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A STUDY OF MRAS BASED SPEED ESTIMATION OF SENSORLESS INDUCTION MOTOR USING MATLAB AND SIMULINK MODELLING

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Abstract: Model reference adaptive system (MRAS) based techniques are one of the best method to estimate the rotor speed due to its performance and straight forward stability approach.These techniques use two different models which have made the speed estimation a reliable scheme especially when the variations.The scheme use the stator equation and rotor equation as the reference model and the adjustable model respectively.The output error from both models is tuned using a PI controller yielding the estimated rotor speed.It presents the identification and parameter estimation of an induction motor model with parameters varying as functions of the operating conditions. A Sensorless torque control system for induction motors is developed. The system allows for fast and precise torque tracking over a wide range of speed. The induction motor is controlled through field orientation techniques that require knowledge of the rotor speed.Since speed sensors decrease the reliability of a drive system (and increase its price), a common trend in motor control is to use an observer to estimate speed.

Keywords: MRAS;three phase induction motor;sensorless field-oriented control (FOC); direct torque control (DTC); adaptive pseudo reduced-order flux observer (APFO)

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INTRODUCTION

Motor drives have been a mature technology for many years, but investigations into sensorless concepts are still taking place. The basic aim of sensorless control research is to achieve dynamic system performance equivalent to an encode red scheme without the disadvantages associated with using a speed encoder. The industry standard is Rotor Flux oriented Vector Control (Amezquita-Brooks *et al.,* 2014), and many applicable rotor speed estimation schemes have been proposed (Finch & Giaouris, 2008). However, operation around, and through zero speed, is problematic and still represents a challenge. Widely used model-based sensorless methods that require the machine voltages and currents include the popular Model Reference Adaptive Schemes (MRAS) (Ravi Teja *et al*., 2012), of which there are many variants such as rotor flux (Schauder, 1992), reactive power (Maiti *et al.,* 2008), back EMF (Rashed & Stronach, 2004), stator current (Orlowska-Kowalska & Dybkowski, 2010), and rotor flux incorporating predictive torque control (Fengxiang *et al.,* 2014). Other techniques include full and reduced order observers (Hinkkanen & Harnefors, 2014), sliding mode observers (Lascu & Andreescu, 2006), and Kalman filters (Yin *et al.,* 2014). Artificial intelligence techniques have also been applied to sensorless control, including Neural Networks (Gadoue *et al.,* 2009) and Fuzzy Logic (Gadoue *et al*., 2010). Recent research activities in the sensorless control area include proposing new MRAS schemes (Benlaloui *et al*., 2014), compensation of inverter nonlinearities (Shen *et al.,* 2014), application of predictive control techniques (Alkorta *et al.,* 2014) improving stator flux estimation (Stojic *et al.,* 2015), and enhancing the stability of flux estimators (Wang *et al.,* 2014). Many of the model based methods are implemented to estimate the stator or rotor fluxes, which are then used to calculate the rotational speed. However, depending on the application and range of operational speeds, limitations in the accuracy of these flux estimators can have a significant effect on the speed estimation accuracy and stability. Hence improving the flux estimation performance of these schemes can lead to a significant improvement in rotor speed estimation.

Flux estimation for induction machines has been well researched in the literature (Gadoue *et al.,* 2009; Jun & Bin, 1998; Wang *et al.,* 2014) with both simple voltage and current model estimators and more complicated schemes proposed. Voltage model flux estimators rely on the machine's terminal voltage, current, and its parameters. This model has the simplest implementation and is inherently sensorless with no rotor speed term dependence. However, it suffers from performance limitations at low speeds concerning parameter inaccuracy and inverter nonlinearities. In addition, the need for open loop integration can cause DC offsets and drift, leading to saturation in the estimated fluxes, and consequently erroneous speed estimates. Current model flux estimates, on the other hand, depend on the machine rotor time constant and are rotor speed dependent. Many different approaches have been proposed to overcome the shortcomings of the pure integrator used in the voltage model. A common approach is to use a Low Pass Filter (LPF) instead of the pure integrator; however, this introduces errors in magnitude and phase around the filter cut-off frequency. This can be improved by expressing the pure integrator as a fixed cut-off LPF with the inclusion of positive feedback. The authors of (Jun & Bin, 1998) discuss and analyze three options for flux estimation, two of which contain limiters, while the third is adaptive but requires PI tuning and is said to be suitable for high performance drives with variation in flux levels. In Lascu & Andreescu (2006) two flux observers are proposed, a sliding mode which uses coordinate transformations, while another is based on the standard voltage models and is amended with voltage offset correction to cancel DC offsets in the flux estimate. The authors of (Hinkkanen & Luomi, 2003) propose a method for the low pass filter implementation with a fixed cut-off frequency, while (Marcetic *et al.,* 2014) investigates discrete rotor flux estimation techniques for MRAS schemes. In Casadei *et al.* (2001) a rotor flux estimator for a Direct Torque Control (DTC) scheme is proposed that implements a correction factor based on the difference between the estimated and reference flux values. Cascaded LPF's are fully discussed in Bose & Patel (1997) for stator flux estimation, while (Karanayil *et al.,* 2004) uses three cascaded LPFs for rotor flux estimation, each with a time constant one third of the original. Programmable LPF's with variable cut-off frequencies have also been proposed, (Comanescu & Xu, 2006) where the cut-off varies with the excitation frequency, while (Stojic *et al.,* 2015) introduces a programmable LPF which is stated to have a simpler implementation, but similar performance to (Comanescu & Xu, 2006). Combined current-voltage mode flux observers are discussed in Wang *et al.* (2014), while in Holtz & Quan (2002) the authors use a pure integrator with additional offset voltage correction for stator flux estimation based on the error between the actual and demanded fluxes. Stator flux estimation for Direct Torque Control (DTC) is analyzed in Wang & Deng (2012a) and Wang & Deng (2012b). A voltage model estimator consisting of a 5th order LPF in series with a High Pass Filter (HPF) is shown in Wang & Deng (2012a), with the combination and differentiating action of the HPF aiming to reduce the sensitivity to DC inputs and cancel the drift. Wang & Deng (2012b) presents a 3rd order LPF implementation. Results show the amplitude and phase are comparable to those from a pure integrator with the addition of zero DC gain. Discussion of the two estimators states the third order is simpler, but the 5th order achieves better harmonic filtering (Wang & Deng, 2012a); however, the authors of (Stojic *et al.,* 2015) list drawbacks of these methods including the requirement to use ωe. Regenerative mode operation and instability of speed estimators in this region has been well documented, with different options to overcome this problem published. The authors of (Harnefors & Hinkkanen, 2014) discuss flux and speed estimation, mentioning problems with regenerative operation and methods for stabilization. Flux estimator design is said to be critical for the success of sensorless schemes, with stator resistance the most critical parameter. Stable estimators for motoring operation are achievable, although with problems at zero speed, with instabilities that affect lower speed regenerative operation listed. In Wang *et al.* (2014) the instability challenge of regenerative operation is discussed, with investigations into the stability of a combined voltage and current model rotor flux estimator; a cross coupling feedback strategy is proposed to enable full torque/speed operation. Stator resistance variation showed stability occurs with values less than nominal, but with steady state speed error, values greater than nominal cause instability. In Kubota *et al.* (2002) the authors propose a solution to their adaptive flux and speed observer (Kubota *et al.,* 1993) by altering the observer gain to allow stable regenerative operation. An alternative strategy for this estimator is modification of the speed adaptive law used, an example of which is shown in Hinkkanen & Luomi (2004). Selection of the feedback gains is also studied in Suwankawin & Sangwongwanich (2006) where the authors look at the design of an adaptive full order observer to improve the stability, which (Suwankawin & Sangwongwanich, 2002) says is caused by unstable zeros. Stability of speed and stator resistance estimators in the regenerative region is discussed in Zaky (2012) and Saejia & Sangwongwanich (2006), mentioning how simultaneously estimating the rotor speed and start resistance can lead to instability in the regenerative region. Analysis in Saejia & Sangwongwanich (2006) shows that the cross coupling between the speed and resistance estimation loops causes the instability, and that under zero/light loads and zero frequency operation correct values are not estimated. Among various techniques proposed for rotor flux and rotor speed estimation, the Torque MRAS (TMRAS) scheme was proposed in Ohtani *et al.* (1992). Although many papers in the literature have referred to this scheme which claims better performance, limited investigations of its performance have been presented, with it being overshadowed by other more popular MRAS schemes. In Tamai *et al.* (1985), the authors compared the Torque MRAS (Ohtani *et al.,* 1992), rotor flux MRAS (Schauder, 1992), and an adaptive flux observer (Kubota *et al.,* 1993) to a set of low speed stepped tests and load impacts, with the effect of parameters and stability discussed. Ohyama *et al* (Schauder, 1992) presents a small signal stability analysis of the TMRAS scheme in Ohtani *et al.* (1992) looking at three different current control loops. Since this, no more work has been carried out to further investigate the performance of the TMRAS scheme especially at low speeds and during regenerative operating conditions. Unlike other methods the TMRAS scheme is inherently sensorless and cannot be operated open loop. In this scheme the rotor speed is estimated using a PI controller in order to minimize the error between the torque producing current demand generated by the speed loop and that calculated via the TMRAS scheme. Rotor flux estimation is an important consideration for this scheme, especially at low speeds, where erroneous flux estimates lead to problems with not only the rotor flux control loop (if used) and the feed forward slip calculation term for indirect vector control operation, but more importantly the estimation of the torque producing current and hence rotational speed. These effects destabilize the whole vector control based system, causing incorrect orientation even for correct machine parameters; hence accurate flux estimation is crucial for this scheme This paper presents a detailed investigation of the low speed operation of the TMRAS scheme including regenerative capability. First, the theoretical concept and implementation of the scheme is described. Then the rotor flux estimation is analyzed, with problems affecting the estimation, especially at low speeds, discussed. An improved rotor flux estimator is proposed to enhance the low speed operation of the scheme.

