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Review of the Rotor Position and Speed Estimation Method of Induction Motor Drives

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Abstract: *The electric drive systems used in industrial applications are increasingly required to meet the higher performance and reliability requirement. Today about 90% of all industrial motor applications use three phase induction motors because of their simplicity in design, easier maintenance, and are less costly than other designs. Electromechanical position sensors, e.g., resolvers, optical encoders, and Hall Effect sensors, are commonly used to obtain rotor position/speed in induction motor drives. The use of these sensors is undesirable in a drive because it increases the cost, size, weight, hardware wiring complexity of drive systems and reliability problem, besides the need for a shaft extension and mounting arrangement. To overcome these drawbacks of using position sensors, much research effort has gone into the development of sensorless drives that have comparable dynamic performance with respect to the sensor-based drives during the last decades. It is possible to estimate the position from machine terminal voltages and currents with the help of an intelligent controller. This paper summarizes different sensorless speed control and estimation techniques of induction motor drives system and their corresponding advantages and disadvantages stated. A comparison between different speed estimation methods was also tabulated and presented.*

Keywords: *Induction Motor, Field Oriented Control, Rotor Position, Sensorless Speed Control*

1.0 Introduction

Induction motors are nonlinear high order dynamic systems of considerable complexity; they are very amenable to a formal mathematical analysis. When operated directly from the line voltages, they operate at a nearly constant speed (Utkin et al, 1999). However, with the help of power electronic converter it is possible to vary the speed of an induction motor. Induction motors are widely used in many residential, commercial, industrial and utility applications due to their manufacturing cost, wide speed range, high efficiency and robustness compared to other types of motors such as brushless DC motors (Farzan , 2004). These advantages have determined an important development of the electrical drives, with induction machine as the execution element, for all related aspects: starting, braking, speed reversal, speed change, etc. Rashidi (2012) stated that they require much more complex methods of control, more expensive and higher rated power converters than DC and permanent magnet machines. The conventional methods of speed control of an induction motor were either too extravagant or too inefficient thus limiting their application to only constant speed drives. Therefore it is of great significance importance to investigate the dynamic control methods of this kind of drives system.

Negm (2000) discloses the advances in microprocessor and power electronics which gives permission to implement modern techniques for induction machines such as field oriented control also known as vector control. This provides higher efficiency; lower operating costs and reduces the cost of drive components. In sensorless field oriented control, the speed and/or position are not directly measurable; their values are estimated using other parameters such as phase voltages and current, that are directly measured. Sensorless drives are becoming more and more important as they can eliminate speed sensors maintaining accurate response. Monitoring only the stator current and voltages, it is possible to estimate the necessary control variables (Novotny and Lipo, 1996). In a hostile environment, speed sensors are difficult to be mounted. However, Toliyat et al, (2003), due to the high order and nonlinearity of the dynamics of an induction motor, estimation of the angle speed and rotor position without the measurement of mechanical variables becomes a challenging problem. The advantages of position and speed sensorless induction motor drives are to reduced hardware complexity and lower cost, reduce size of drive machine, eliminate of sensor cable, better noise immunity, increasing reliability and less maintenance requirements.

Various position and speed control algorithms for induction motor drives have been devised in the literature. In the last decade, many researches have been carried on the design of sensorless control schemes of the Induction Motor. Benchaib et al (1999) presented a sliding mode controller with rotor flux estimation for induction motor drives. Rotor flux was also estimated using a sliding mode observer. Most methods are basically based on the Model Reference Adaptive System schemes (MRAS) (Cirrincione and Pucci, 2005). Bilal et al, (2004) used a reactive-power-based-reference model derived in both motoring and generation modes but one of the disadvantages of this algorithm is its sensitivity to detuning in the stator and rotor inductances. The basic MRAS algorithm is very simple but its greatest drawback is the sensitivity to uncertainties in the motor parameters. Ouhrouche, (2002) proposed another method based on the Extended Kalman Filter (EKF) algorithm. The EKF is a stochastic state observer where nonlinear equations are linearized in every sampling period. An interesting feature of the EKF is its ability to estimate simultaneously the states and the parameters of a dynamic process. This is generally useful for both the control and the diagnosis of the process. Kyo and Frede, (2006) used the EKF algorithm to simultaneously estimate variables and parameters of the IM in healthy case and under different Induction Motor faults. An extended Kalman filter was also used by Kim et al (1994) for speed estimation of vector controlled induction motor drive. Unfortunately, Cheng and Hai, (2002) stated that this approach contains some inherent disadvantages such as its heavy computational requirements and difficult design and tuning procedure. Luenberger Observer for state estimation of Induction motor was used in. The Extended Luenberger Observer (ELO) is a deterministic observer which also linearizes the equations in every sampling period. There is other type of methods for state estimation that is based on the intelligent techniques is used in the recent years by many authors (Sbita and Ben, 2007).

2. FIELD ORIENTED CONTROL

The vector control allows not only control of the voltage amplitude and frequency, like in the scalar control methods, but also the instantaneous position of the voltage, current and flux vectors. This improves significantly the dynamic behavior of the induction motor. However, induction motor has a nonlinear behavior and there exist a coupling in the motor, between flux and the produced electromagnetic torque. Therefore, several methods have been proposed for decoupling torque and flux. These algorithms are based on different ideas and analysis the first vector control method of induction motor was *Field Oriented Control* (FOC) presented by F. Blaschke, (1972) and Lipo et al, (1985) in early of 70s. There are two types of Field Oriented Control: direct field oriented control and indirect field oriented control. Usually, Indirect FOC is preferred to Direct FOC because the natural robustness of an induction motor drive is reduced by flux sensors used in Direct FOC. In the vector control scheme, a complex current is synthesized from two quadrature components, one of which is responsible for the flux level in the motor, and another which controls the torque production in the motor. FOC control will allow us to decouple the torque and the magnetizing flux components of stator current. With decoupled control of the magnetization, the torque producing component of the stator flux can now be thought of as independent torque control. The control problem is reformulated to resemble the control of a DC motor.

