4.1 Introduction

It has been assumed so far in all the considerations of induction machine that a speed (or position) sensor is available and that it provides the required feedback signal for closed loop speed control (and the speed/position information for co-ordinate transformation, where required). Sensors mounted on the machine shaft are in general not desirable for a number of reasons. First of all, their cost is substantial. Secondly, their mounting requires a machine with two shaft ends available – one for the sensor, and the other one for the load coupling. Thirdly, electrical signals from the shaft sensor have to be taken to the controller and the sensor needs a power supply, and these require additional cabling. Finally, presence of a shaft sensor reduces mechanical robustness of the machine and decreases its reliability. It is for all these reasons that substantial efforts have been put in recent past into possibilities of eliminating the shaft mounted sensor. However, the information regarding actual speed and/or position of the rotor shaft remains to be necessary for closed loop speed (and/or) position control (and co-ordinate transformation, if applicable) even if the shaft sensor is not installed. Hence the speed (and/or position) has to be estimated somehow, from easily measurable electrical quantities (in general, stator voltages and currents). This Chapter discusses issues related to speed estimation and simplest speed estimation technique i.e. open-loop speed estimation technique. A drive in which the speed/position sensor is absent is usually called ‘sensorless’ drive, where ‘sensorless’ symbolizes absence of the shaft sensor. However, the sensors required for stator current measurement (and, in many cases, stator voltage measurement as well) remain to be present so that the term ‘sensorless’ is somewhat misleading. Sensorless vector control of an induction machine has attracted wide attention in recent years. Many attempts have been made in the past to extract the speed signal of the induction machine from measured stator currents and voltages. The first attempts have been restricted to techniques which are only valid in the steady-state and can only be used in low cost drive applications,
not requiring high dynamic performance. More sophisticated techniques are required for high performance applications in vector controlled drives. In a sensorless drive, speed information and control should be provided with an accuracy of 0.5% [Holtz 2006] or better, from zero to the highest speed, for all operating conditions and independent of saturation levels and parameter variations. In order to achieve good performance of sensorless vector control, different speed estimation schemes have been proposed, so that a variety of speed estimators exist nowadays. In general, all the existing speed estimation algorithms belong to one of the following three groups:

1. speed estimation from the stator current spectrum;
2. speed estimation based on the application of an induction machine model;
3. speed estimation by means of artificial intelligence techniques (artificial neural networks and fuzzy logic).

Estimation can also be defined as the determination of constants or variables for any system, according to a performance level and based in the measurements taken from the process. Speed sensorless estimation as its name implies, is the determination of speed signal from an induction motor drive system without using rotational sensors. It makes use the dynamic equations of the induction motor to estimate the rotor speed component for control purposes. Estimation is carried out using the terminal voltages and currents which are readily available using sensors. There are various rotor speed estimation schemes available in the market [Holtz 2006]. These schemes are based on different algorithms with the purpose to improve the performance of the speed estimation process. The schemes range from open loop basis to closed loop basis with its own advantages and disadvantages. To estimate the speed of the induction motor, type of scheme chosen is a factor to consider which at the end will determine the design complexity, feasibility and performance of the selected scheme. In this chapter, an overview of the speed sensorless estimation schemes available will be discussed. Majority of existing speed estimation schemes are based on the induction machine model.

In general, speed sensorless estimation can be divided into two common groups; estimation based on direct synthesis from induction motor dynamic equations and estimation based on rotor slot harmonics as illustrated in Figure 4.1.

4.2 Drawbacks and limitations

Before looking into individual approaches, the common problems of the speed and flux estimation are discussed briefly for general field-orientation and state estimation algorithms.
4.2.1 Parameter sensitivity

One of the important problems of the sensorless control algorithms for the sensorless induction motor drives is the insufficient information about the machine parameters which yield the estimation of some machine parameters along with the sensorless structure. Among these parameters, stator resistance, rotor resistance and rotor time-constant play very important role than the other parameters since these values are more sensitive to temperature changes.

The knowledge of the correct stator resistance $R_s$ is important to widen the operational region towards the lower speed range. Since at low speeds the induced voltage is low and stator resistance voltage drop becomes dominant, a mismatching stator resistance induces instability in the system. On the other hand, errors made in determining the actual value of the rotor resistance $R_r$ may cause both instability of the system and speed estimation error proportional to $R_r$. Also, correct $T_r$ value is vital decoupling factor in the sensorless control scheme.

4.2.2 Pure integration

The other important issue regarding many of the topologies is the integration process inherited from the induction motor dynamics where an integration process is needed to calculate the state variables of the system. However, it is difficult both to decide on the initial value, and prevent the drift of the output of a pure integrator. Usually, to overcome this problem a low-pass filter replaces the integrator.

4.2.3 Overlapping-loop problem

In a sensorless control system, the control loop and the speed estimation loop may overlap and these loops influence each other. As a result, outputs of both of these loops may not be designed independently and in some bad cases this dependency may influence the stability or performance of the overall system. The algorithms, where terminal quantities of the machine are used to estimate the fluxes and speed of the machine, are categorized in two basic groups. First one is *the open-loop observers* in a sense that the on-line model of the machine does not use the feedback correction. Second one is *the closed-loop observers* where the feedback correction is used along with the machine model itself to improve the estimation accuracy.
4.3 Sensorless speed estimation techniques

As being explained in previous section, the speed estimation schemes based on the direct synthesis of the induction motor equations can be broadly group into two groups. The first one is the open loop observer which does not have the feedback correction and the other one is the closed loop observer which make use of the feedback correction to improve the estimation accuracy. The open loop calculation method is simple to implement but prone to error because of high dependency on the machine parameters. The closed loop group observers for speed estimation are much more versatile in terms of performance such as the Luenberger observers, Kalman Filter observers, MRAS estimators and rotor slot harmonics estimator. Each of these speed estimation schemes differs from each other in terms of equations and structure used but they share the same objective to provide the speed information and to improve the performance of the induction motor drive system. Uniquely, the difference exhibits their advantages and disadvantages which will be explained in section 4.4 of this chapter. The different sensorless speed estimation schemes are explained as follows:
4.3.1 Rotor slot harmonics scheme

The space harmonics of the air-gap flux-linkage in a symmetrical three-phase and five-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 motors. The rotor slot harmonics can be detected by using two different techniques; utilizing either the stator voltages or the stator currents.

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.

