalanced operating conditions. The model is derived by means of winding functions. No symmetry is assumed.

The parameters of the model are calculated directly from the geometry and winding layout of the machine. The behavior of an induction machine during starting is simulated using this model. The results are shown to be in good agreement with the solution obtained by a conventional d - q model for symmetric conditions. The new model is then extended to the solution of a wide variety of fault conditions such as broken bars and end rings and open or short circuited motor coils.

7.2.2 LMI-based Gain Scheduled Robust Flux Observer

Induction motors are widely used in industry, due to their relatively low cost and high reliability. One way to obtain a speed or torque control with a dynamic performance similar to that of a more expensive DC-motor is to use Field Oriented Control (FOC) [38]. In general an estimate of the rotor flux is needed in most of these control schemes. Therefore a rotor flux observer must be employed.

The dynamic behavior of the induction motor is affected by time variations, mainly in the rotational speed and ın the rotor and stator resistances. The rotor flux observer must be robust with regard to these variations.

The simplest flux estimation method is an open loop observer based on stator current measurements [910]. This method suffers from poor robustness and a slow convergence rate. Several methods have been suggested to overcome this [40-41], but most of these are hard to tune or difficult to ımplement. For industrial purposes the ideal observer scheme is easy to implement in hardware and does not require tuning..

In the nineties, several control design problems have been formulated in terms of LMIs. Efficient methods exist for solving these convex optimisation problems [42]. In [43] Gahinet and Apkarian provided solutions to *H1* control problems in terms of LMIs. In 1993 Packard suggested using LMIs for gain scheduling synthesis of systems on linear fractional form [44]. In [45] Helmersson suggested a controller synthesis method including both robustness to uncertain parameters and gain scheduling. The synthesis problem is in the form of a rank constrained LMI problem. The performance of the observer will be demonstrated through simulations.

[46] Describes a robust flux observer is developed using structured singular value (.) and Linear Matrix Inequalities (LMI). The method used makes it very simple to include online measurements of the rotational speed for gain scheduling, but the main objective is to achieve an observer suitable for speed sensorless control. The observer requires very little tuning and is robust to variations in rotor and stator resistances

7.3 FUZZY AND NEURAL CONTROL of INDUCTION MOTOR

AC motors, particularly the squirrel-cage induction motor (SCIM), enjoy several inherent advantages like simplicity, reliability, low cost and virtually maintenance-free electrical drives. However, for high dynamic performance industrial applications, their control remains a challenging problem because they exhibit significant nonlinearities and many of the parameters, mainly the rotor resistance, vary with the operating conditions. Field orientation control (FOC) or vector control (Vas, 1990) of an induction machine achieves decoupled torque and flux dynamics leading to independent control of the torque and flux as for a separately excited DC motor. FOC methods are attractive but suffer from one major disadvantage: they are sensitive to motor parameter variations such as the rotor time constant and an incorrect flux measurement or estimation at low speeds (Trzynadlowski, 1994). Consequently, performance deteriorates and a conventional controller such as a PID is unable to maintain satisfactory performance under these conditions.

Recently, there has been observed an increasing interest in combining artificial intelligent control tools with classical control techniques. The principal motivations for such a hybrid implementation is that with fuzzy logic and neural networks issues such as uncertainty or unknown variations in plant parameters and structure can be dealt with more effectively, hence improving the robustness of the control system. Conventional controls have on their side well-established theoretical backgrounds on stability and allow different design objectives such as steady state and transient characteristics of the closed loop system to be specified. Several works contributed to the design of such hybrid control schemes (Cao *et al.*, 1996[47]; Chen and Chang, 1998[48]; Shaw and Doyle, 1997[49]).

In [50] three control methods are introduced and applied to an indirect field-oriented induction motor. In the first design approach the basic fuzzy logic controller (FLC), regarded as a kind of variable structure controller (VSC) (Hung *et al.*, 1993[51]) for which stability and robustness are well established, is developed. This follows the interpretation of linguistic IF–THEN rules as a set of controller structures that are switched according to the process states (Kawaji and Matsunaga, 1994[52]).

The second design approach is based on the well-known internal model control concept (Morari and Zafiriou, 1989[53]). To improve the robustness of the controller, neural networks are introduced to form the forward and inverse model control algorithm in place of the classical model-based structure. In the third approach, the basic idea of the proposed controller is similar to the gainscheduling technique. The design is based on a reducedorder state space model of the motor drive from which a family of local state space models covering the operating range of the drive system are defined. We then use the state feedback design concept to get a linear state feedback controller for each local model (Cao *et al.*, 1999[47]; Mei *et al.*, 1998[54]). These local controllers are inferred into one global state feedback controller using a simple fuzzy inference technique.