In recent years sensorless induction motor drives have been widely used due to their attractive features such as reliability, flexibility, robustness and poor cost. One of the most well-known methods used for control of induction motor drives are the Field Oriented Control (FOC) developed by Blaschke. FOC of induction motor drives is known to have a good dynamic performance with comparable to that of the Direct Torque Control (DTC) techniques developed by Takahashi. FOC technique has been used popularly for sensorless control of induction motor drives. However, when a very high accuracy is desired, the performance of speed estimation is not good particularly at low speeds. The main reason of the speed estimation error is imprecise of flux observer and the off-set of the stator current sensor. The method based on model reference adaptive system (MRAS) is one of the major approaches for rotor speed estimation. A rotational transducer such as a Tachogenerator, an encoder, was often mounted on the IM shaft. Various sensorless field oriented control (FOC) methods for induction motor drives have been proposed (Schauder, 1992; Cirrincione & Pucci, 2005) an adaptive full-order flux observers (AFFO) is used. Adaptive full-order flux observers (AFFO) for estimating the speed of an IM were developed using Popov's and Lyapunov's stability criteria (Kubota *et al.,* 1993; Lin & Chen, 1999). Although computationally efficient, an AFFO with a nonzero gain matrix may become unstable The proportionality constant in the adaptive algorithm has to be adapted for different speeds. If the gain matrix of the AFFO is set to zero, no adaptation is required. However, large speed errors may appear under heavy loads, and steady-state speed disturbances may occur at light loads (Lin & Chen, 1999). An adaptive pseudo reduced-order flux observer (APFO) for sensorless FOC was proposed in Lin & Chen (1999) using the Lyapunov method. By the application of APFO, the performance of the estimator was improved as compared to the AFFO. However, its superior performance was demonstrated only at medium and high-speed levels. In a MRAS system, rotor flux-linkage components of the induction machine (which are obtained by using measured quantities, e.g., stator voltages and currents) are estimated in a reference model and are then compared with, estimated by using an adaptive model (Saejia & Sangwongwanich, 2006). Then effort is made to reduce this error to zero using adaptive mechanism (**Fig. 1**). In this paper, a robust and accurate observer for estimating the speed of induction motors at both high speeds and low speeds, is developed, MRAS to determine the motor speed and thereby establishes vector controlled of motor as well as overall speed control. This paper presents the theory, modeling, simulation results of the proposed model reference adaptive system-based reduced-order flux observer for induction motor drives. Reduced-order flux observer for sensorless FOC is proposed of an IM. The Reduced order flux observer consumes less computational time and has a better speed response than the Full order flux observer over a wide speed range.

ROTOR FLUX ERROR-BASED MRAS

The rotor-flux-error-based MRAS for IM drives was first proposed by Tamai et al. (2014) in 1985 (Shen *et al.,* 2014). A basic structure of rotor-flux-error-based MRAS is shown in **Fig. 1**. The reference model, which is independent of the rotor speed, calculates the rotor flux (cr) from the machine terminal voltage and current signals while the adaptive model, which is dependent on the rotor speed, estimates the rotor flux (ˆcr). The error (εr) between these two state variables is then used to drive an adaptation mechanism which generates the estimated speed (vˆr) (Comanescu & Xu, 2006; Holtz & Quan, 2002). The reference and adaptive model are obtained from the machine dynamics Equations (1–4) as

$$p\psi_{dr} = \frac{L_r}{L_m}\left(v_{ds} - R_s i_{ds} - \sigma L_s p i_{ds}\right) \quad (1)$$

$$p\psi_{qr} = \frac{L_r}{L_m}\left(v_{qs} - R_s i_{qs} - \sigma L_s p i_{qs}\right) \quad (2)$$

$$p\hat{\psi}_{dr} = -\hat{\omega}_r\hat{\psi}_{qr} - \frac{1}{T_r}\hat{\psi}_{dr} + \frac{L_m}{T_r}i_{ds} \quad (3)$$

$$p\hat{\psi}_{qr} = \hat{\omega}_r\hat{\psi}_{dr} - \frac{1}{T_r}\hat{\psi}_{qr} + \frac{L_m}{T_r}i_{qs} \quad (4)$$

where (1) and (2) belong to the reference model, whereas (3) and (4) belong to the adaptive model.The error between the two models is given by

$$\varepsilon_r = \psi_{qr}\hat{\psi}_{dr} - \psi_{dr}\hat{\psi}_{qr} \quad (5)$$

Although the proposed method of rotor-flux-based MRAS speed estimator using algorithmic method by Tamai et al. is simple, but suffers from inaccuracy due to the error in the speed adaptation because of the inaccurate estimation of the rotor time constant. In addition, an off-set error is also produced because of the smooth change in the stator resistance with temperature, especially at low speed of operation (Wang & Deng, 2012b). Later Schauder in 1989 (Schauder, 1992) modified Tamai et al.'s idea by introducing a high-pass filter in both the reference and adaptive model to reconstruct rotor flux and thereby to estimate the rotor speed. The idea proposed is less complex and more effective than the previous approach, and hence further well utilised in Harnefors & Hinkkanen (2014) and Kubota *et al.* (2002). However, because of the high sensitivity of the rotor-flux on **Fig. 2** Simulation results for rotor-flux-error-based MRAS (Suwankawin & Sangwongwanich, 2002): actual and reference rotor fluxes.