In general, the stator voltage and frequency of dominant component (fundamental slot-harmonic frequency) of the slot harmonic voltages are given by the following equations.

\[ u_s = u_{sh} + u_{s3} + \sum_k u_{shk} \]  

(4.1)

Where \( u_s \) = resulting stator voltage

- \( u_{sh} \) = slot harmonic component voltage
- \( u_{s3} \) = third harmonic component of voltage
- \( u_{shk} \) = extra time harmonic voltages and k is time harmonic order

\[ f_{sh} = N_r f_r \pm f_1 \]

\[ = 3Nf_1 - N_r f_{sl} \]

\[ = \left[ \frac{Z_r (1-s)}{p} \right] f_1 \]  

(4.2)

where \( N_r = 3N \mp 1 \)

and \( f_{sh} \) = fundamental slot-harmonic frequency

- \( f_r \) = rotational frequency of the rotor
- \( f_1 \) = stator frequency
- \( f_{sl} \) = slip frequency
- \( N_r \) = no. of rotor slots per pole pairs
\[ Z_r = \text{no. of rotor slots} \]
\[ s = \text{slip} \]
\[ P = \text{no. of pole pairs} \]
\[ \omega_r = \text{angular rotor speed} \]

The rotor speed can be obtained by the following equation.

\[ \omega_r = 2\pi \frac{f_{sh} + f_1}{N_r P} \]  \hspace{1cm} (4.3)

### 4.3.2 Open-loop estimation scheme

Open-loop estimators, in general, use different forms of the induction motor differential equations. Current model based open-loop estimators use the measured stator currents and rotor speed. The speed dependency of the current model is very important since this means that although using the estimated flux eliminates the flux sensor, the position sensor is still required. On the other hand, voltage model based open loop estimators use the measured stator voltage and current as inputs. These types of estimators require a pure integration that is difficult to implement for low excitation frequencies due to the offset and initial condition problems. Cancellation method open loop estimators can be formed by using measured stator voltage, stator current and rotor velocity as inputs, and use the differentiation to cancel the effect of the integration. However, it suffers from two main drawbacks. One is the need for the derivation which makes the method more susceptible to noise than the other methods. The other drawback is the need for the rotor velocity similar to current model.

A full order open-loop observer, on the other hand, can be formed using only the measured stator voltage and rotor velocity as inputs where the stator current appears as an estimated quantity. Because of its dependency on the stator current estimation, the full order observer will not exhibit better performance than the current model. Furthermore, parameter sensitivity and observer gain are the problems to be tuned in a full order observer designs. These open loop estimator structures are all based on the induction motor model, and they do not employ any feedback. Therefore, they are quite sensitive to parameter variations, which yield the estimation of some machine parameters along with the sensorless structure.

Since \( x-y \) components are non flux/torque producing, they do not play any role and hence they are omitted from further consideration.

Simplifying and modifying the five-phase induction motor equations in section 3.4 describe a new set of equations representing the stator voltages and currents in terms of
differential equations represented in matrix form by the following equation.

\[
\begin{bmatrix}
\frac{dv_d}{dt} \\
\frac{dv_q}{dt} \\
\frac{dw}{dt}
\end{bmatrix} = \frac{L_r}{L_m} \begin{bmatrix}
v_d \\
v_q \\
\psi_d \\
\psi_q
\end{bmatrix} - \begin{bmatrix}
(R_s + \sigma L_s p) & 0 \\
0 & (R_s + \sigma L_s p)
\end{bmatrix} \begin{bmatrix}
i_d \\
i_q
\end{bmatrix}
\]

The rotor speed equation is given as follows:

\[
\dot{\omega}_r = \frac{1}{\psi_r^2} \left[ \psi_d \left( \frac{dv_d}{dt} \right) - \psi_q \left( \frac{dv_q}{dt} \right) - \frac{L_r}{T_r} \left( \psi_d i_q - \psi_q i_d \right) \right]
\]

where, \( \psi_r^2 = \psi_d^2 + \psi_q^2 \)

These equations will be used in the construction of an open loop estimator for simulation purpose. The open loop estimator block diagram is illustrated in Figure 4.2. As can be seen from figure, the open loop estimator imposes no feedback for rotor speed correction and hence it is easily liable to lower accuracy of speed estimation.

4.3.3 Observers

In section 4.3.2, an open loop speed estimator has been described. In open loop estimator, especially at low speeds, parameters variation has significant influence on the performance of the drive both at steady state and transient state. However, it is possible to improve the robustness against parameters mismatch and also signal noise by using closed loop observers. The most commonly used observers are Luenberger and Kalman filter types.
4.3.3.1 Luenberger observer

This scheme is based on the fact that one observer estimates the rotor flux and the speed is derived by the stator current error and the estimated rotor flux. In terms of classification, the scheme that adopts an observer could be also treated as MRAS, where the motor is considered as the reference model and the observer is considered as the adjustable model.

The induction motor model in terms of state variables in stationary reference frame is given as follows:

\[
\begin{align*}
\frac{d}{dt} \begin{bmatrix} i_s \\ \psi_r \end{bmatrix} &= \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} i_s \\ \psi_r \end{bmatrix} + \begin{bmatrix} B_1 \\ 0 \end{bmatrix} \psi_s = A \begin{bmatrix} i_s \\ \psi_r \end{bmatrix} + B \psi_s \\
\end{align*}
\]

\[
\begin{align*}
i_s &= \begin{bmatrix} C_1 \\ C_2 \end{bmatrix} \begin{bmatrix} i_s \\ \psi_r \end{bmatrix} \\
\end{align*}
\]

where \( A \) is the motor parameters matrix, \( B \) is the input matrix, \( C \) is the output matrix, \( \begin{bmatrix} i_s & \psi_r \end{bmatrix}^T \) is the state variables vector, and \( \psi_s \) (stator voltage) is the command. The stator current and the rotor flux are estimated by the full order Luenberger state Observer described by the following equation:

\[
\frac{d}{dt} \begin{bmatrix} \hat{i}_s \\ \hat{\psi}_r \end{bmatrix} = A \begin{bmatrix} \hat{i}_s \\ \hat{\psi}_r \end{bmatrix} + B \psi_s + G(\hat{i}_s - i_s)
\]

In equations (4.7) and (4.8) the different terms are explained as follows:

- \( A = \begin{bmatrix} -[1/T_r + (1-\sigma)/T_e] J \end{bmatrix} \)
- \( B = \begin{bmatrix} I_s/L_r, O_2 \end{bmatrix} \)
- \( C = \begin{bmatrix} I_s, O_2 \end{bmatrix} \)
- \( v = \psi_s = [v_{ds}, v_{qs}] \)
- \( \hat{x} = [\hat{i}_s, \hat{\psi}_r] \)
- \( i_s = [i_{ds}, i_{qs}] \), \( \hat{i}_s = [\hat{i}_{ds}, \hat{i}_{qs}] \)
- \( J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \)

\( I_2 = diag(1,1), \) is a second order identity matrix.

\( O_2, \) is a 2x2 zero matrix.
In state matrix $\hat{A}$, the different terms are as follows:

$L_m$ and $L_r$ are the magnetising inductance and rotor self-inductance respectively, $L_s$ is the stator transient inductance, $T_s = L_s / R_s$ and $T_r = L_r / R_r$ are the stator and rotor transient time constants respectively, and $\sigma = 1 - L_m^2 / (L_m L_r)$ is the leakage factor.

The observer gain matrix is defined as

$$ G = \begin{bmatrix} g_1 I_2 + g_2 J \\ g_3 I_2 + g_4 J \end{bmatrix} $$

which yields a 2x4 matrix. The four gains in $G$ can be obtained from the eigen-values of the induction motor as follows:

$$ g_1 = -(k-1)(\frac{1}{T_s} + \frac{1}{T_r}) $$

$$ g_2 = (k-1)\hat{\omega}_r $$

$$ g_3 = (k^2 - 1) \left( - \frac{1}{T_s} + \frac{(1-\sigma)}{T_r} \right) \frac{L_s}{L_r} + \frac{L_m}{L_r} \right) + \frac{L_m}{T_r} \left( k-1 \left( \frac{1}{T_s} + \frac{1}{T_r} \right) \right) $$

$$ g_4 = -(k-1)\hat{\omega}_r \frac{L_m}{L_r} $$

It follows that the four gains depend on the estimated speed, $\hat{\omega}_r$.