These controllers are evaluated under simulations for a variety of operating conditions of the drive system and the results demonstrate the ability of the proposed control structures to improve the performance and robustness of the drive system. A speed observer based on neural networks is designed and included in the closed-loop control structure to achieve a sensorless operation of the drive system.

7.3.1 Vector Control Using ANN Speed Estimation

Accurate speed information is necessary to realize high performance and high-precision speed control of an induction motor. The speed is achieved by using mechanical sensors such as resolvers or pulse encoders.

Since the late 1980s, speed-sensorless control methods of induction motors using the estimated speed instead of the measured speed have been studied. They have estimated the speed from the instantaneous values of stator voltages and currents using the induction motor model. Recently, other approaches such as model reference adaptive system (MRAS) methods, extended Kalman filter algorithms, etc., have been implemented to achieve more accurate and robust speed estimation performance [55-58]. However, an induction motor is a highly coupled, nonlinear dynamic plant, and its parameters vary with time and operating conditions. Therefore, it is very difficult to obtain good performance for an entire speed range and transient states using previous methods.

Recently, the use of neural networks (NNs) to identify and control nonlinear dynamic systems has been proposed. because they can approximate a wide range of nonlinear functions to any desired degree of accuracy. Moreover, they have the advantages of extremely fast parallel computation, immunity from input harmonic ripples, and fault tolerance characteristics. Since 1990, there have been some investigations into the application of NNs to power electronics and ac drives, including speed estimation [59-62].

In [63], three-layer NN was used with offline training (before the motor is working). This technique gives a fairly good estimate of the speed and is robust to parameter variation. However, the neural network speed estimator should be trained sufficiently with various patterns to get good performance. In [64], a two-layer NN was used to estimate induction motor speed with online training, but this lies more in the realm of adaptive control than NNs. The speed value is not obtained at the output, but at one of the weights. Moreover, only one weight is adjusted in the training. Therefore, it would be very sensitive to parameter variations and system noises.

In [65] a speed estimation method of an induction motor is proposed. A multilayer NN with one hidden layer is used. The speed value is obtained at the NN output and the feedback is connected between the output and the input node. The multilayer and recurrent structure makes it robust to parameter variations and system noises. The weights of the neurons are continuously modified by backpropagation during the speed-sensorless drive with online training. Therefore, no offline training and training patterns are needed.

7.3.2 A Fuzzy Observer for Direct Torque Control

The direct torque control (DTC) has become one of the favoured control schemes for induction motors recently [66-68]. In DTC systems, the torque is controlled by controlling the amplitude and rotational speed of the stator flux.

The same principle has been successfully applied impermanent magnet (PM) motors in [69]. To control the stator flux, the actual flux is estimated. The variation of R_I may influence the calculation of stator flux significantly and thereby the overall performance of the DTC systems, so accurate estimation of R_I is important. The change of stator resistance is also a slowly heating process and it its expected that the fuzzy observer will give the accurate value of stator resistance on line. This paper illustrates a fuzzy observer for the n-line calculation of the stator resistance and examines its accuracy in doing so.

7.3.3 Performances of Fuzzy-Logic-Based Indirect Vector

In order to achieve high performance, field-oriented control of induction motor (IM) drive is employed [70]. However, the controller design of such a system plays a crucial role in system performance. The decoupling characteristics of vector-controlled IM are adversely affected by the parameter changes in the motor. The motor-control issues are traditionally handled by fixed-gain proportional-integral (PI) and proportional-integral- derivative (PID) controllers. However, the fixed-gain controllers are very sensitive to parameter variations, load disturbances, etc. Thus, the controller parameters have to be continually adapted. The problem can be solved by several adaptive control techniques which depend on the exact system mathematical model.

It is often difficult to develop an accurate system mathematical model due to unknown load variation, unknown and unavoidable parameter variations due to saturation, temperature variations, and system disturbances. In order to overcome the above problems, recently, the fuzzy-logic controller (FLC) is being used for motor control purpose. The application of FLC has faced some disadvantages during hardware and software implementation due to its high computational burden [71].

The earlier reported works for fuzzy-logic applications in motor drives [72-73] are based on either simulation or experimental results at low-speed operating conditions. [74] Describes the successful application of the FLC for normal speed control of IM drives. The complete vector control scheme of IM incorporating the FLC has been successfully implemented in real time using digital-signal processor (DSP) controller-board DS1102. The performances of the proposed drive have also been compared with those obtained from the conventional PI controller both theoretically and experimentally. It is found that the proposed FLC is insensitive to temperature changes, inertia variations, and load torque disturbances. This novel FLC could be a suitable replacement for the conventional PI controller for high-performance drive systems.