The vector control algorithm is based on two fundamental ideas. The first is the flux and torque producing currents. An induction motor can be modeled most simply (and controlled most simply) using two quadrature currents rather than the familiar three phase currents actually applied to the motor. These two currents called direct (I_d) and quadrature (I_q) are responsible for producing flux and torque respectively in the motor. The second fundamental idea is the reference frames. To decouple the torque and flux producing component, it is necessary to engage several mathematical transforms. The idea of a reference frame is to transform a quantity that is sinusoidal in one reference frame, to a constant value in a reference frame, which is rotating at the same frequency. This control is based on projections which transform a three phase time and speed dependent system into a two co-ordinate (d and q co-ordinates) time invariant system (Prasad et al, 2012). These projections lead to a structure similar to that of a DC machine control. Field orientated controlled machines need two constants as input references: the torque component (aligned with the q co-ordinate) and the flux component (aligned with d co-ordinate). As Field Orientated Control is simply based on projections the control structure handles instantaneous electrical quantities. This makes the control accurate in every working operation (steady state and transient) and independent of the limited bandwidth mathematical model. Figure 2 illustrate a Sensorless Vector Control of Induction Motor Drive.

2.1 Reference Frame Transformation

A change of variables is often used to reduce the complexity of these differential equations. Using these transformations, many properties of electrical machines can be studied without complexities in the voltage equations. It is used to reduce the complexities of time varying variables. Clarke, (1943) proposed a transformation that uses three-phase currents i_a, i_b and i_c to calculate currents in the two-phase orthogonal stator axis: i_α and i_β. Figure 2 illustrates the coordinate frames and voltage and current vectors of induction motor, with a, b and c being the phase axes, $\alpha\beta$ being a fixed Cartesian coordinate frame align with phase a, and d and q being a rotating Cartesian coordinate frame aligned with rotor flux.

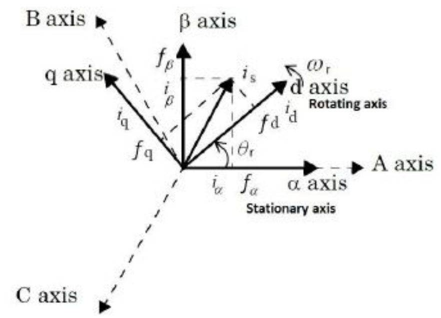

Figure 1: Stator Current in the d,q Rotating Reference Frame and its Relationship with the a, b and c Stationary Reference Frame.

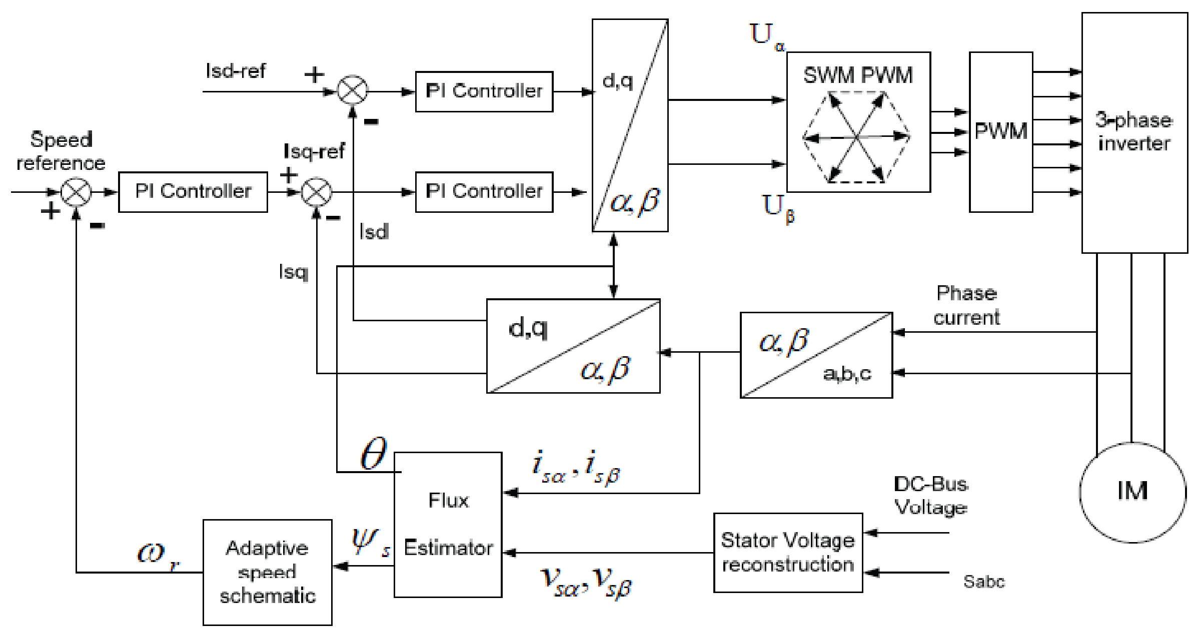

Figure 2: Sensorless Vector Control of Induction Motor Drive.

The Clarke Transformation basically have two fixed reference frame components "$\alpha\beta$" as output and three, time varying, components "*abc*" as input. The resulting Clarke transformation is given by;

$$[F_{\alpha\beta 0}] = T_{\alpha\beta 0}\,[F_{abc}] \tag{1}$$

Where F represent either voltage vector v, current vector i, flux linkage ψ vector.

$$T_{abc\rightarrow\alpha\beta} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{2}$$

$$i_\alpha = \frac{2}{3}\, i_a - \frac{1}{3}\,(i_b + i_c) \tag{3}$$

$$i_\beta = \frac{\sqrt{3}}{2}\,(i_b - i_c) \tag{4}$$

Park's transformation essentially eliminates the time-varying inductances of a symmetrical induction machines by transforming the stator variables to a reference frame fixed in the rotor. These two currents in the fixed coordinate stator phase i_α and i_β are transformed to the i_{sd} and i_{sq} currents components in the d,q frame with the Park transform

The resulting Park Transformation is given by; (Park, R.H. 1929).

$$T_{\alpha\beta\rightarrow dq} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (5)$$

$$i_d = i_\alpha \cos\theta + i_\beta \sin\theta \quad (6)$$

$$i_q = -i_\alpha \sin\theta + i_\beta \cos\theta \quad (7)$$

θ is the rotor angle. A reverse vector rotation can be accomplished simply by changing the sign on the sin (θ) input value. The vector rotation is illustrated by Figure 1.