The motor speed can be estimated by:

$$ \hat{\omega}_r = K_p \left( \epsilon_{ds} \hat{\psi}_{qr} - \epsilon_{qs} \hat{\psi}_{pr} \right) + K_i \int \left( \epsilon_{ds} \hat{\psi}_{qr} - \epsilon_{qs} \hat{\psi}_{pr} \right) dt \quad (4.9) $$

where $\epsilon_{ds} = (i_{ds} - \hat{i}_{ds})$ and $\epsilon_{qs} = (i_{qs} - \hat{i}_{qs})$ are the current errors calculated as the difference between the measured and the estimated currents. The block diagram for Luenberger observer is represented in Fig. 4.3. The basic Luenberger observer is applicable to a linear, time-invariant deterministic system.

![Figure 4.3. Luenberger based speed estimation structure.](image-url)
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The block diagram for Luenberger observer is represented in Fig. 4.3. The basic Luenberger observer is applicable to a linear, time-invariant deterministic system.

4.3.3.2 Kalman filter observer

The Kalman filter is basically an observer for linear systems, but the gain matrix is chosen to have an optimum filtering when both inputs and outputs are corrupted by noise. The noise affecting the system can be taken into account by:

\[
\frac{dx(t)}{dt} = A(t)x(t) + B(t)v(t) + G(t)u(t) \quad (4.10)
\]

\[
y(t) = C(t)x(t) + w(t) \quad (4.11)
\]

where \( x(t), v(t), y(t) \) represent, respectively, the state variables (stator and rotor currents), the commands variables (the stator voltage) and the output variables (the stator current components), \( u(t) \) and \( w(t) \) are the input noise and the output noise, respectively. Usually \( u(t) \) and \( w(t) \) are considered to be white noises (and thus uncorrelated with inputs and states), although this is not a necessary restriction. Thus their covariance matrices, denoted as \( Q(t) \) and \( R(t) \) are diagonal respectively.

Kalman filters can be implemented in either continuous or discrete form. In most cases, the discrete form is used, because the control is digital. For non-linear systems, as it is the case of induction motors where the rotor speed can be regarded as a time varying parameter, a linearized model must be derived to use the Kalman filter algorithm, which is referred as the Extended Kalman Filter (EKF). The structure for EKF scheme is depicted in Fig. 4.4. The parameter to be estimated (the rotor speed) can be introduced as a new state variable. The linearization is done by assuming that the speed is constant during the sampling time. The system equations in the discrete time domain are:

\[
x(k+1) = A_d x(k) + B_d v(k) + G_d u(k) \quad (4.12)
\]

\[
y(k) = C_d x(k) + w(k) \quad (4.13)
\]

where

- \( G(t) \) = weighting matrix of noise
- \( w(t) \) = noise matrix of state model (system noise)
- \( v(t) \) = noise matrix of output model (measurement noise)

\( G(t), w(t), \) and \( v(t) \) are assumed to be stationary, white, and Gaussian noise, and their expectation values are zero.

The EKF equation for the estimation of stator and rotor currents and of the rotor speed is:
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\[
\begin{bmatrix}
    x(k+1) \\
    \omega_r(k+1)
\end{bmatrix} = A_d(k) \begin{bmatrix}
    x(k) \\
    \omega_r(k)
\end{bmatrix} + B_{de}(k)v(k+1) + K(k)(y(k+1) - Cx(k))
\]

(4.14)

where \( A_{de}(k) = \begin{bmatrix} A_d(k) & 0 \\ 0 & 1 \end{bmatrix} \) and \( B_{de}(k) = \begin{bmatrix} B_d(k) \\ 0 \end{bmatrix} \)

If the system matrix, the input and output matrices of the discrete system are denoted by \( A_d, B_d \) and \( C_d \), while the state and the output of the discrete system are denoted by \( x(k) \) and \( y(k) \), then

\[
A_d = \begin{bmatrix}
    1 - T/T_s^* & 0 & TL_m/(L_s L_r) & \omega_r TL_m/(L_s L_r) & 0 \\
    0 & 1 - T/T_s^* & -\omega_r TL_m/(L_s L_r) & TL_m/(L_s L_r T_r) & 0 \\
    TL_m/T_r & 0 & 1 - T/T_r & -T \omega_r & 0 \\
    0 & TL_m/T_r & T \omega_r & 1 - T/T_r & 0 \\
    0 & 0 & 0 & 0 & 1
\end{bmatrix}
\]

\[
B_d = \begin{bmatrix}
    T / L_s & 0 \\
    0 & T / L_s \\
    0 & 0 \\
    0 & 0 \\
\end{bmatrix}
\]

\[
C_d = \begin{bmatrix}
    1 & 0 & 0 & 0 & 0 \\
    0 & 1 & 0 & 0 & 0
\end{bmatrix}
\]

\[
x(k) = [i_d(k) i_q(k) \psi_d(k) \psi_q(k) \omega_r(k)]^T
\]

\[
u(k) = [u_d(k) u_q(k)]^T
\]

\[
y(k) = [i_d(k) i_q(k)]^T
\]

where \( L_s = \sigma L_s = \left(1 - \frac{L_m^2}{L_s L_r}\right) L_s \), \( T_s^* = \frac{L_s}{R_s + R_r (L_m / L_r)^2} \) and \( T \) is the sampling time.

Figure 4.4. Extended Kalman filter scheme block diagram.
4.3.4 Model reference adaptive system estimators

Tamai has proposed one speed estimation technique based on the Model Reference Adaptive System (MRAS) in 1987. Two years later, Schauder presented an alternative MRAS scheme which is less complex and more effective. The MRAS approach uses two models. The model that does not involve the quantity to be estimated (the rotor speed, $\omega_r$) is considered as the reference model. The model that has the quantity to be estimated involved is considered as the adaptive model (or adjustable model). The output of the adaptive model is compared with that of the reference model, and the difference is used to drive a suitable adaptive mechanism whose output is the quantity to be estimated (the rotor speed). The adaptive mechanism should be designed to assure the stability of the control system. 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.

![Figure 4.5. General structure of MRAS based estimator scheme (a) using space vector notation (b) using space vector components.](image)
Fig. 4.5 illustrates the basic structure of MRAS. Different approaches have been developed using MRAS, such as rotor flux based MRAS (RF-MRAS), back e.m.f based MRAS (BEMF-MRAS), reactive power based MRAS (RP-MRAS) and artificial intelligence based MRAS (ANN-MRAS). In the following a basic description of these schemes will be discussed.

4.4 Advantages and disadvantages of speed sensorless estimation schemes

In the past, researchers have developed various estimators or observers by manipulating the induction motor equations in the effort to eliminate the shaft sensors and increase the drives system reliability. Therefore they are distinct in their own ways. This part highlights some of the advantages and disadvantages of the available speed estimation schemes.