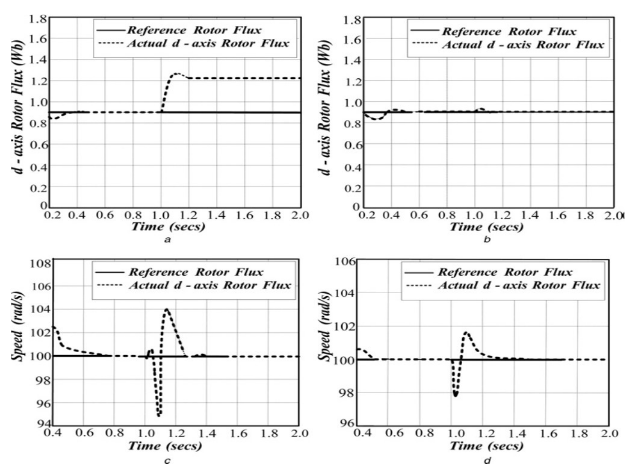

Fig.1 Simulation results for rotor-flux-error-based MRAS (Shen *et al.,* 2014): actual and reference rotor fluxes, (a) Without rotor resistance estimator , (b) With rotor resistance estimator, actual and reference rotor speed, (c) Without rotor resistance estimator, (d) With rotor resistance estimator.

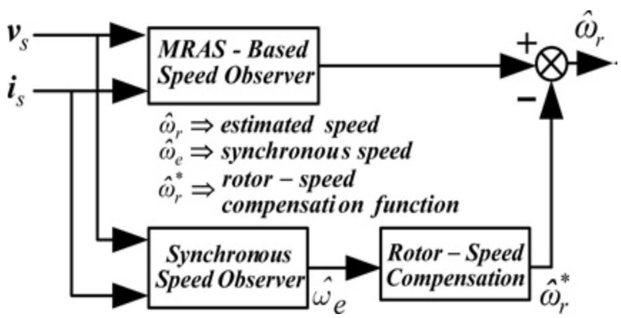

Fig. 2 MRAS-based rotor-flux-oriented speed observer scheme (Suwankawin & Sangwongwanich, 2006)

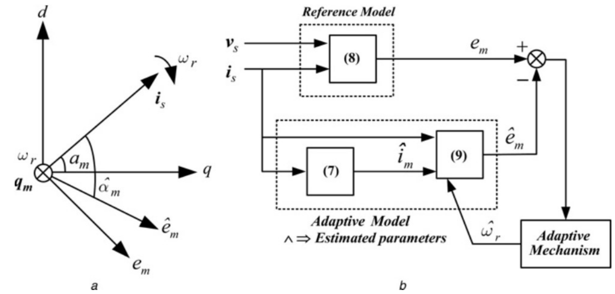

Fig 3 Back-EMF error-based MRAS: (a) Coordinates in stationary reference frame, (b) Structure of back-EMF error-based MRAS system for speed estimation (Saejia & Sangwongwanich, 2006)

The proposed estimator is highly sensitive to the motor-parameter variations (Marcetic *et al.,* 2014; Casadei *et al.,* 2001). Reference Karanayil *et al.* (2004) discusses the flux-based MRAS rotor resistance estimator, in which the updating algorithm for rotor resistance is done using proportional–integral (PI) controller. It has been observed that without rotor resistance estimator, the actual rotor flux and speed deviate from the reference flux and the reference speed, respectively, for a step change in rotor resistance at 1 s (**Figs. 2a–2b**). On the contrary, with rotor-flux-based MRAS rotor resistance estimator, the actual rotor flux and the actual speed track of the reference rotor flux and the reference rotor speed, respectively, within a short period (**Figs. 2c–2d**). Moreover, without rotor resistance estimator, the controller slightly fails to control the torque for a step change in rotor resistance at 1 s.

However, with the rotor-flux-based MRAS rotor resistance estimator, the instantaneous torque control is achieved. Further experimental results are presented in Comanescu & Xu (2006).

An online estimation of rotor time constant of an IM using rotor-flux-error-based MRAS is proposed in Holtz & Quan (2002) where the identified rotor time constant is utilised for the estimation of slip-angular velocity. Thus, the position of rotor flux can be estimated accurately even though the rotor time constant deviates from the nominal value. A speed observer for an IM consisting of a non-linear speed estimator combined with an open-loop rotor flux observer is proposed in Wang & Deng (2012a). It is application is, however, limited to motor loads and less than half rated load for low-speed applications.

In Wang & Deng (2012b), a rotor current-based sensorless MRAS observer is proposed for estimating the rotor position in induction machines by adaptive tuning of the stator inductance. For speed observation under variable load conditions at different rotational frequencies, a double scheme methodology (**Fig. 3**) combining both the MRAS based and the synchronous speed observers through a compensation function is proposed in Harnefors & Hinkkanen (2014).

Under no-load condition however, rotor-flux-oriented MRAS scheme is employed for estimation of speed without any compensation. In Kubota *et al.* (2002), an online rotor-resistance identification and correction scheme using rotor-flux-based MRAS is proposed. The scheme is found to be independent of stator resistance variation. The most recent study Kubota *et al.* (1993) demonstrates a discrete rotor flux and speed estimators for high-speed shaft-sensorless IM drives with experimental results. However, the rotor-flux-based MRAS schemes suffer fromparameter sensitivity; inaccuracy at lowspeed because of poor signal-to-noise ratio, increased inverter non-linearity; and deterioration of estimation at zero-speed operation because of dominant stator resistance drop and flux pure-integration problem (Yin *et al.,* 2014; Hinkkanen & Luomi, 2004).

BACK-EMF ERROR-BASED MRAS

Peng & Fukao (1994) proposed an alternative new MRAS scheme for estimating speed using counter electromotive force or back EMF. The back-EMF-based MRAS technique does not require any pure integration in its reference and adaptive models Instead of using the rotor fluxes in reference and adaptive models, the back EMF is estimated and compared with the measured quantity to produce a speed error correction signal (Saejia & Sangwongwanich, 2006; Schauder, 1992; Lin & Chen, 1999). The back EMF in terms of machine parameters is calculated with the help of following equations:

$$\boldsymbol{v}_s = R_s \boldsymbol{i}_s + \sigma L_s p \boldsymbol{i}_s + \boldsymbol{e}_m \tag{6}$$

$$p\boldsymbol{i}_m = \boldsymbol{\omega}_r \otimes \boldsymbol{i}_m - \frac{1}{T_r}\boldsymbol{i}_m + \frac{1}{T_r}\boldsymbol{i}_s \tag{7}$$

$$\boldsymbol{e}_m = \boldsymbol{v}_s - \left(R_s \boldsymbol{i}_s + \sigma L_s p \boldsymbol{i}_s\right) \tag{8}$$

$$\boldsymbol{e}_m = L'_m\, p\boldsymbol{i}_m = L'_m\left(\boldsymbol{\omega}_r \otimes \boldsymbol{i}_m - \frac{1}{T_r}\boldsymbol{i}_m + \frac{1}{T_r}\boldsymbol{i}_s\right) \tag{9}$$

where ωr is rotational angular velocity whose direction is determined according to a system of coordinates (**Fig. 4a**). **Figure 4b** shows a back-EMF error-based MRAS using back EMF vector (em) as error signal in place of the rotor flux vector (cr) for speed identification. To estimate the EMF vector (em), two independent observers are configured: one based on (8) regarded as reference model and another based on (7), (9) regarded as adaptive model.