Inverse transformation is given by;

$$[F_{abc}] = T_{\alpha\beta 0}^{-1} [F_{\alpha\beta 0}] \quad (8)$$

3. SPEED ESTIMATION TECHNIQUES OF INDUCTION MOTOR DRIVES

These include different methods used in speed and position estimation of Induction Motor drives. The three most widely used techniques are classified as; Frequency signal Injection based method; Rotor Slot Harmonics methods and Fundamental Machine Model-based method as shown in Figure 3 (Mousavi et al, 2014). Fundamental Machine Model-based methods have the advantage of simplicity in design and good performance at high speeds; however they have the drawback of exhibiting lower accuracy at low speeds due to parameter variations.

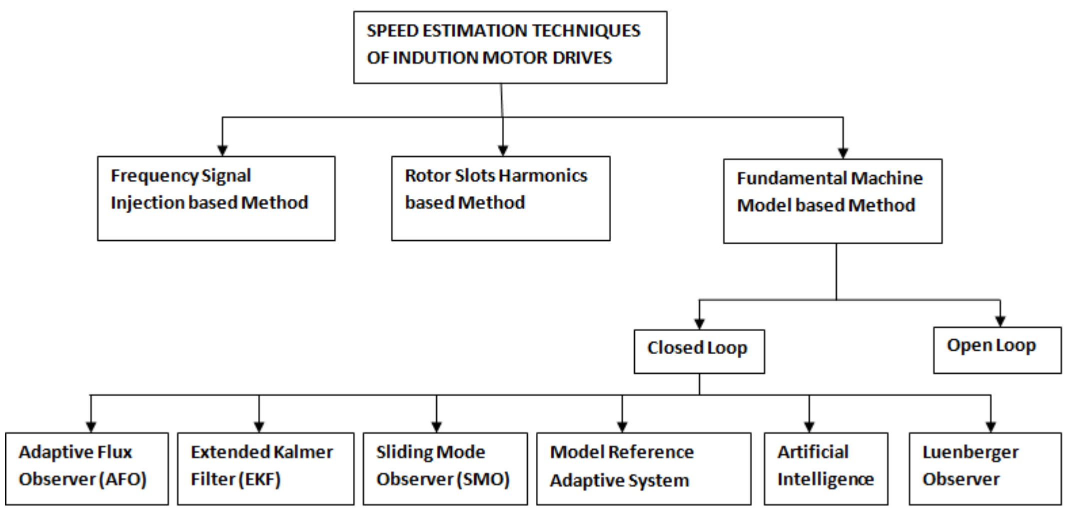

Figure 3: Speed Estimation Techniques of Induction Motor Drives

3.1 Frequency Signal Injection based Method

Speed estimation in this method is based on signal injection. If a frequency signal is injected into the rotor winding, the corresponding signal obtained from the stator winding will contain the rotor-position information. In other words, the phase difference between the stator and rotor voltages in an Induction Motor is a function of the rotor position. If the injected voltage rotates synchronously with the rotor, no rotor current will be induced. Identifying the extra rotor current, and controlling its amplitude to zero by adjusting the frequency of the voltage signal is the basis of speed estimation in this method.

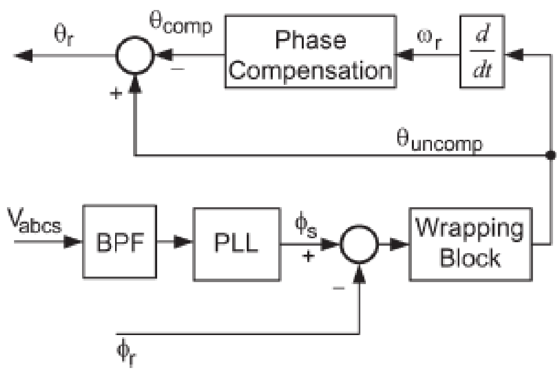

Figure 4: Block Diagram of Frequency Signal Injection Algorithm

The rotor angular information is obtained by implementing the simple algorithm shown in Figure 4. The measured stator voltage is filtered by a band pass filter (BPF) centered at the frequency injected in the rotor, i.e., ω_f. The angular position of the space vector of the filtered stator voltage, *φs*, is obtained due to the use of a phase-locked loop (PLL). This step by step process is shown in the flow chart in Figure 5. No machine parameters are needed in order to implement the algorithm.

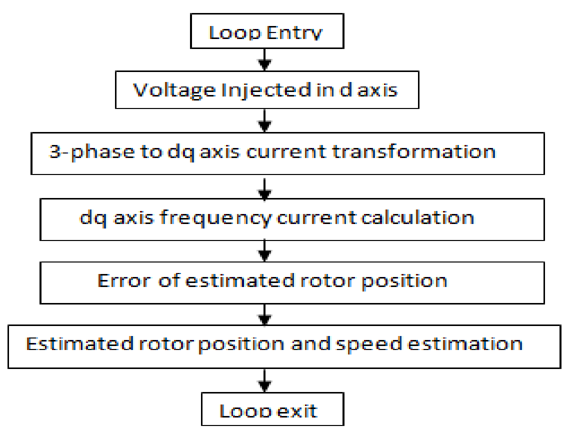

Figure 5: Flow chart of Frequency Signal Injection Algorithm

A pulse-width modulation (PWM) converter is utilized to generate the frequency signal injected on the rotor; the frequency of the injected signal has to be at least an order of magnitude below the switching frequency. If this is not the case, the PWM converter will introduce unwanted harmonics. On the other hand, Longya et al (2012) admit that the high-frequency signal on the stator will have to be properly filtered from the line voltage. Therefore, it is recommended to place the frequency of the injected signal at a reasonable spectral distance from the grid frequency.

Joachim Holtz, (2002) however came a conclusion that a common drawback of signal-injection methods is that their dynamic response is usually only moderate.

3.2 Rotor Slot Harmonics

The method of speed estimation is based on detecting space harmonics induced by rotor slots (Joachim Holtz, 2002). The rotor slot harmonics can be detected by using two different techniques; Utilizing stator voltages and utilizing stator currents.