4.4.1 Open Loop Estimator

**Advantages**
- Simple in construction

**Disadvantages**
- Estimator's accuracy depends greatly on the accuracy of machine parameters used.
- Suitable for low speed operation.
- The need for the derivation makes the method more susceptible to noise.

4.4.2 Model Reference Adaptive System (MRAS)

**Advantages**
- A potential solution for implementing high performance control systems, especially when dynamic characteristics of a plant are poorly known, or have large and unpredictable variations.

**Disadvantages**
- The implementation of the two models in different reference frames affects the complexity and robustness of the MRAS scheme.
- The speed adaptive algorithm used affects the stability and dynamic performance of the closed-loop MRAS.
4.4.3 Kalman Filter (Observer)

_Advantages_

- Kalman filter algorithm and its extension are robust and efficient observers for linear and nonlinear systems, respectively.
- A major advantage of the Kalman filtering approach is its fault tolerance which permits system parameter drifts. Therefore, exact models are not required.
- The developments in the real time computational speed of digital signal processing chips makes the Kalman filter a powerful approach to sensorless vector control.

_Disadvantages_

- Robustness and sensitivity to parameter variation still unsatisfied.

4.4.4 High Frequency Signal (Rotor Slot harmonics)

_Advantages_

- Have the potential for wide-speed and parameter insensitive sensorless control, particularly during low speed operation, including zero speed.

_Disadvantages_

- Due to measurement bandwidth limitation, it has not been directly used for rotor speed estimation.

4.4.5 Artificial Intelligence Scheme

_Advantages_

- Neural networks have learning capability to approximate very complicated nonlinear functions, and therefore considered as universal approximation.

_Disadvantages_

- Requirement of much training or knowledge base to understand the model of a plant or a process.

4.5 Open-loop speed estimation

In the context of speed estimation based on an induction machine model, the term 'open loop speed estimation' means that the speed estimation purely relies on the equations of an induction machine model. In other words, a corrective action within the speed estimator is not present. If there is certain corrective action within the model based speed estimator, such an estimator is termed 'closed loop speed estimator'. Note that the meaning of 'open loop' and 'closed loop' in this context is not in any way related to the speed control loop of the
drive - this loop is always closed and that is precisely the reason why the speed is estimated in the first place. The first attempt to operate the induction machine with closed loop speed control but without using a speed sensor was based on an analogue slip calculator that computed the slip frequency and dates back to 1974. The slip frequency is the difference between the stator frequency and the electrical frequency corresponding to rotor speed. By calculation of the slip frequency, the speed of the rotor can be determined. The slip information is obtained by measuring the electrical quantities applied to the machine. By performing simple signal processing operations on the measured quantities, an analogue signal proportional to the slip level is derived and used to control the machine. This scheme is applicable only in steady-state, in a limited speed range, and is therefore inappropriate for high performance vector control. During the last couple of years, several open-loop rotor speed estimation methods were developed for sensorless vector control of induction machine. Calculation of the rotor speed is based on the induction machine dynamic model. Rotor speed is calculated as the difference between the machine's synchronous electrical angular speed and the angular slip frequency.

In this part of the chapter various rotor speed and slip frequency estimators are obtained by considering the voltage equations of the induction machine. The schemes explained below use the monitored stator voltages and currents or the monitored stator currents and reconstructed stator voltages. In general, the accuracy of open-loop estimators depends greatly on the accuracy of the machine parameters used. At low rotor speed, the accuracy of the open-loop estimator is reduced, and in particular, parameter deviations from their actual values have great influence on the steady-state and transient performance of the drive system which uses an open-loop estimator. Furthermore, high accuracy is achieved if the stator flux is obtained by a scheme which avoids the use of pure integrators.

In general, open-loop speed estimators depend on various parameters of the induction machine. The stator resistance ($R_s$) has important effects on the stator flux linkages, especially at low speeds, and if the rotor flux linkages is obtained from the stator flux linkages, then the rotor flux linkage accuracy is also influenced by the stator resistance. However, it is possible to have a rather accurate estimate of the appropriate 'hot' stator resistance by using a thermal model of the induction machine.

In some schemes, the rotor flux linkage estimation requires the rotor time constants, which can also vary, since it is the ratio of the rotor self-inductance and the rotor resistance, and the rotor resistance can vary due to temperature effects and skin effects, and the rotor
self-inductance can vary due to skin effect and saturation effects. The changes of the rotor resistance due to temperature changes are usually slow changes. Due to main flux saturation, the magnetizing inductance \( L_m \) can change and thus the stator self-inductance \( L_s = L_{sl} + L_m \) and rotor self-inductance \( L_r = L_{rl} + L_m \) can also change even if the leakage inductances \( L_{sl}, L_{rl} \) are constant. The changes of the rotor self-inductance due to saturation can be fast. Due to leakage flux saturation, \( L_{sl}, L_{rl} \) and the stator transient inductance \( L'_s \) can also change. In a vector-controlled drive, where the rotor flux amplitude is constant, the variation of \( L_m \) are small.

### 4.5.1 Open-Loop Estimator-1

An expression for the rotor speed can be obtained directly by using the rotor-voltage space vector equation expressed in the stationary reference frame \((\omega_g = 0)\). For the induction motor, the direct axis rotor-voltage equation becomes [section 3.4]:

\[
0 = R_r i_{dr} + \frac{d\psi_{dr}}{dt} + \omega_r \psi_{qr}
\]

where \( \psi_{dr} = L_{ij} i_{dr} + L_{r} i_{ds} \)

Solving (4.15) and (4.16) we get, the expression for the rotor speed

\[
\omega_r = \frac{1}{\psi_{qr}} \left[ - \frac{d\psi_{dr}}{dt} - \frac{\psi_{dr}}{T_r} + \frac{L_m}{T_r} i_{ds} \right]
\]

where, rotor time constant \( T_r = L_r / R_r \) and rotor flux linkage space vector can be expressed as

\[
\psi_{dr} = \frac{L_r}{L_m} (\psi_{ds} - L'_s i_{ds}) \quad \text{and} \quad \psi_{qr} = \frac{L_r}{L_m} (\psi_{qs} - L'_s i_{qs})
\]

where \( L'_s \) is the stator transient inductance.

The derivative of \( \psi_{dr} \) and \( \psi_{qr} \) is given by equation as follows:

\[
\frac{d\psi_{dr}}{dt} = \frac{L_r}{L_m} (\psi_{ds} - R_s i_{ds} - L'_s \frac{di_{dr}}{dt})
\]

and

\[
\frac{d\psi_{qr}}{dt} = \frac{L_r}{L_m} (\psi_{qs} - R_s i_{qs} - L'_s \frac{di_{qr}}{dt})
\]
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A possible simulink implementation is shown in Fig. 4.6. It can be seen that this requires several machine parameters, some of which vary with temperature, skin effect, and saturation. Thus speed can only be obtained accurately if these parameters are accurately known. At low speeds the accuracy of this estimator is limited. Fig. 4.7 shows the five-phase induction motor speed characteristics for fixed voltage and fixed frequency supply and using vector controlled technique. The open-loop speed estimator-1 produces large ripples in the transient period and less ripples in the steady-state period as shown in Fig. 4.7 (a) and Fig. 4.7(b). The production of ripples is due to the presence of integrators and differentiators.