However, the Peng's method fails to estimate speed accurately owing to the increased non-linear characteristics of the controllers in the low-speed region including zero-speed startup operation because of the stator resistance dependence (Yin *et al.,* 2014; Suwankawin & Sangwongwanich, 2006; Saejia & Sangwongwanich, 2006). Moreover, this MRAS estimator shows unsatisfactory performance because of the requirement of differentiation of the stator currents (Saejia & Sangwongwanich, 2006).

To make speed estimation completely robust to stator resistance variations, the cross-product of the back EMF error vector and the stator current vector (i.e. reactive power-error-based estimator) is considered by Peng and Fukao in later half of Saejia & Sangwongwanich (2006). However, the proposed estimator is reported to be unstable in the generating mode of drive's operation (Wang & Deng, 2012a). As a counter measure, the overall error signal is generated by taking the sum of two component-error signals where both the speed and stator resistance estimators have been employed. The first component is the modulus of cross-product of the estimated rotor flux vector and the error in estimated back EMF voltage vector, whereas the second component is the scalar product of the same quantities as given by:

$$\varepsilon = \left|\hat{\psi}_{\mathrm{r}} \times \Delta e_{\mathrm{s}}\right| + k_{\omega\mathrm{r}}\hat{\psi}_{\mathrm{r}} \times \Delta e_{\mathrm{s}} \tag{10}$$

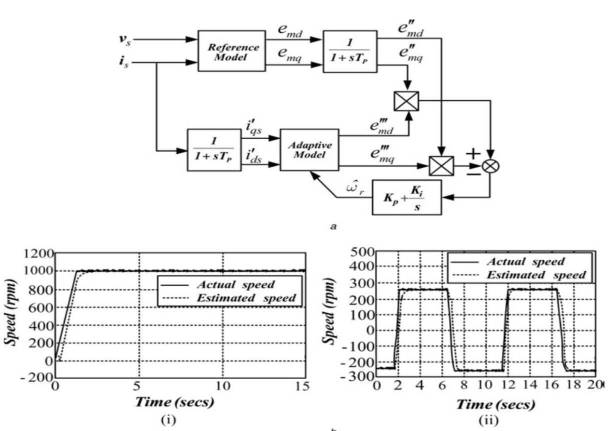

Fig 4 Back-EMF error-based MRAS (a) Speed estimator ,(b) Performance of a back-EMF-based MRAS speed estimator for vˆ r : (i) 1000 rpm (105 rad/s) and (ii) ±250 rpm (26 rad/s) (Suwankawin & Sangwongwanich, 2006).

By incorporating both the cross and scalar products in error signal, a non-zero error signal can be obtained in all operating modes. However, in the case of back-EMF error-based MRAS, although the individual estimators as proposed are stable independently, interaction between the two estimators may result in the overall estimation scheme being unstable.

REACTIVE POWER-ERROR-BASED MRAS

The choice of reactive power as the error parameter in MRAS automatically makes the system immune to the variations in stator resistances (Wang & Deng, 2012a; Wang & Deng, 2012b). Moreover, the unique structure of MRAS with the instantaneous and steady-state reactive power completely eliminates the requirement of any flux estimation in the process of computation (Rashed & Stronach, 2004). Thus, the method is less sensitive to integrator-related problems such as drift and saturation (requiring no integration). This also makes the estimation at or near zero-speed quite accurate (Maiti *et al.,* 2008; Orlowska-Kowalska & Dybkowski, 2010). At low speed, since the applied stator voltage is low, the resistance drop becomes comparable with applied voltage, leading to a difficulty in maintaining stable operation. To avoid this difficulty, instantaneous reactive power is chosen as a state variable for both the reference and adaptive models in a reactive power-error-based approach as proposed in Saejia & Sangwongwanich (2006) resulting an improved transient performance (Wang *et al.,* 2014).

Here, a new quantity, instantaneous reactive power (qm) is introduced as

$$\boldsymbol{q}_{\mathrm{m}} \triangleq \boldsymbol{i}_{\mathrm{s}} \otimes \boldsymbol{e}_{\mathrm{m}} \tag{11}$$

Substituting (8) and (9) for em in (11) and noting that is⊗is = 0, following equations are obtained

$$\boldsymbol{q}_{\mathrm{m}} = \boldsymbol{i}_{\mathrm{s}} \otimes \left(\boldsymbol{v}_{\mathrm{s}} - \sigma L_{\mathrm{s}} p \boldsymbol{i}_{\mathrm{s}}\right) \tag{12}$$

$$\boldsymbol{q}_{\mathrm{m}} = L'_{\mathrm{m}}\left(\left(\boldsymbol{i}_{\mathrm{m}} \bullet \boldsymbol{i}_{\mathrm{s}}\right)\omega_{\mathrm{r}} + \frac{1}{T_{\mathrm{r}}}\boldsymbol{i}_{\mathrm{m}} \otimes \boldsymbol{i}_{\mathrm{s}}\right) \tag{13}$$

Using (12) as the reference model and (7), (13) together as the adaptive model, a reactive power-error-based MRAS which is completely robust to stator and rotor resistance thermal variations (**Fig. 5**).

The adaptive model of this scheme as proposed in Saejia & Sangwongwanich (2006) contains derivative terms which affects the accuracy of the estimated quantity. The scheme proposed in Hinkkanen & Luomi (2003) and Casadei *et al.* (2001) uses both the instantaneous and steady-state reactive power for the estimation of speed and rotor time constant of IM drive. The use of instantaneous reactive power in the reference model makes it completely free from the machine parameters. On the other hand, the choice of steady-state reactive power in the adaptive model eliminates the derivative terms from the same. Therefore the accuracy in the estimated quantity is improved. The expressions for instantaneous and steady-state reactive powers for reference and adaptive models are obtained as:

$$q_{\mathrm{ref}} = (v_{qs}i_{ds} - v_{ds}i_{qs}) \tag{14}$$

$$q_{\mathrm{est}} = \sigma L_s \omega_e \left(i_{ds}^2 + i_{qs}^2\right) + \omega_e \frac{L_m}{L_r}(\psi_{qr}i_{qs} + \psi_{dr}i_{ds}) \tag{15}$$

where (15) is derived from (14) by replacing the stators d- and qaxes voltages and making the derivative terms zero. It is important to note that the flux estimation is not required in any step of the computation and the expressions (14), (15) are free from stator resistances. Substituting, cdr = Lmids and cqr = 0 for the indirect FOC of IM drives in (15), the more simplified expression of qest is obtained as:

$$q_{\mathrm{est}} = \sigma L_s \omega_e \left(i_{ds}^2 + i_{qs}^2\right) + \omega_e \frac{L_m^2}{L_r} i_{ds}^2 \tag{16}$$

However, in Rashed & Stronach (2004), the same reactive power-error-based MRAS (14–16) is used for online estimation of rotor resistance for sensorless indirect field-oriented controlled IM drives in which flux-tuning controllers (**Fig. 6**) (i.e., PI controllers) are used for flux orientation. Said and Benbouzid used a reactive power-based approach for the estimation of rotor resistance, using rotor current model in Wang & Deng (2012b).