Zwicky et al, (1987) and Asher et al, (1992) used the technique of utilizing stator voltage to estimate the rotor speed, the space harmonics of the air-gap flux-linkage in a symmetrical three-phase induction motor are generated because of the non-sinusoidal distribution of the stator windings and the variation of the reluctance due to stator and rotor slots, which are called m.m.f. space harmonics, stator slot harmonics, and rotor slot harmonics, respectively. The rotor slot harmonics can be utilized to determine the rotor speed of induction machines. When the air-gap m.m.f contains slot harmonics, slot-harmonic voltages are induced in the primary windings when the rotor rotates. The magnitude and the frequency of the slot-harmonic voltages depend on the rotor speed, so they can be utilized to estimate the slip frequency and rotor speed. Generally we only use the frequency of the slot-harmonic voltages since the magnitude depends not only on the rotor speed, but also on the magnitude of the flux-linkage level and the loading conditions.

If V_{sA}, V_{sB} and V_{sC} are the stator induction machine voltages, then $V_{SO} = V_{SA} + V_{SB} + V_{SC}$ will contain rotor slot harmonics voltage V_{Sh}. Due to the main flux saturation, it will also contain a third harmonic component V_{S3}. If an inverter supplies power to the induction machines, extra time harmonic voltage V_{ShK} will be present as well. In general;

$$V_{SO} = V_{Sh} + V_{S3} + \sum V_{Shk} \tag{9}$$

The frequency is the dominant component (fundamental slot harmonic frequency) of the slot harmonic voltage is given by (Peter Vas, 1993).

$$\begin{aligned} F_{sh} &= N_r F_r \pm F_1 \\ &= 3NF_1 - N_r F_{S1}, \text{ where } N_r = 3N \pm 1 \\ &= \left[\frac{Zr\,(1-s)}{P} \pm 1\right] F_1 \end{aligned} \tag{10}$$

Where:

F_{sh} is the fundamental slot-harmonic frequency; F_r is the rotor rotational frequency; F_{sl} is the slip frequency; s is the slip; F_1 is the stator electrical frequency; N_r is the number of rotor slots per pole-pair; Z_r is the number of rotor slots and P is the number of pole-pairs. From equation (10) the rotor speed (w_r) can be obtained by;

$$w_r = 2\pi \frac{Fsh \pm F1}{NrP} \tag{11}$$

In a speed-sensorless high-dynamic performance drive, utilizing the stator currents technique is preferred since the monitoring of the stator currents is always required, but the voltage monitoring can be avoided. The basic steps to estimate rotor speed using stator currents are almost the same with those using stator voltages. A Fast Fourier Transform (FFT) is used to detect the slot-harmonic frequency f_{sh}, and f_1 can be obtained from the angle of the rotor flux linkage vector. So from equation (11), the rotor speed can be estimated Peter Vas, (1998).

The major drawback of the rotor slot harmonics is that the approach needs high precision measurements which increase the hardware/software complexity. Because at low speeds the magnitude of the slot-harmonic voltage decreases, special considerations are required in the low speed range. Estimate the rotor speed by monitoring the stator voltages is not as preferred as by monitoring the stator currents, since it's always necessary to monitor the stator currents in a high-performance induction machine control system and, if we can estimate the rotor speed only from the stator currents, we can reduce the number of sensors required. Also, they suffer from large computation time, complexity and limited bandwidth control.

3.3 Fundamental Machine Model Based Method

A great deal of research interest is given to the third category of speed estimation, which is based on machine model because of its simplicity. In this category, the motor terminal variables and its parameters are used in some way to estimate its operating speed. This category can be classified according to the algorithm used for speed estimation either as an open loop or closed loop estimator.

In the open loop estimator, the rotor speed and slip frequency estimators are obtained by considering the voltage equations of the induction machine (Peter Vas, 1998). No feedback is used to check the correctness of the estimation. Open-loop speed estimators are simple and easy to implement. They are based on the fundamental induction machine model.

Closed-loop estimators unlike the open loop estimator contain a correction form involving an estimation error to adjust the response of the estimator. These closed-loop estimators are referred to as observers. Compared to open-loop estimators, observers are more robust against parameter mismatch and also signal noise. Some of the machine model based methods of speed estimation are adaptive flux observer, sliding mode observer, extended kalmer filter, model reference adaptive system, artificial intelligence, luenberger observer

i. ***Adaptive Flux Observer***

Adaptive flux observers (AFO) are also used for speed estimation of induction motor drives. The observer is basically structured composing of three main parts: an induction-motor model, observer's feedback gains, and a rotor speed adaptation mechanism as shown in Figure 6. The speed estimation characteristics is achieved by carefully selecting the observer's feedback gains and PI gains adaptation mechanism (Surapong et al, 2006).

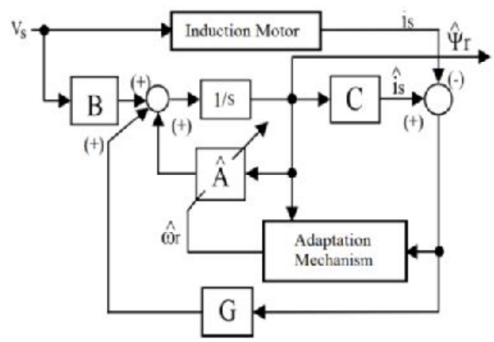

Figure 6: Block diagram of adaptive flux observer

The Induction Motor model in terms of state variables in stationary reference frame is given by the following equation:

$$\frac{d}{dt}\begin{bmatrix} i_s \\ \psi_r \end{bmatrix} = \begin{bmatrix} \frac{-Rs}{Ls} & 0 \\ 0 & \frac{-Rs}{Ls} \end{bmatrix}\begin{bmatrix} i_{\alpha s} \\ i_{\beta s} \end{bmatrix} + \begin{bmatrix} \frac{1}{Ls} & 0 \\ 0 & \frac{1}{Ls} \end{bmatrix}\left(\begin{bmatrix} V_{\alpha s} \\ V_{\beta s} \end{bmatrix} - \begin{bmatrix} e_{\alpha s} \\ e_{\beta s} \end{bmatrix}\right) \quad (12)$$

$$\frac{d}{dt}\begin{bmatrix} i_s \\ \psi_r \end{bmatrix} = Ax + BV_s \quad (13)$$

$$i_s = Cx$$

Where A is the motor parameters matrix, B is the inputmatrix; C is the output matrix, $[i_s \ \psi_s]^T$ is the state variables vector, and v_s(stator voltage) is the command and $i_s = [i_{ds} \ i_{qs}]^T$ is the stator current.