![Simulink diagram for open-loop estimator-1 using 2 integrators, 2 differentiators and 5 machine parameters.](image)

![Five-phase induction motor speed characteristics using open-loop speed estimator-1, for (a) fixed voltage and fixed frequency supply (b) using vector control technique.](image)

(a)  
(b)  

Figure 4.6. Simulink diagram for open-loop estimator-1 using 2 integrators, 2 differentiators and 5 machine parameters.

Figure 4.7. Five-phase induction motor speed characteristics using open-loop speed estimator-1, for (a) fixed voltage and fixed frequency supply (b) using vector control technique.
4.5.2 Open-Loop Estimator-2

It is possible to obtain another rotor speed estimator, which can be obtained from equation (4.17) by substitution of equations (4.18) and (4.19). Thus we get

\[
\omega_r = -\frac{1}{(\psi_{qs} - L_s i_{qs})} \left[ v_{ds} - (R_s + \frac{L_s}{T_r})i_{ds} - \frac{di_{ds}}{dt} + \frac{\psi_{ds}}{T_r} \right]
\] (4.21)

or

\[
\omega_r = -\frac{1}{(\psi_{ds} - L_s i_{ds})} \left[ v_{qs} - (R_s + \frac{L_s}{T_r})i_{qs} - \frac{di_{qs}}{dt} + \frac{\psi_{qs}}{T_r} \right]
\] (4.22)

An estimator using equation (4.21) is shown in Fig. 4.8. The speed estimator shown in Fig. 4.3 requires four machine parameters and accuracy of the speed estimator once again greatly depends on these. Fig. 4.9 shows the five-phase induction motor speed characteristics for fixed voltage and fixed frequency supply and using vector controlled technique. The open-loop speed estimator-2 produces large ripples in the transient period and less amplitude ripples in the steady-state period as shown in Fig. 4.9(a) and Fig. 4.7(b). A low amplitude ripples introduces in the speed characteristics at the loading period. The production of ripples is again due to the presence of integrators and differentiators.

![Simulink diagram for open-loop estimator-2 using 2 integrators, 1 differentiator and 4 machine parameters.](image-url)
4.5.3 Open-Loop Estimator-3

The expression for rotor speed estimator is given as

$$\omega_r = \frac{v_{sy}}{|\psi_s|} \left( |L_s i_{sx}| - \frac{v_{sx}}{\omega_r} \right) \quad (4.23)$$

This speed expression can be obtained straightforward to use first the rotor voltage equation in the stationary reference frame, and the resulting equation is then transformed into the stator-flux-oriented reference frame.

Where

$$|\psi_s| = \psi_{sx} + j\psi_{sy} \quad \dot{i}_s = i_{sx} + ji_{sy} \quad \text{and} \quad \psi_{sx}$$

$$u_{sx} = -\frac{|\psi_s|}{T_r} + \omega_r L_s i_{sy} \quad (4.24)$$

$$u_{sy} = \omega_r (|\psi_s| - \frac{v_{sx}}{\omega_r} \dot{i}_{sx}) \quad (4.25)$$

The numerator of eqn (4.23) contains only $v_{sy}$ and not the quadrature-axis stator flux. This is physically due to fact that in the stator-flux-oriented reference frame the quadrature-axis stator flux is zero. The above estimator can be effectively used in a stator-flux-oriented vector control scheme even at relatively low stator frequency. An estimator using eqn (4.23) is shown in Fig. 4.10. It is possible to obtain an expression for the rotor time constant $T_r$ by using eqns (4.23) and (4.24).

Fig. 4.11 shows the five-phase induction motor speed characteristics for fixed voltage and fixed frequency supply and using vector controlled technique. The open-loop speed estimator-3 produces large ripples in the transient period only and in the steady-state period ripples are almost absent as shown in Fig. 4.11(a) and Fig. 4.1(b). The production of ripples
in the starting is again due to the presence of integrators and differentiators. This speed estimator is much better than first two speed estimators which discussed earlier.

![Simulink diagram for open-loop estimator-3.](image)

Figure 4.10. Simulink diagram for open-loop estimator-3.

![Five-phase induction motor speed characteristics using open-loop speed estimator-3.](image)

Figure 4.11. Five-phase induction motor speed characteristics using open-loop speed estimator-3, for (a) fixed voltage and fixed frequency supply (b) using vector control technique.

### 4.5.4 Open-Loop Estimator-4

Rotor speed is calculated as the difference between the machine's synchronous electrical angular speed and the angular slip frequency. In other words,

\[
\omega_r = \omega_{mr} - \omega_{sl}
\]  

(4.26)

Where \( \omega_r \) is the rotor speed, \( \omega_{mr} \) is the speed of rotor flux and \( \omega_{sl} \) is the angular slip frequency. In a rotor flux oriented controlled induction machine, it is possible to obtain the
angular slip frequency by using the rotor voltage equation of the machine in the rotor flux oriented reference frame. The angular slip frequency can be calculated from:

$$\omega_{sl} = \frac{L_m}{T_r} \frac{i_{qs}}{\psi_r}$$  \hspace{1cm} (4.27)

where $i_{qs}$ can be obtained from the torque equation as:

$$i_{qs} = \frac{2T_e}{3P} \frac{L_r}{\psi_r}$$  \hspace{1cm} (4.28)

Substitution of equation (4.28) into (4.27), considering that $\psi_r = \psi_{dr}$ in the rotor flux oriented reference frame and that

$$T_e = \frac{3}{2} P \frac{L_m}{L_r} (\psi_{dr} i_{qs} - \psi_{qr} i_{ds})$$  \hspace{1cm} (4.29)

Yields

$$\omega_{sl} = \frac{L_m}{T_r} \frac{1}{\psi_r^2} (\psi_{dr} i_{qs} - \psi_{qr} i_{ds})$$  \hspace{1cm} (4.30)

The electrical angle $\phi_r$ of the rotor flux vector is defined as:

$$\phi_r = \tan^{-1} \left( \frac{\psi_{qr}}{\psi_{dr}} \right)$$  \hspace{1cm} (4.31)

The derivative of the angle equation (4.31) can be used to obtain the electrical angular speed of the rotor flux. Therefore,

$$\omega_{mr} = \frac{d\phi_r}{dt} = \frac{d\psi_{qr}}{dt} - \frac{\psi_{dr}}{\psi_r^2} \frac{d\psi_{dr}}{dt}$$  \hspace{1cm} (4.32)

If the rotor flux components are known, the electrical angular speed of rotor flux can be calculated by using equation (4.32). It is convenient to estimate the rotor flux components from the stator voltage equations. Derivatives of the rotor flux components can be then given as:

$$\frac{d\psi_{dr}}{dt} = \frac{L_r}{L_m} \left( v_{ds} - R_s i_{ds} - \sigma L_s \frac{di_{ds}}{dt} \right)$$

$$\frac{d\psi_{qr}}{dt} = \frac{L_r}{L_m} \left( v_{qs} - R_s i_{qs} - \sigma L_s \frac{di_{qs}}{dt} \right)$$  \hspace{1cm} (4.33)

Electrical angular speed of rotor flux, given with (4.32), and angular slip frequency (4.30) are thus calculated using (4.33) and measured stator voltages and currents. Finally, the rotor speed is estimated from:
\[
\omega_r = \omega_{mr} - \omega_{sl} = \frac{d\psi_{qr}}{dl} - \frac{d\psi_{qr}}{dl} \frac{L_m}{T_r} \frac{1}{\psi_r^2} (\psi_{dr}i_{qs} - \psi_{qr}i_{ds})
\]  

(4.34)

Fig. 4.12 shows the simulink diagram of implementation of the speed estimation scheme based on the equations given above. The inputs are stator currents and stator voltages in stationary reference frame. Stator currents can be measured from the machine terminals. Stator voltages can be measured from the machine terminals or reconstructed from the inverter switching states and measured DC link voltage.