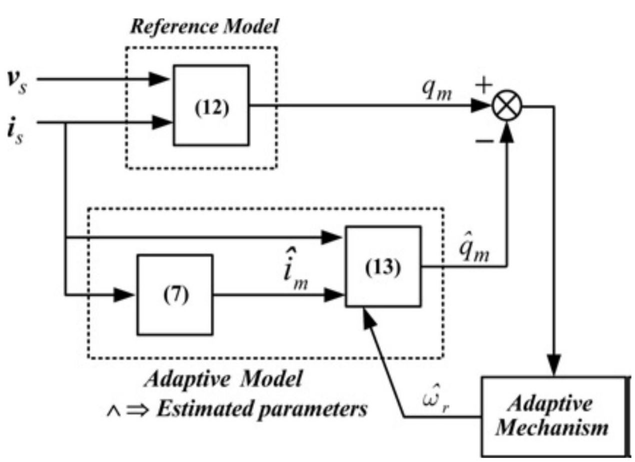

Fig 5 Basic structure of reactive power-error-based MRAS system for speed estimation (Saejia & Sangwongwanich, 2006) are achieved.

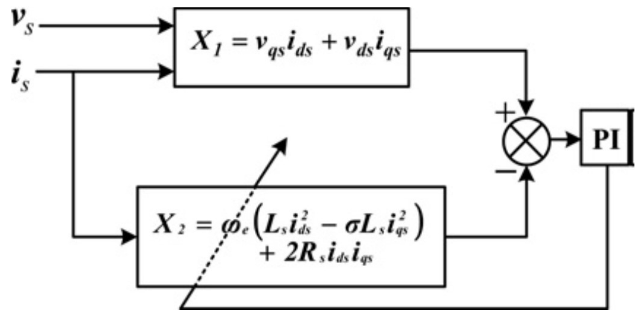

Fig. 6 X-MRAS structure for rotor speed estimation NEW X-MRAS

The simulation results confirm the robustness of rotor resistance estimation scheme over stator resistance mismatch. However, the transient behaviour of this method under stator resistance variations has not been investigated (Bose & Patel, 1997).

A reactive power-error-based MRAS speed estimator is proposed in Orlowska-Kowalska & Dybkowski (2010). The technique works satisfactorily at very low speed, but not at zero stator frequency. At dc excitation, the rotor speed estimation also fails because of the lack of measurement of the rotor dynamics on the stator side. This can be overcome by injecting a low-amplitude, high-frequency signal into the control drive (Karanayil *et al.,* 2004; Comanescu & Xu, 2006). However, the harmonics in the injecting signal causes an additional loss in the system because of pronounced skin effect. An alternate technique is to use a very low resolution encoder with the instantaneous speed observer (Holtz & Quan, 2002) because of its robustness under harsh environment.

A novel MRAS (introduced as X-MRAS)-based speed estimator designed with instantaneous and steady-state values of V* × I (or v* × i) (where V = stator voltage vector and I = stator current vector) in the reference and adaptive models, respectively, is presented in (Bose & Patel, 1997; Holtz & Quan, 2002). In this X-MRAS (**Fig. 7**), 'X' is defined as a fictitious quantity which is neither reactive power nor active power. The IM stator voltages in the synchronously rotating reference frame are given by (Karanayil *et al.,* 2004).

$$v_{qs} = R_s i_{qs} + \omega_e \sigma L_s i_{ds} + p\sigma L_s i_{qs} + \frac{L_m}{L_r}\left(\omega_e \psi_{dr} + p\psi_{qr}\right) \tag{17}$$

$$v_{ds} = R_s i_{ds} - \omega_e \sigma L_s i_{qs} + p\sigma L_s i_{ds} - \frac{L_m}{L_r}\left(\omega_e \psi_{qr} - p\psi_{dr}\right) \tag{18}$$

The instantaneous value of X (i.e. $\boldsymbol{v}^* \times \boldsymbol{i}$) is given by

$$X_1 = v_{qs}i_{ds} + v_{ds}i_{qs} \tag{19}$$

Using (17) and (18) in (19) and simplifying the instantaneous value of X for FOC

$$X_2 = \omega_e[L_s i_{ds}^2 - \sigma L_s i_{qs}^2] + 2R_s i_{ds} i_{qs} \tag{20}$$

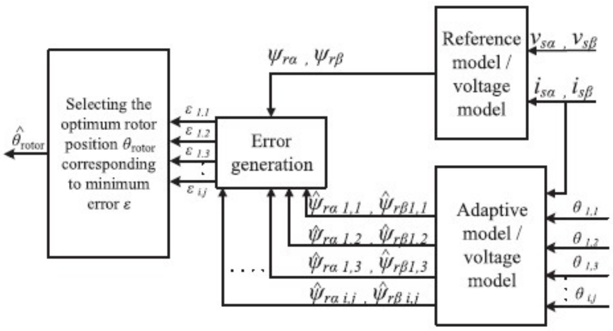

Fig.7 Block diagram of the proposed MRAS estimator.

Since, X1 is independent of rotor speed, selected as reference model whereas X2 is chosen as the adaptive model because of rotor speed dependence. It also eliminates the requirement of both flux estimation and derivative operations.

The estimated speed is observed to follow the actual speed which in turn tracks the reference speed in both motoring (**Figs. 8a–8b**) and regenerative modes (**Figs. 9a–9b**: second quadrant, **Figs. 10a–10b**: fourth quadrant) of drive's operation. In all these operations, the flux orientation is not disturbed as observed in **Figs. 10–11**. The proposed estimator has also been successfully used for stator resistance estimation. An attractive X-MRAS using single current sensor for vector controlled IM drive is presented in Wang & Deng (2012a).

METHODOLOGY

The principle of the proposed predictive MRAS estimator is derived from the FCS-MPC concept. In contrast to the conventional MPC, FCS considers the discrete nature of the inverter insolving the control optimization problem. The cost function is evaluated at each single switching state of the inverter, and the state with the minimum cost function is chosen to be applied in the next sampling instant (Hinkkanen & Luomi, 2004). This method, therefore, has the advantages of both simplicity and design flexibility making it attractive to electric drives applications (Casadei *et al.,* 2001).The FCS-MPC approach is applied in this paper to design the adaptation mechanism in MRAS speed estimators. An optimization problem is formulated to find the rotor position in order to minimize a cost function, which is the speed tuning signal ε (4) in the case of the MRAS estimator.

In contrast to the FCS-MPC, the rotor position, which varies continuously between 0◦ and 360◦, does not have the same discrete nature as the inverter output. Therefore, a search method is to be applied to discretize the rotor position into a finite number of positions to allow evaluating the cost function at each of these discrete positions. This search is performed within an iteration-