The state vectors can be estimated by the following equations

$$\frac{d}{dt}\tilde{i} = A\tilde{i} + Bu + G(\tilde{i} - i) \quad (14)$$

$$i = C\tilde{i}$$

Where G is the observer feedback gain. The goal of the observer feedback gain is to drive the speed estimation error to zero. It is achieved by properly selecting the observer gain G and PI gains. The feedback gain G is chosen to ensure global stability, and robust dynamic performance of the closed loop observer. Pole placement approach is adopted in designing the observer gain G and the PI gains. The observer poles should be proportional to the motor poles in order to get stability at all speeds. The accuracy of this method is affected by parameter variations, especially at low speeds, because the observer gain G depends on induction motor parameters (Zhang et al, 2010).

The adaptation mechanism is based on Lyponov theory and the rotor speed is estimated as follows;

$$\omega_r = \left(K_p + \frac{K_I}{s}\right)\left[\left(\tilde{i}_{sd} - i_{sd}\right)\psi_{rq} - \left(\tilde{i}_{sq} - i_{sq}\right)\psi_{rd}\right] \quad (15)$$

Where $\left(\tilde{i}_{sd} - i_{sd}\right)$is the direct axis stator current error calculated as the difference between the measured and the estimated currents, and $\left(\tilde{i}_{sq} - i_{sq}\right)$ is the stator current error in the quadrature axis.

The major drawback of AFO as stated by Hinkkanen, (2004) is it needs estimation of the machine parameters, especially at very low frequencies because the back emf is very low and the voltage drop on the stator resistance has a major effect. Another problem is that the machine model-based methods of sensorless drives are incapable of operating stably during a long time under rated load at zero stator frequency. This instability is maximized at regenerative mode of operation in the very low speed region.

ii. Sliding mode observer

Sliding mode observers (SMO) are widely used for speed estimation of induction motor drives. The sliding mode observer is designed to estimate the rotor angular position and speed of induction motor. The sliding mode observer for estimating rotor position angle is based on a stator current estimator using discontinuous control. Due to the fact that only stator currents are directly measurable in Induction motor drive, the sliding mode manifold or surface s (x) = 0 as shown in Figure 7 is selected on the real stator current trajectory. In this way, when the estimated currents, i.e., state, reach the manifold and then the sliding mode happens and has been enforced, the current estimation error becomes zero and the estimated currents track the real ones regardless of certain disturbances and uncertainties of the drive system (Utkin et al, 1999) .

Figure 7: Sliding Mode in Non-Linear System

The sliding mode dynamics depend on the switching surface equation and not on the control. Hence the design procedure can be decoupled into two stages: first, select equation of sliding mode, to design the dynamics of the motion in accordance with performance criterion; secondly, find the discontinuous control such that the state would reach the manifold *s* (*x*) = 0 and sliding mode exists in this manifold.

The induction motor can be represented by its dynamic model expressed in the stationary reference frame in terms of the stator current and rotor flux by the following state equations;

$$\frac{d}{dt}\tilde{i}_s = A\tilde{i}_s + Bu + k\ \mathrm{sgn}\ (\tilde{i}_s - i_s) \qquad (16)$$

Where $A = \begin{bmatrix} -\frac{Rs}{L} & 0 \\ 0 & -\frac{Rs}{L} \end{bmatrix}$ $\quad B = \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & \frac{1}{L} \end{bmatrix}$

$\tilde{i}_s = \tilde{i}_{\alpha\beta s} = [\ \tilde{i}_{\alpha s}\ \tilde{i}_{\beta s}]^T$ Estimated αβ currents vectors

R_s and L are the stator winding resistance and armature inductance respectively; and

$$K_1 = k\ [I, -I]^T = kI \qquad (17)$$

Where $K_1$is the gain matrix and k is the switching gain. The equation of rotor speed estimation can be written in the following form based on Lyapunov theory:

$$\tilde{\omega}_r = -\ k\int [\mathrm{sgn}(\tilde{i}_{\alpha s} - i_{\alpha s})\psi_{r\beta} - \mathrm{sgn}(\tilde{i}_{\beta s} - i_{\beta s})\psi_{\alpha r}]\ dt \qquad (18)$$

The complete block diagram of the sliding mode observer based rotor position estimator is shown in Figure 8.

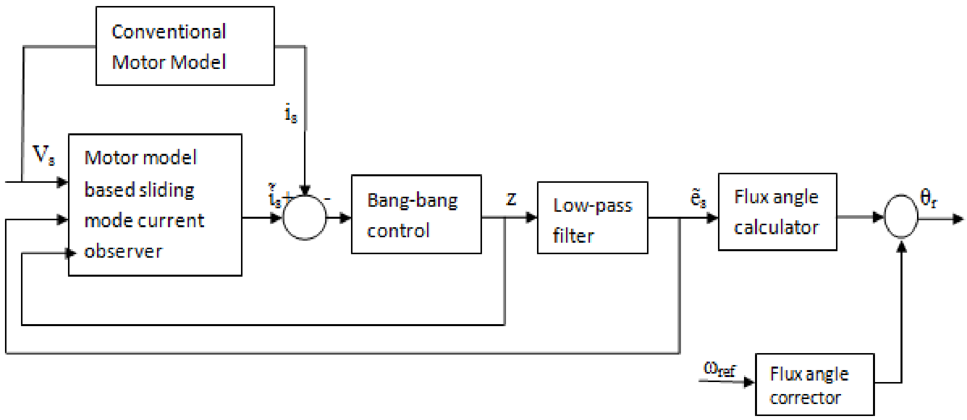

Figure 8: Block Diagram of the Sliding Mode Observer Based Rotor Flux Position Estimator

The main advantages of SMO are its fast dynamic response, robustness, and simplicity in design and implementation. However, the major drawback of the SMO is the effect of chattering whichappears as an undesired oscillation on the system trajectory with finite frequency and amplitude, and leadsto low control accuracy, high wear of moving mechanical parts, high heat loss in power circuits, and control loop instability (Utkin et al, 1999)(Rao, 2009). For chattering reduction, several suppression methods have been analyzed recently, including the use of saturation, or use of a sigmoid function instead of a sign function for chattering reduction or elimination.

iii. ***Extended Kalmer Filter***

The extended Kalman Filter is a recursive stochastic state estimator. The Kalman filter is a special kind of observer that provides optimal filtering of the noises in measurement and inside the system if the covariances of these noises are known. The extended Kalman filter (EKF) is based on the nonlinear extended induction motor model that includes the rotor speed as a state variable (Shi et al, 2002).The Kalman filter is based on the minimization of the estimation error and it is suitable for obtaining model parameters and eliminating measurement noises.