Figure 4.12. Simulink diagram for open-loop estimator-4.

Figure 4.13. Five-phase induction motor speed characteristics using open-lop speed estimator-4, for (a) fixed voltage and fixed frequency supply (b) using vector control technique.
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The problems encountered in the implementation of this scheme are two-fold. Firstly, since it is model based, accuracy of speed estimation is affected by parameter variation effects. Secondly, the scheme involves pure integration that fails at very low and zero frequency due to offset and drifts problems. This kind of speed estimator works without failure above 10% of rated synchronous speed.

Fig. 4.13 shows the five-phase induction motor speed characteristics for fixed voltage and fixed frequency supply and using vector controlled technique. The open-loop speed estimator-4 produces almost no ripples in the transient period as well as in the steady-state period as shown in Fig. 4.13(a) and Fig. 4.13(b). This speed estimator is much better than the speed estimators which discussed earlier.

4.5.5 Open-Loop Estimator-5

An alternative speed estimation method is again based on the induction machine voltage equations and the flux equations in stationary reference frame. The rotor speed can be calculated directly using these equations. From the machine voltage equations and flux equations the rotor current components in stationary reference can be expressed as a function of the stator flux:

\[ i_{dr} = \frac{1}{L_m}(\psi_{ds} - L_s i_{ds}) \]
\[ i_{qr} = \frac{1}{L_m}(\psi_{qs} - L_s i_{qs}) \]  

From rotor voltage equation, eliminating the rotor resistance \( R_r \), it is possible to obtain the rotor speed as follows:

\[ \omega_r = \frac{i_{dr} \frac{d\psi_{qr}}{dt} - i_{qr} \frac{d\psi_{dr}}{dt}}{i_{dr}\psi_{dr} + i_{qr}\psi_{qr}} \]  

Substitution of equations (4.35) into rotor speed equation (4.36) enables rotor speed to be expressed as:

\[ \omega_r = \frac{(\psi_{ds} - L_s i_{ds}) \frac{d\psi_{qr}}{dt} - (\psi_{qs} - L_s i_{qs}) \frac{d\psi_{dr}}{dt}}{(\psi_{ds} - L_s i_{ds})\psi_{dr} + (\psi_{qs} - L_s i_{qs})\psi_{qr}} \]  

where stator flux components and rotor flux components can be estimated by means of the following equations:
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\[
\psi_{ds} = \int (v_{ds} - R_s i_{ds}) \, dt
\]
\[
\psi_{qs} = \int (v_{qs} - R_s i_{qs}) \, dt
\]

\[
\psi_{dr} = \frac{L_r}{L_m} \psi_{ds} - \frac{\sigma L_s L_r}{L_m} i_{ds}
\]
\[
\psi_{qr} = \frac{L_r}{L_m} \psi_{qs} - \frac{\sigma L_s L_r}{L_m} i_{qs}
\]

(4.38)
(4.39)

Fig. 4.14 shows the simulink diagram of implementation of the speed estimation scheme based on the equations given above. Fig. 4.15 shows the five-phase induction motor speed characteristics for fixed voltage and fixed frequency supply and using vector controlled technique. The open-loop speed estimator-5 produces small ripples in the transient period only and in the steady-state period ripples are almost absent as shown in Fig. 4.15(a) and Fig. 4.5(b). The production of ripples in the starting is again due to the presence of integrators and differentiators.

Figure 4.14. Simulink diagram for open-loop estimator-5.

Figure 4.15. Five-phase induction motor speed characteristics using open-loop speed estimator-5, for (a) fixed voltage and fixed frequency supply (b) using vector control technique.
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However, due to its limitations, this estimation technique has been deliberately considered as the last scheme, since this direct approach cannot be used in two cases: under sinusoidal steady-state conditions and also when the rotor flux is constant. In this scheme two low pass filters are used for getting accurate value of rotor speed. To obtain high accuracy, the two low-pass filters must be identical. This speed estimator depends on various machine parameters but does not depend on the rotor resistance.

Problems related to practical application of this method are the same as those stated in conjunction with the previous method.

4.6 Discussion of results

Fig. 4.7, 4.9, 4.11, 4.13 and 4.15 shows the five-phase induction motor speed characteristics for fixed voltage and fixed frequency supply and using vector controlled technique for speed estimator-1, -2, -3, -4 and -5 respectively. The first two open-loop speed estimators produces large ripples in the transient period and small ripples in the steady-state periods, whereas third speed estimator produces ripples in the transient period only. The production of ripples in the starting is due to the presence of integrators and differentiators. The fourth and fifth speed estimators show best results i.e. almost ripple free speed signals.

The developed model of a five-phase induction motor indicates that the open-loop techniques used for three-phase machines can be easily extended to multi-phase machines. For multi-phase machines open-loop based speed estimator requires only $d$ and $q$ components of stator voltages and currents. From the model of a five-phase induction machine, it has been shown that the stator and rotor $d$ and $q$ axis flux linkages are function of magnetising inductance $L_m$ and stator and rotor $d$ and $q$ axis currents, whereas the $x$ and $y$ axis flux linkages are function of only their respective currents. Therefore in speed estimation for multi-phase machine the $x$ and $y$ components of voltages and currents are not required. The speed can be estimated using only $d$ and $q$ components of stator voltages and currents.

4.7 Performance analysis of an open-loop estimator

4.7.1 Field weakening and strengthening mode

The accuracy of open-loop estimators depends greatly on the accuracy of the machine parameters used. At low rotor speed, the accuracy of the open-loop estimator is reduced, and in particular, parameter deviations from their actual values have great influence on the steady-state and transient performance of the derive system which uses an open-loop estimator.
Furthermore, high accuracy is achieved if the stator stator flux is obtained by a scheme which avoids the use of pure integrators.

The important information on the field angle and the mechanical speed is conveyed by the induced voltage of the stator winding, independent of the respective method that is used for sensorless control. The induced voltage \( E_i = E_i - R_i I_i \) is not directly accessible by measurement. It must be estimated either directly from the difference of the two voltage space vector terms \( E_i \) and \( R_i I_i \), or directly when an observer is employed.