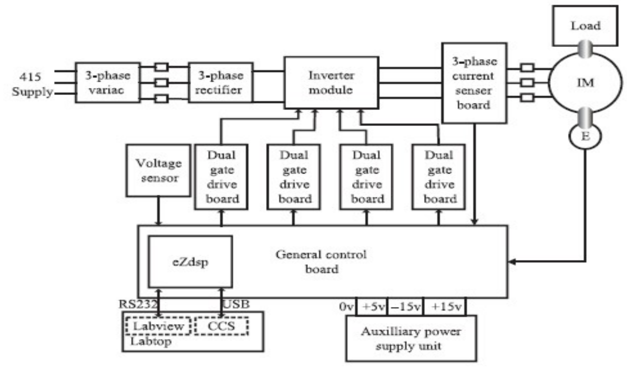

Fig. 8 Experimental Setup

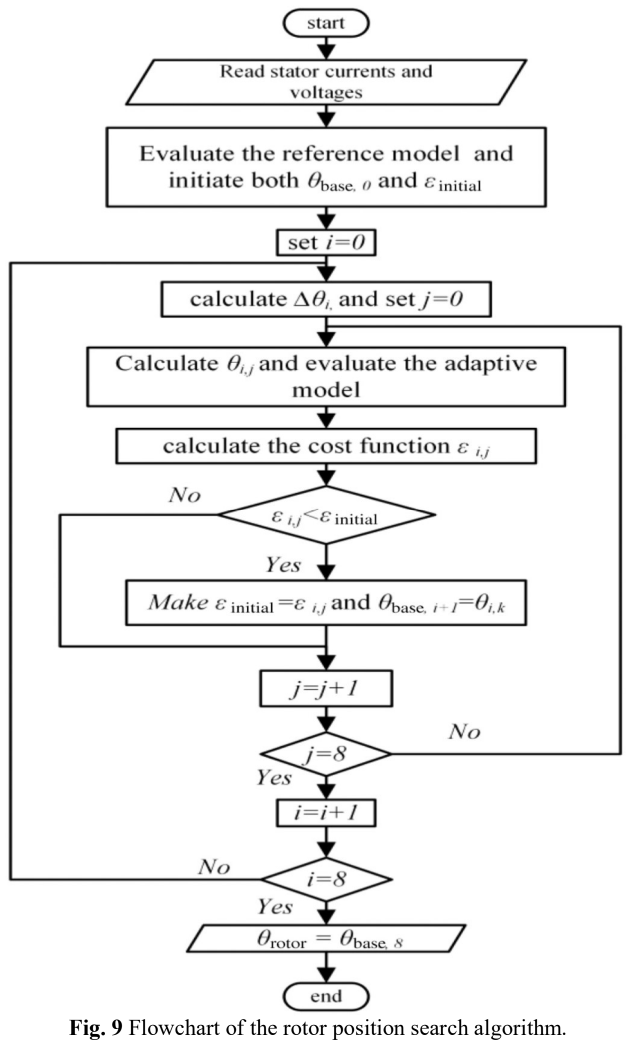

Fig. 9 Flowchart of the rotor position search algorithm.

based process. The block diagram of the proposed predictive MRAS estimator is shown in **Fig. 3**. The flowchart of the proposed search algorithm is shown in **Fig. 9**. The algorithm starts by calculating the reference

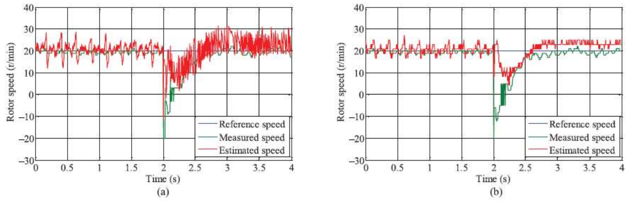

Fig. 10 Open loop estimation, 20 r/min and 75% load, rotor speed. (a) Classical MRAS. (b) Predictive MRAS.

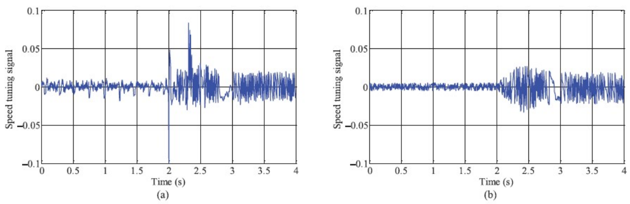

Fig. 11 Open loop estimation 20 r/min and 75% load, speed tuning signal. (a) Classical MRAS. (b) Predictive MRAS. estimator at all operating speeds

model outputs $\psi r\alpha$, $\psi r\beta$ from the stator voltages and currents. The discretization of the rotor position begins by starting from an initial base angle θbase,0 and then displacing this angle by a displacement ($\Delta\theta i$) which is calculated as follows:

$$\Delta\theta_i = 45^\circ \cdot 2^{-i} \quad (6)$$

where i is the order of the current iteration. The displacement of the base angle θbase within each iteration is carried out to get eight discrete rotor positions as follows:

$$\theta_{i,j} = \theta_{\text{base}} + \Delta\theta_i.(j-4) \quad (7)$$

where j is the order of the displacement. In the initial iteration (i = 0), the base angle θbase is chosen to be 0◦ with $\Delta\theta$ = 45° according to (6). Applying (7) will produce eight discrete positions: 0°, 45°, 90°, 135°, 180°, −45°, −90°, and −135°. Each of these discrete positions ($\theta i,j$) is used to calculate the adaptive model outputs corresponding to each a drawback of the method is the high computational effort required to run the search algorithm eight times in each sampling period.

However, the rotor position, as amechanical variable, changes relatively slowly and hence it does not vary significantly between two time samples. Therefore, instead of initiating the search algorithm in each sampling period with zero angle (θbase, 0 = 0), it can be initialized by the output of the algorithm in the last sampling instant θbase,0 = θrotor(k − 1). As a result, the number of the iterations required by the search algorithm to find the optimal solution can be significantly reduced as the search is performed only around the previous rotor position. This simplified scheme is referred to as "modified-predictive." Experimentally, it was found that only the last iteration loop (i = 7) is required to find the rotor position using the modifiedpredictive scheme without affecting the estimation accuracy. This significantly reduces the execution time of the proposed scheme from 103 to 39 µs. For comparison purpose, **Table 1** shows the execution times for the two versions of the proposed predictive scheme in addition to the PI-based classical MRAS observer. It should be mentioned here that these times are specific for the TMS320F28335 floating point microcontroller used in the experiments and it can be further reduced if a faster microcontroller is applied. From now on, the term "predictive estimator" will be used to refer to the modified scheme with the reduced execution time.

The proposed predictive scheme applies an iterative search method to find the rotor position. This is fundamentally different from other MRAS estimators available in the literature, such as those using PI, SM, and FL adaptation mechanisms. The proposed method does not require any gain tuning like the aforementioned schemes which make the design of the estimator much simpler and ensure the optimum operation.

Application of the proposed scheme always ensures that the speed tuning signal is driven to almost zero in each sampling period. The scheme is capable of achieving minimum error in one sampling time following any disturbance. This results in the proposed scheme having a significant advantage over other approaches.

RESULTS: EXPERIMENTAL SETUP

The experimental platform used to validate the proposed estimator (**Figs. 12–14**) consists of a 2.2-kW, 380-V, star-connected, four-pole, three-phase squirrel cage IM. The motor parameters are presented in **Table 2**. The motor is loaded by a 4.19-kW, 380-V, eight-pole, 2000-r/min permanent-magnet synchronous machine driven by

Table 1. Execution time

Symbol	Execution time
PI	14 µs
Predictive	103 µs
Modified predictive	39 µs

Table 2. Motor parameters

Symbol	Quantity	Value
Rs	Stator resistance	2.35 Ω
Rr	Rotor resistance	1.05 Ω
Ls	Stator inductance	0.344209 H
Lr	Rotor inductance	0.348197 H
Lm	Mutual inductance	0.33209 H
J	Motor inertia	0.22 kg.m²