The Kalman filter KF is a special kind of observer, which provides optimal filtering of noises in measurement and inside the system if the covariance matrices of these noises are known. The process and the measurement noises are both assumed to be Gaussian with a zero mean. The general model of the controlled system in discrete form can be written as by Pavel et al, (2013):

$$x(t + T) = Ax(t) + Bu(t) + w(t) \quad (19)$$

Measurement model provides prediction of measurement

$$y(t) = Cx(t) + v(t) \quad (20)$$

Where T is the sampling period, A = state matrix, B = matrix of inputs, C = matrix of outputs. Matrix C defines the measurement relations to the state variable x. The system noise w has a covariance matrix Q and the measurement noise v has a covariance matrix R, which characterize the uncertainties in the states and correlations within it. The state covariance matrix P is obtained in prediction part of the algorithm. After fulfillment actual measurement, it is then corrected. The elements of their covariance matrices (Q and R) serve as design parameters for the convergence of the algorithm.

The Kalman filter algorithm and its extensions are robust and efficient observers for linear and nonlinear system respectively. The advantage of this Filter is its recursive structure, in which the coefficients in each step are adjusted on the basis of available information to provide the best estimate of a future state, it also has a good dynamic behavior, disturbance resistance, and it can work even under standstill conditions (Anwin and Jayanand , 2014). One of the drawbacks of using extended Kalman filter for speed estimation of vector controlled induction motor drive Smidl, and Peroutka, (2012), is having a heavy computational requirements, difficulty in design and tuning procedure, The major drawback of the speed estimation using the EKF is the condition that the load dynamics is to be known which is not usually possible.

iv. ***Model Reference Adaptive Systems (MRAS)***

Model Reference Adaptive Systems (MRAS) are used to estimate quantities using a reference model and an adaptive model. However, rotor flux MRAS, first introduced by Schauder, (1992) is the most popular MRAS strategy and significant attempts have been made to improve its performance. The MRAS speed estimation structure consists basically of a reference model, adjustable model and an adaptive mechanism. The general idea behind MRAS is to create a closed loop controller with parameters that can be updated to change the response of the system. The difference between the outputs of the two models drives an adaptive mechanism that provides the quantity that is to be estimated, having the advantage of high speed of adaptation. The reference model, which is independent of the rotor speed, calculates the state variable, $x_\alpha x_\beta$ from the terminal voltage and current. The adjustable model, which is dependent on the rotor speed, estimates the state variable, $\hat{x}_\alpha \hat{x}_\beta$. The error ε between calculated and estimated state variables is then used to drive an adaptation mechanism which generates the estimated speed, ω for the adjustable model as shown in the block diagram of Figure 9.Theerror is fed into an adaptation mechanism, which is designed to ensure the stability of the MRAS. Thus, the update of the control parameters must be performed based on this error. This strategy allows the parameters to converge to ideal values (Agrebi et al, 2010).

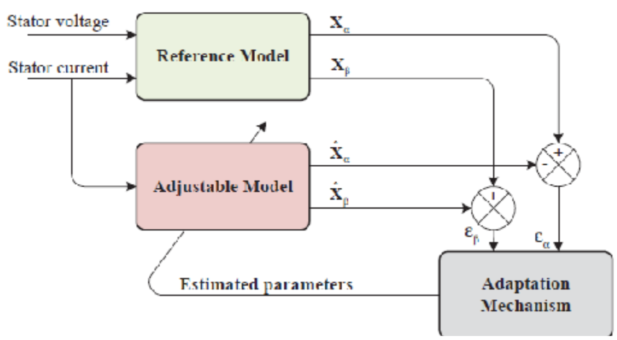

Figure 9: Rotor speed estimation structure using MRAS

The rotor flux equations obtained from the reference model is given by;

$$\frac{d}{dt}\varphi_{dr} = \frac{L_v}{L_m}[V_{ds} - (R_s + \sigma S L_s)i_{ds}] \quad (21)$$

$$\frac{d}{dt}\varphi_{qr} = \frac{L_v}{L_m}[V_{qs} - (R_s + \sigma S L_s)i_{qs}] \quad (22)$$

Where $\sigma = 1 - \frac{L_m^2}{L_r L_s}$, $L_{1s} = L_s - L_m$ and $L_{1r} = L_r - L_m$

φ is the flux

Similarly the rotor flux equation obtained from the adaptive model is given by;

$$\frac{d}{dt}\varphi_{dr} = \frac{L_m}{T_r} i_{ds} - \omega_r \varphi_{qr} - \frac{1}{T_r}\varphi_{dr} \quad (23)$$

$$\frac{d}{dt}\varphi_{qr} = \frac{L_m}{T_r} i_{ds} - \omega_r \varphi_{dr} - \frac{1}{T_r}\varphi_{qr} \quad (24)$$

Where $T_r = \frac{L_r}{R_r}$

The voltage model's stator-side equations (21) and (22) which are defined as a reference model. The model receives the machine stator voltage and current signals and calculates the rotor flux vector signals. The current model flux equations (23) and (24) are defined as an adaptive model. Mugdha et al, 2015) proposed an adaptation algorithm with P-I control can be used to tune the speed value until the two flux values match. The estimated speed is derived as follows:

$\omega_r = \varsigma\,(k_p+\frac{k_i}{s})$ (25)

Where, $\varsigma = A\text{-}B = \varphi^s_{dr}\varphi^s_{qr} - \varphi^s_{qr}\varphi^s_{dr}$ (26)

In steady state, $\varsigma = 0$ balancing the flux.