In the upper speed range above a few Hz stator frequency, the resistive voltage \( R_i I_i \) is small as compared with the stator voltage \( E_i \) of the machine, and the estimation of \( E_i \) can be done with good accuracy. Even the temperature dependent variation of the stator resistance is negligible at higher speed. The performance is exemplified by the Fig. 4.16 and Fig. 4.17. Fig. 4.17 showing a speed reversal between ±1600 and ±2000 rpm that includes field weakening. If operated at frequencies above the critical low speed range, a sensorless ac drive with a shaft sensor, even passing through zero speed in a quick transition is not a problem.

As the stator frequency reduces at lower speeds the stator voltage reduces almost in direct proportion, while the resistive voltage \( R_i I_i \) maintains its order of magnitude. It becomes the significant term at low speed. It is particularly the stator resistance \( R_i \) that determines the estimation accuracy of the stator flux vector. A correct initial value of the stator resistance \( R_i \) is easily identified by conducting a dc test during initialization. Considerable variation of the resistance takes place when the machine temperature changes at varying load. These need to be tracked to maintain the system stable at low speed.

![Figure 4.16. Open-loop speed estimator performance for fixed voltage and fixed frequency supply in field weakening mode at (a) 1800 rpm (b) 2100 rpm (c) 2400 rpm.](image)
Figure 4.17. Open-loop speed estimator performance for vector control in field weakening mode at (a) ±1600 rpm (b) ±2000 rpm.

Figure 4.18. Open-loop speed estimator performance for fixed voltage and fixed frequency supply in field strengthening mode at (a) 375 rpm (b) 150 rpm (c) 30 rpm.

Figure 4.19. Open-loop speed estimator performance for vector control in field strengthening mode at (a) ±400 rpm (b) ±100 rpm (c) ±50 rpm.

4.7.2 Parameter sensitivity and effect of line faults

As to ensure a fair comparison on the estimators' performance, the parameters of a 5-phase, 4-poles squirrel cage type induction motor have been used as given in Appendix A. Knowledge of motor's parameter is important for the simulation since the estimators are highly parameters dependent and hence, they are exposed to inaccuracy in estimation as the parameters vary. The performance of the estimators can be evaluated based on three criteria of comparison which are the tracking capability, parameter sensitivity and line faults.
4.7.2.1 Tracking capability

Tracking capability is one of the key criteria of the comparison. The performance of an estimator is evaluated in terms of convergence of the estimated rotor speed to the actual speed. An estimator is said to have good tracking capability if the estimated value can track the actual value at high and even at close to zero speed. Using the same parameters in the IM and the open-loop estimator, the tracking performance of the estimator can be examined by changing the motor parameters \((R_s, R_r, L_s, L_r, J)\).

4.7.2.2 Parameter sensitivity

It is understood that the estimator's performance are highly dependent on the IM parameters since its structure realization is directly extracted from the IM dynamic equations. The IM parameters are affected by variations in the temperature and the saturations levels of the machine. Incorrect setting of parameters in the motor and that instrumented in the vector controller and estimators will results in the deterioration of performance in terms of steady state error and transient oscillations of rotor flux and torque. As a consequence, parameter sensitivity has been treated as a secondary issue in a vector controlled IM drives system.

Some of the parameters detuning effect being studied are the stator resistance \(R_s\), rotor resistance \(R_r\), stator self-inductance \(L_s\), rotor self-inductance \(L_r\), and motor moment of inertia \(J\). Amongst these parameters, stator resistance \(R_s\) variation has been observed to have large influence on the estimator's performance. Others parameters have minimum effects but as the variations becomes larger, the effect to the estimator's performance also becomes significant.

The open-loop estimator-4 has been selected for the performance analysis because this estimator shows the best results.

(A) Effect of variation of rotor resistance, \(R_r\):

The rotor resistance \(R_r\) is one of the variables that exist explicitly in the equations used to construct the structure of the estimators. Variation in the \(R_r\) will directly vary the rotor time constant value \(T_r\). Incorrect value of \(T_r\) affects the accuracy of estimation, leading to variation in the rotor speed response. In this part, some simulations with different values of \(R_r\) have been carried out to examine the effect of the parameter variation to the estimator
performance. The $R_r$ value in the motor is changed to 10% and 50% from its nominal value and the simulation results are shown. The following effects are observed:

As the value of $R_r$ is increased to 10% and 50% from its nominal value, the estimator's smooth response at rated value tend to deviate slightly from the normal response. When the value of $R_r$ is increased to 100% from its nominal value, the deviation of the estimated speed to the actual speed becomes significant especially during transient period (at starting). The large disturbances are observed for increased value of $R_r$. The rotor time constant value $T_r$ becomes relatively smaller as the value of the $R_r$ is increased from its nominal value and inaccurate value in the estimated rotor flux linkages at lower speed. The variation in the $R_r$ values also affects the tracking performance as depicted in Fig. 4.20-4.21. The deviation is significant for large changes of $R_r$.

![Figure 4.20](image)

**Figure 4.20. Effect of incorrect setting of $R_r$ value to estimator's response for**

(a) Normal $R_r$, (b) $R_{rev} = 1.1 R_r$, (c) $R_{rev} = 1.5 R_r$.

![Figure 4.21](image)

**Figure 4.21. Effect of incorrect setting of $R_r$ value to open-loop estimator’s response in presence of a vector controller**

(a) Normal $R_r$, (b) $R_{rev} = 1.1 R_r$, (c) $R_{rev} = 1.5 R_r$.

Speed response for the variation of rotor resistance, $R_r$ (by 10% and 50% ) from its rated value is shown in Fig.4.21, keeping the parameters of the estimator unchanged. When the rotor resistance, $R_r$ is increased by 10% then ripples increases to about 1500rpm, with the decrease in the tracking capability in the transient period. However, it increases to about 3500rpm with the further increase of rotor resistance, $R_r$ by 50%. In this condition, the
tracking capability is decreased in the transient as well as in loaded condition. It should be noted that, with the change in the value of $R_s$, there is the increase in ripples content only in the transient period, along with the decrease in the tracking capability, especially in transient as well as in loaded period.

(B) **Effect of variation of stator resistance, $R_s$:***

Other parameter that exists in the equations related to model based speed estimators is the $R_s$. It has been widely reported that this parameter can cause severe effect to the estimators' response during low speed operation.

It is clear from the simulation diagrams that even small variations of $R_s$ adversely affect the speed response of the estimator. A comparative analysis using the different estimators is shown by the simulation results as shown in figures. Usually the effect of $R_s$ variation is associated with the term $R_s \frac{di}{dt}$ which becomes relatively larger as the frequency decreases. The frequency will decrease at low speed and thus varying the stator voltages and currents. Therefore, small changes in $R_s$ value will severely affect the estimated speed.

![Figure 4.22](image1.png)

**Figure 4.22.** Effect of incorrect setting of $R_s$ value to estimator's speed response

(a) Normal $R_s$. (b) $R_{snew} = 1.1 R_s$. (c) $R_{snew} = 1.5 R_s$.