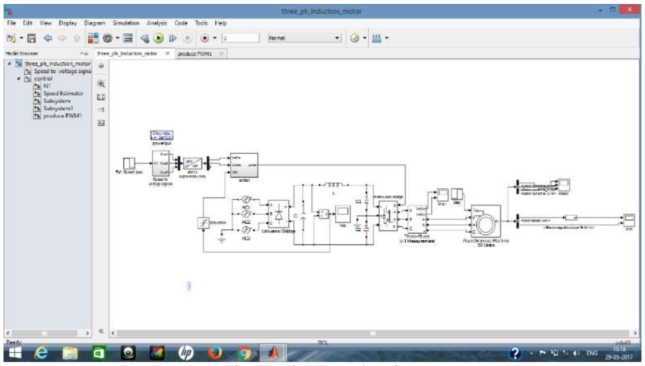

Fig. 12 Three Phase Induction Motor

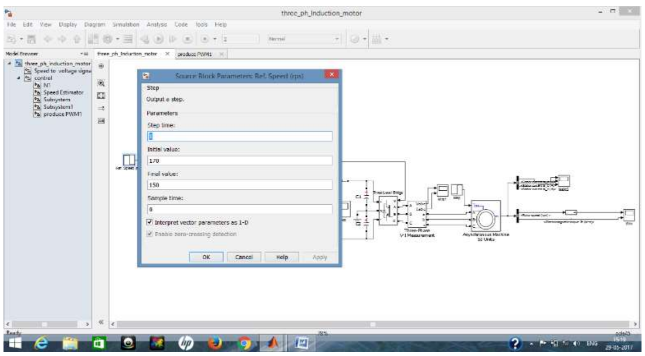

Fig. 13 Entering the value of reference speed input

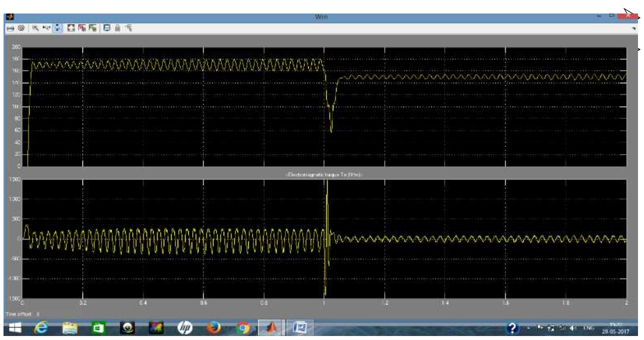

Fig. 14 Output graph of speed

Y – axis REPRESENT ROTOR SPEED
X - axis REPRESENT SWITCHING TIME

a Unidrive SP controller manufactured by Control Techniques. The load machine allows independent control of the load torque.

The ac drive consists of a three-phase diode bridge rectifier, and an insulated-gate bipolar transistor (IGBT)-based, three-phase bridge inverter. To control the ac drive, a TMS320F28335 floating-point microcontroller is used. The control algorithm, based on the FOC scheme, is written in C-code and is developed using Code Composer Studio CCS5.5 software. The inverter switching frequency is 10 kHz with a dead-time period of 1 μs and the FOC algorithm is executed with the same sampling frequency. A 16 384 pulses/revolution R1120 Gurley incremental optical encoder is used to measure the actual motor speed, and three CAS-15NP hall-effect current sensors are used to measure the motor phase currents. In addition, an LV25-P voltage sensor is applied to monitor the dc-link voltage.

In order to practically implement both MRAS schemes, the integrator in the reference model was replaced by a lowpass filter with a cutoff frequency of 2 Hz to minimize drift and initial condition problems associated with pure integration. As the reference voltage signals available in the controller unit are used in reference model (1), a compensation for the inverter nonlinearity (Suwankawin & Sangwongwanich, 2006) and a dead-band compensator (Suwankawin & Sangwongwanich, 2002) are implemented.

CONCLUSIONS

The speed estimator is an adaptive sliding mode observer. Gain adaptation of the observer is needed to stabilize the observer when integration errors are present.

The design and implementation issues of the observer were analyzed.

The control algorithm is field oriented using discrete time sliding mode controllers for current and flux tracking.

This low speed behavior is acceptable for HEV applications, when motor speed falls below stall speed only at start-up and shut down.

APPLICATION

1. The propulsion system of a hybrid electric vehicle (HEV) comprises both an internal combustion engine (ICE) and an electric motor (EM).

2. This structure presents a relative advantage in control over other induction motor applications

3. The advantage is that the induction motor will virtually operate only at speeds above the idle speed of the ICE

4. All known speed Sensorless techniques are sensitive to variation of parameters. The induction motor parameters vary with the operating conditions

5. Operating flux levels will change with loading demands in order to obtain maximum energy efficiency.

6. The parameters of the induction motor model will change as the motor changes operating conditions

REFERENCES

Alkorta, P., Barambones, O., Cortajarena, J. A. & Zubizarreta, A. (2014) Efficient Multivariable Generalized Predictive Control for Sensorless Induction Motor Drives. *IEEE Trans. Ind. Electron.*, **61**(9), 5126−5134. 10.1109/TIE.2013.2281172

Amezquita-Brooks, L., Liceaga-Castro, J. & Liceaga-Castro, E. (2014) Speed and Position Controllers Using Indirect Field-Oriented Control: A Classical Control Approach. *IEEE Trans. Ind. Electron.*, **61**(4), 1928–1943. 10.1109/TIE.2013.2262750

Benlaloui, I., Drid, S., Chrifi-Alaoui, L. & Ouriagli, M. (2014) Implementation of a New MRAS Speed Sensorless Vector Control of Induction Machine. *IEEE Trans. Energy Convers.*, **30**(2), 588−595. 10.1109/TEC.2014.2366473

Bose, B.K. & Patel, N. R. (1997) A programmable cascaded low-pass filter-based flux synthesis for a stator flux-oriented vector controlled induction motor drive. *IEEE Trans. Ind. Electron.*, **44**(1), 140−143. 10.1109/41.557511

Casadei, D., Serra, G. & Tani, A. (2001) Steady-state and transient performance evaluation of a DTC scheme in the low speed range. *IEEE Trans. Power Electron.*, **16**(6), 846−851. 10.1109/63.974383

Cirrincione, M. & Pucci, M. (2005) An MRAS-based sensorless highperformance induction motor drive with a predictive adaptive model. *IEEE Trans. on Industrial Electronics*, **52**(5), 532–551. 10.1109/TIE.2005.844247

Comanescu, M. & Xu, L.Y. (2006) An improved flux observer based on PLL frequency estimator for sensorless vector control of induction motors. *IEEE Trans. Ind. Electron.*, **53**(1), 50−56. 10.1109/TIE.2005.862317

Fengxiang, W., Zhe, C., Stolze, P., Stumper, J.-F., Rodriguez, J. & Kennel, R. (2014) Encoderless Finite-State Predictive Torque Control for Induction Machine With a Compensated MRAS. *IEEE Trans. Ind. Inf.*, **10**(2), 1097−1106. 10.1109/TII.2013.2287395

Finch, J.W. & Giaouris, D. (2008) Controlled AC electrical drives. *IEEE Trans. Ind. Electron.*, **55**(2), 481–491. 10.1109/TIE.2007.911209

Gadoue, S. M., Giaouris, D. & Finch, J. W. (2009) Sensorless Control of Induction Motor Drives at Very Low and Zero Speeds Using Neural Network Flux Observers. *IEEE Trans. Ind. Electron.*, 56, 3029−3039. 10.1109/TIE.2009.2024665

Gadoue, S.M., Giaouris, D. & Finch, J.W. (2010) MRAS Sensorless Vector Control of an Induction Motor Using New Sliding-Mode and Fuzzy-Logic Adaptation Mechanisms. *IEEE Trans. Energy Convers.*, 25, 394-402. 10.1109/TEC.2009.2036445

Harnefors, L. & Hinkkanen, M. (2014) Stabilization Methods for Sensorless Induction Motor Drives – A Survey. *IEEE. J. Emerging Sel. Topics Power Electron.*, **2**(2), 132−142. 10.1109/JESTPE.2013.2294377

Hinkkanen M. & Luomi, J. (2003) Modified integrator for voltage model flux estimation of induction motors. *IEEE Trans. Ind. Electron.*, **50**(6), 818−820. 10.1109/IECON.2001.975976

Hinkkanen, M. & Luomi, J. (2004) Stabilization of regenerating-mode operation in sensorless induction motor drives by full-order flux observer design. *IEEE Trans. Ind. Electron.*, **51**(6), 1318- 1328. 10.1109/TIE.2004.837902