The three most commonly used speed estimation using MRAS are the rotor flux-based MRAS, back emf-based MRAS, and stator current-based MRAS.In MRAS methods using the rotor flux and back EMF, the relationship between the model error and the speed estimation error is unclear; therefore, the MRAS controller gain has a nonlinear characteristic. As a result, these methods are difficult to estimate speed in a low speed region and at zero-speed owing to the increment of this nonlinear characteristic (Marwali and Keyhani, 1997). Whereas in stator current based MRAS, the stator current error is represented as a function of the first degree for the error value in the speed estimation. Therefore, this method can produce fast speed estimation and is robust to variations in the parameter error. In addition, Chul, (2004) offers a considerable improvement in the performance of a sensorless vector controller at a low speed.

Among various types of adaptive system configuration, MRAS is important since it leads to relatively easy-to-implement systems with high speed of adaptation for a wide range of applications. A successful MRAS design can yield the desired values with less computational error (especially the rotor flux based MRAS) than an open loop calculation and often simpler to implement. Youseff et al, (2018), the basic MRAS algorithm is very simple, robustness and fast convergence with small computational time. Peng and Fukao, (1994) stated that its greatest drawback is the sensitivity to uncertainties in the motor parameters, pure integration problems, difficulties of designing the adaptation mechanism block which may limit the performance at low and zero speed region of operation (Peter Vas, 1998)(Peng and Fukao, 1994).

v. Luenberger Observer

The basic Luenberger observer (LO) is applicable to a linear, time-invariant deterministic system, while the extended Luenberger observer (ELO) is applicable to a non-linear time-varying deterministic system. When an error compensator is added to the equations of the induction machine in the stationary reference frame, a full-order adaptive state observer can be constructed. The rotor speed is considered as a state variable. The dynamic equations of a basic Luenberger observer can be given by Peter Vas, 1998, and Ambrosii et al, 2000. Note that the symbol ~ indicates that a variable is estimated;

$$\frac{d}{dt}\tilde{x} = \tilde{A}\tilde{x} + BU + G(i_s - \tilde{i}_s) \tag{27}$$

$$\tilde{i} = C\tilde{x}$$

Where $\tilde{x} = \begin{bmatrix} \tilde{i}_s \\ \lambda_r \end{bmatrix}$ (28)

$$\tilde{i}_s = [\tilde{i}_{sd}, \tilde{i}_{sq}]^T \tag{29}$$

$$\hat{\lambda}_{rq} = [\hat{\lambda}_{rd}\,, \hat{\lambda}_{rq}] \tag{30}$$

$$U = [U_{sd}, U_{sq}] \tag{31}$$

$$\hat{\omega}_{re} = K_p(\hat{\lambda}_{rq}e_{sd} - \hat{\lambda}_{rd}e_{sq}) + K_i \int (\hat{\lambda}_{rq}e_{sd} - \hat{\lambda}_{rd}e_{sq})\, dt \tag{32}$$

$$e = (i_s - \tilde{i}_s) \tag{33}$$

Where $\hat{A} = \begin{bmatrix} -\left[\frac{1}{T'_s} + (1-\sigma)T'_r\right] I_2 & \left[\frac{L_m}{L'_s L_r}\right]\left[\frac{I_2}{T_r} - \omega_{re}(t)J\right] \\ \frac{L_m I_2}{T_r} & -\frac{I_2}{T_r} + \omega_{re}(t)J \end{bmatrix}$ (34)

$$B = \begin{bmatrix} \frac{I_2}{L'_s U'_{sd}} \\ 0_2 \end{bmatrix}, \quad C = [I_2, 0_2], \quad I_2 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad 0_2 = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}, \quad J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}, \ \sigma = 1 - \frac{L_S^2}{(L_S L_r)}$$

G is the observer gain matrix, which is selected so that the system will be stable, $\frac{d}{dt}\tilde{x}$is the observer state vector, K_p and K_i are the proportional and integral gain constants respectively. The block diagram is shown in Figure 10.

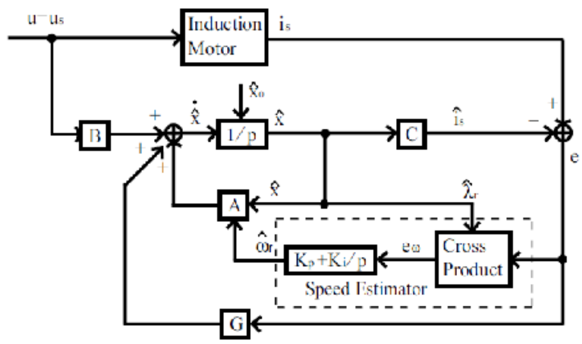

Figure 10: Structure of Luenberger Observer

For an Extended Luenberger Observer, the dynamic state equations are given by Song et al, (2000);

$$\frac{d}{dt}x = f\,[x(t)] + BU(t) \tag{35}$$

$$y(t) = Cx(t)$$

$$\frac{d}{dt}\tilde{x} = A[\tilde{x}(t\text{-}\tau)] + BU(t) \ + G[\tilde{x}(t\text{-}\tau)][y(t) - C\tilde{x}(t\text{-}\tau) + g[\tilde{x}(t\text{-}\tau) \tag{36}$$

Where $A = \frac{df}{dx}$is the system Jacobian matrix. τ is the step length or the sampling time. G is the gain matrix to make the system stable. G is not constant; it depends on the past estimates of the system state vector.

$$g(x) = f(x) - A(x) \tag{18}$$

By adjusting the gain matrix, the performances of the extended Luenberger observer(such as speed of response, speed of convergence, robustness against parameter drift, and so on.) can be altered. It's applicable to most of the industrial systems to produce unbiased estimates.