Holtz, J. & Quan, J. (2002) Sensorless vector control of induction motors at very low speed using a nonlinear inverter model and parameter identification. *Proc.* IEEE Trans. Ind. Appl., Conference. 36th IAS Annual Meeting. 10.1109/IAS.2001.955988

Jun, H. & Bin, W. (1998) New integration algorithms for estimating motor flux over a wide speed range. *IEEE Trans. Power Electron.*, **13**(5), 969−977. 10.1109/63.712323

Karanayil, B., Rahman, M.F. & Grantham, C. (2004) An implementation of a programmable cascaded low-pass filter for a rotor flux synthesizer for an induction motor drive. *IEEE Trans.Power Electron.*, **19**(2), 257−263. 10.1109/TPEL.2003.823181

Kubota, H.; Matsuse, K. & Nakano, T. (1993) DSP-based speed adaptive flux observer of induction motor. IEEE *Trans. Ind. Applicant.*, **29**(2), 344–348. 10.1109/IAS.1991.178183

Kubota, K., Sato, I., Tamura, Y., Matsuse, K., Ohta, H. & Hori, Y. (2002) Regenerating-mode low-speed operation of sensorless induction motor drive with adaptive observer. *IEEE Trans. Ind. Appl.*, **38**(4), 1081−1086. 10.1109/TIA.2002.800575

Lascu, C. & Andreescu, G.D. (2006) Sliding-mode observer and improved integrator with DC-offset compensation for flux estimation in sensorless-controlled induction motors. *IEEE Trans. Ind. Electron.*, 53, 785−794. 10.1109/TIE.2006.874275

Lin, Y.N. & Chen, C.L. (1999) Adaptive pseudo reduced-order flux observer for speed sensorless field oriented control of IM. *IEEE Trans. Ind. Electron.*, **46**(5), 1042–1045.

Maiti, S., Chakraborty, C., Hori, Y. & Ta, M.C. (2008) Model reference adaptive controller-based rotor resistance and speed estimation techniques for vector controlled induction motor drive utilizing reactive power. *IEEE Trans. Ind. Electron.*, **55**(2), 594−601. 10.1109/TIE.2007.911952

Marcetic, D.P., Krcmar, I.R.; Gecic, M.A., Matic, P.R. (2014) Discrete Rotor Flux and Speed Estimators for High-Speed Shaft-Sensorless IM Drives. *IEEE Trans. Ind. Electron.*, **61**(6), 3099−3108. 10.1109/TIE.2013.2258311

Ohtani, T., Takada, N. & Tanaka, K. (1992) Vector Control of Induction-Motor without Shaft Encoder. *IEEE Trans. Ind. Appl.*, **28**(1), 157−164. 10.1109/28.120225

Orlowska-Kowalska, T. & Dybkowski, M. (2010) Stator-Current-Based MRAS Estimator for a Wide Range Speed-Sensorless Induction-Motor Drive. IEEE *Trans. Ind. Electron.*, **57**(4), 1296−1308. 10.1109/TIE.2009.2031134

Qu, Z.C., Hinkkanen, M. & Harnefors L. (2014) Gain Scheduling of a Full-Order Observer for Sensorless Induction Motor Drives. *IEEE Trans. Ind. Appl.*, **50**(6), 3834−3845. 10.1109/TIA.2014.2323482

Rashed, M. & Stronach, A.F. (2004) A stable back-EMF MRAS-based sensorless low-speed induction motor drive insensitive to stator resistance variation. *IEEE Proc. Electr. Power Appl.*, **151**(6), 685−693. 10.1049/ip-epa:20040609

Ravi Teja, A.V., Chakraborty, C., Maiti, S. & Hori, Y. (2012) A New Model Reference Adaptive Controller for Four Quadrant Vector Controlled Induction Motor Drives. *IEEE Trans. Ind. Electron.*, **59**(10), 3757−3767. 10.1109/TIE.2011.2164769

Saejia, M. & Sangwongwanich, S. (2006) Averaging analysis approach for stability analysis of speed-sensorless induction motor drives with stator resistance estimation. *IEEE Trans. Ind. Electron.*, **53**(1), 162−177. 10.1109/TIE.2005.862301

Schauder, C. (1992) Adaptive speed identification for vector Control of induction motor without rotational Transducers. *IEEE Trans. Ind. Applic.*, **28**(5), 1054–1061. 10.1109/28.158829

Shen, G., Yao, W., Chen, B., Wang, K., Lee, K. & Lu, Z. (2014) Automeasurement of the Inverter Output Voltage Delay Curve to Compensate for Inverter Nonlinearity in Sensorless Motor Drives. *IEEE Trans. Power Electron.*, **29**(10), 5542−5553. 10.1109/TPEL.2013.2293134

Stojic, D., Milinkovic, M., Veinovic, S. & Klasnic, I. (2015) Improved Stator Flux Estimator for Speed Sensorless Induction Motor Drives. *IEEE Trans. Power Electron.*, **30**(4), 2363−2371. 10.1109/TPEL.2014.2328617

Suwankawin, S. & Sangwongwanich, S. (2002) A speed-sensorless IM drive with decoupling control and stability analysis of speed estimation. *IEEE Trans. Ind. Electron.*, **49**(2), 444−455. 10.1109/41.993278

Suwankawin, S. & Sangwongwanich, S. (2006) Design strategy of an adaptive full-order observer for speed-sensorless induction-motor

Drives-tracking performance and stabilization. *IEEE Trans. Ind. Electron.,* **53**(1), 96-119. 10.1109/TIE.2005.862308

Tamai, S., Sugimoto, H. & Yano, M. (1985) Speed-Sensorless Vector control of induction motor with Model reference Adaptive system. *Proc.* IEEE-IAS Annual Meeting, 613─620.

Wang, K., Chen, B., Shen, G., Yao, W., Lee, K. & Lu, Z. (2014) Online Updating of Rotor Time Constant Based on Combined Voltage and Current Mode Flux Observer for Speed-Sensorless AC Drives. *IEEE Trans. Ind. Electron.,* **61**(9), 4583─4593. 10.1109/TIE.2013.2288227

Wang, K., Yao, W., Lee, K. & Lu, Z. (2014) Regenerating Mode Stability Improvements for Combined Voltage and Current Mode Flux Observer in Speed Sensorless Induction Machine Control. *IEEE Trans. Ind. Appl.,* **50**(4), 2564─2573. 10.1109/TIA.2014.2301869

Wang, Y. & Deng, Z. (2012a) An Integration Algorithm for Stator Flux Estimation of a Direct-Torque-Controlled Electrical Excitation Flux-Switching Generator. *IEEE Trans. Energy Convers.,* **27**(2), 411─420. 10.1109/TEC.2012.2188139

Wang, Y. & Deng, Z. (2012b) Improved Stator Flux Estimation Method for Direct Torque Linear Control of Parallel Hybrid Excitation Switched-Flux Generator. *IEEE Trans. Energy Convers.,* **27**(3), 747─756. 10.1109/TEC.2012.2200898

Yin, Z.-G., Zhao, C., Zhong, Y.-R. & Liu, J. (2014) Research on Robust Performance of Speed-Sensorless Vector Control for the Induction Motor Using an Interfacing Multiple-Model Extended Kalman Filter. *IEEE Trans. Power Electron.,* **29**(6), 3011─3019. 10.1109/TPEL.2013.2272091

Zaky, M.S. (2012) Stability Analysis of Speed and Stator Resistance Estimators for Sensorless Induction Motor Drives. *IEEE Trans. Ind. Electron.,* **59**(2), 858─870. https://doi.org/10.1109/TIE.2011.2161658