vi. ***Artificial Intelligence (AI)***

Different from mathematical-model-based analysis techniques, artificial-intelligence based techniques, such as artificial neural networks (ANN), fuzzy-logic systems, fuzzy neural networks, etc., do not require a precise analytical expression of the machine and drive system. Artificial Neural Networks (ANN) represents a tool for solving of real problems, where conventional analytical methods do not suffice or where further simplification of the problem is not allowed. In systems that are conditioned with additional criteria of security and reliability of operation, they are used as an additional source of information for making final decisions. An ANN is composed of a large number of neurons that are mutually connected and process data in parallel, according to dynamic condition of the neural network and according to its inputs. Since ANNs are, through the process of learning, able to adapt to input information and predefined requirements, they are classified among adaptive systems. Two additional characteristics of ANNs, namely associability and simplification, are connected with learning, too (Morteza and Farzan, 2005). Moreover, they have the advantages of fast parallel computation, immunity from input harmonic ripple, and fault tolerance characteristics (Peter Vas, 1998). Neural network estimator or directly generate a rotor speed estimate as its output. Artificial-intelligence-based speed estimation techniques can obtain a speed estimation that is not based on the mathematical model of the controlled system. It is shown that this algorithm can work in a wide speed range and has good dynamic performance and stability Yoo et al, (2001). It is believed that this type of approach will find increasing application in the future. But it needs to be trained or has the knowledgebase to understand the model of a plant or a process. The training algorithm decides the learning speed, the stability and the dynamic performance of the system. This method is also computationally intensive and relatively complicated.

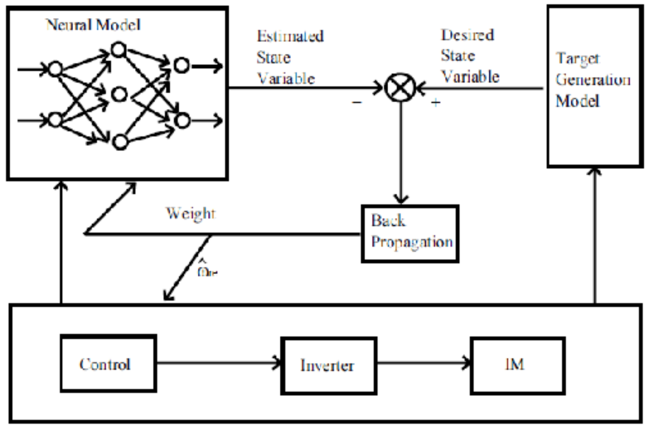

Figure 11: Speed estimation method with artificial neural network (ANN)

4. DISCUSSION

Table 1 shows the comparison between the different speed estimation methods stating the pros and cons of each rotor position and speed estimation methods of induction machine.

TABLE I: SUMMARY AND GENERAZATION OF PROS AND CONS OF EACH ROTOR POSITION AND SPEED ESTIMATION TECHNIQUES

Techniques	Authors	Pros	Cons
Frequency Signal Injection	Joachim Holtz, (2006), Longya Xu et al (2012)	-No machine parameters are needed in order to implement the algorithm	-Their dynamic response is usually only moderate
Rotor Slot Harmonics	Joachim Holtz, (200), Peter Vas, (1998)	-Using the stator currents, it can help to reduce the number of sensors required.	-The major drawback of the rotor slot harmonics is that the approach needs high precision measurements which increase the hardware/software complexity. -Also, they suffer from large computation time, -complexity and limited bandwidth control.

Adaptive Flux Observer	Surapong et al (2006), Harnefors and Hinkkanen, (2008), M. Hinkkanen, (2004)	-Good global stability. -robust dynamic performance.	-The major drawback of AFO is it needs estimation of the machine parameters, especially at very low frequencies -Another problem is that the machine model-based methods of sensorless drives are incapable of operating stably during a long time under rated load at zero stator frequency. This instability is maximized at regenerative mode of operation in the very low speed region.
Sliding Mode Observer	Rao, (2009), S. Alireza et al (2012)	- fast dynamic response -Robustness -Simplicity in design and implementation.	-Effect of chattering which leads to low control accuracy -High wear of moving mechanical parts, -High heat loss in power circuits - control loop instability
Extended Kalmer Filter (EKF)	Smidl, and Peroutka, (2012), Anwin and Jayanand (2014)	-It has a good recursive structure, -It also has a good dynamic behavior -disturbance resistance -and it can work even under standstill conditions	-It has a heavy computational requirements -difficulty in design and tuning procedure -the load dynamics needs to be known which is not usually possible.
Model Reference Adaptive System(MRAS)	Peter Vas, (1998), Youseff et al, (2018) Peng and Fukao, (1994)	-Very simple in design, -robustness -and fast convergence with small computational time.	-Sensitivity to uncertainties in the motor parameters, -pure integration problems, -difficulties of designing the adaptation mechanism block which may limit the performance at low and zero speed region of operation

Artificial Intelligence (AI)	Morteza and Farzan, (2005), J. Yoo et al, (2001)	-The algorithm can work in a wide speed range - has good dynamic performance and stability	-This method is also computationally intensive. -relatively complicated

5. CONCLUSION

A review of different methods for rotor position and speed sensorless control of induction motor drives and their corresponding merits and demerits has been presented. The methodology and design each scheme was discussed. There are three main classes of rotor position and speed estimator for the induction motor; Frequency signal Injection based method; Rotor Slot Harmonics methods and Fundamental Machine Model-based method. Robustness against parameter variations Steady state error, dynamic behavior, noise sensitivity, low speed operation, parameter sensitivity, complexity, and computation time are some of the important parameters to evaluate the effectiveness of the schemes. Frequency signal injection requires no machine parameters in order to implement the algorithm. But their greatest drawback is that their dynamic response is usually only moderate. The major drawback of rotor slot harmonics is that the approach needs high precision measurements which increase the hardware/software complexity, they also suffer from large computation time, complexity and limited bandwidth control. A great deal of research interest is given to the third category of speed estimation, which is based on machine model because of its simplicity. In this category, the motor terminal variables and its parameters are used in some way to estimate its operating speed. Among fundamental model based methods, SMO has the best behavior. MRAS has a very simple design, robustness and fast convergence with small computational time; however, their adaptation mechanism design is difficult. Adaptive flux observer has good behavior at high and medium speeds, robust dynamic performance; however, it has considerable inaccuracy at low speeds. In a noisy environment, EKF is the best choice since it performs as optimal filtering; however, it has a heavy computational requirements and difficulty in design and tuning procedure. Artificial Intelligence algorithm can work in a wide speed range, has good dynamic performance and stability; however, this method is also computationally intensive and relatively complicated. Finally, each rotor position and speed estimation method of sensorless induction motor application requires a specific design, which takes into consideration the required performance, hardware and the designer skills.

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