![Figure 4.23](image2.png)

**Figure 4.23.** Effect of incorrect setting of $R_s$ value to open-loop estimator's response in presence of a vector controller

(a) Normal $R_s$. (b) $R_{snew} = 1.1 R_s$. (c) $R_{snew} = 1.5 R_s$. 

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Fig. 4.22 and Fig. 4.23 are showing the change in speed response of estimator with the variation of stator resistance, $R_s$ (by 10% and 50%) from its rated value in motor. When there is the change of 10% in $R_s$, ripple increases in the entire operating region, having the maximum value of about 2000rpm in the transient period. However the tracking capability is not affected. When $R_s$ is increased by 50%, ripple content further increases, having the maximum value of about $1.5 \times 10^4$rpm. Tracking capability is affected mainly during the transient period.

It should be noted as the value of stator resistance, $R_s$ increases, there is a tremendous increases of ripples in the entire operating region, showing that the estimator depends strongly on $R_s$. Change in $R_s$ also effects the tracking capability, both in transient and steady-state periods. Motor behavior also deviates from its normal operation.

(C) Effect of variation of rotor inductance, $L_r$:

Another parameter that can vary is $L_r$. Variation in the $L_r$ will directly vary the rotor time constant value, $T_r$. Incorrect value of $T_r$ affects the accuracy of estimation, leading to variation in the rotor speed response.

Figure 4.24. Effect of incorrect setting of $L_r$ value to open-loop estimator’s response
(a) $L_{new} = 0.9 \ L_r$ (b) Normal $L_r$ (c) $L_{new} = 1.1 \ L_r$.

Figure 4.25. Effect of incorrect setting of $L_r$ value to open-loop estimator’s speed response in presence of a vector controller (a) $L_{new} = 0.9 \ L_r$ (b) Normal $L_r$ (c) $L_{new} = 1.1 \ L_r$.
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In this part, Simulations with different values of $L_r$ have been carried out to examine the effect of the parameter variation to the estimator performance without using a vector controller and in presence of a vector controller. The $L_r$ value in the motor is changed to $0.9L_r$, $1.1L_r$ and $1.5L_r$, and the simulation results are shown. The following affects are observed:

As the value of the $L_r$ increases the estimator performance deteriorates in terms of tracking capability. The settling time also varies with the variation in $L_r$. Large disturbances are observed for larger values of $L_r$. The rotor time constant value $T_r$ becomes relatively larger as the value of the $L_r$ is increased from its rated value and inaccurate value in the estimated rotor flux linkages at lower speed.

(D) Effect of variation of stator inductance, $L_s$:

In this part, some simulations with different values of $L_s$ have been carried out to examine the effect of the parameter variation to the estimator performance in absence of the vector controller and in presence of the vector controller. The $L_s$ value in the motor is changed to $0.9L_s$ and $1.1L_s$, and the simulation results are shown. The following affects are observed:

![Figure 4.26. Effect of incorrect setting of $L_s$ value to open-loop estimator's response](image)

(a) $L_{new} = 0.9L_s$ (b) Normal $L_s$ (c) $L_{new} = 1.1L_s$.

![Figure 4.27. Effect of incorrect setting of $L_s$ value to open-loop estimator's response in presence of a vector controller](image)

(a) $L_{new} = 0.9L_s$ (b) Normal $L_s$ (c) $L_{new} = 1.1L_s$. 

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As the value of the $L_c$ changes the estimator performance deteriorates in terms of tracking capability and ripples during the transient period. Large disturbances are observed especially during transient period for larger values of $L_c$.

**(E) Effect of incorrect moment of inertia, $J$ setting:**

It is always crucial not to underestimate the motor parameters variation on the estimation process because small changes from its rated value might severely affect the accuracy of estimation. This includes the motor moment of inertia parameter, $J$. Though it do not exist in the IM dynamic equations extracted for speed estimators, however the implication of $J$ variation should not be neglected. The only relation involved with this parameter is equation (4.40)

$$T_e = J \frac{d\omega_r}{dt} + B\omega_r + T_L$$

which proportionately relates $J$ with the torque produced. Therefore, any changes in $J$ will vary the torque values. For that reason, the effect of variation in $J$ has been studied and the following results explained the behaviour of open-loop estimators prior to these changes. The tracking performance of the estimators is unaffected with changes in $J$ values. The performance of the open-loop estimator has been examined with value of $J$ in the IM is set to $0.8J$ and $1.2J$ respectively from its rated value and the values instrumented in the estimators is kept unchanged. The open-loop estimator response has undergone a shift in the rising and falling time due to changes in the torque response. It is observed that as the change in the $J$ values is increased from $0.8J$ to $1.2J$, the time for the estimators to reach steady state also has increased. The longer time taken for rising and falling of the response is influenced by the torque response also.

Figure 4.28. Effect of incorrect setting of J value to Open Loop Estimator’s speed response for a fixed voltage and fixed frequency supply (a) $J_{new} = 0.8 \, J$ (b) Normal $J$ (c) $J_{new} = 1.2 \, J$. 


Figure 4.29. Effect of incorrect setting of $J$ value to open-loop estimator’s speed response in presence of a vector controller (a) $J_{1a} = 0.8$ (b) Normal (c) $J_{1a} = 1.2$ $J$.

(F) Effect of line faults (single phasing) on the estimator's performance:

The effect of line fault (single phasing) on the estimator’s performance is illustrated in this section obtained from the simulation results. This is the first time in the literature that the author has investigated the performance of the speed estimators during the fault conditions. Till now no author has observed the performance of any speed estimator during any type of fault in the supply line. The single phasing fault may occur in any of the phase of induction motor. Also the fault may occur during any of the operating region of the motor - transient, steady state, or loaded condition. The open-loop speed estimator is investigated here when one of the incoming phases comes in direct contact with the ground. Three cases are studied for speed estimator namely when single phasing occurs during (a) Transient (starting) period (b) Steady state no-load period (c) Steady state loading period. A comparative study is made in terms of tracking capability and production of ripples.

From the simulation results when the single phasing occurs during any of the operating region, the estimators speed response almost follows the actual speed response of the motor showing a good tracking capability. Large ripples are found only in case of open-loop scheme. Very small ripples are found in other cases. However the motor operation deviates from its normal operation during this condition.

Figure 4.30. Effect of single phasing on open-loop speed estimator during (a) transient (starting) period (b) steady-state no-load period (c) steady-state loading period.
4.8 Summary

It is well acknowledged that so many efforts have been put in the past to extract speed or position signal of an induction motor. The speed information which is important for control purposes could be extracted using sensor. However, the presence of sensor itself has reduced the drive reliability as well as increased the drive's size. This situation has put the induction motor drive at disadvantage when talking about its good dynamic response and performance for variable speed control. Its predecessor, the dc machine is always a good choice but with the development of several new methods to extract the speed or position signal, it has put the induction motor drive as a better choice for variable speed control. This technique is called "speed sensorless technique", which refers to the elimination of the shaft sensor used to obtain the speed information.

For the past 20 years, the researchers have developed many strategies for speed sensorless estimation. All the techniques differ from one to another but they complement to each other in terms of objectives and performances. The strategies range from open loop to closed loop structure and hence indicate the later has better performance. Although the list of speed sensorless estimation strategies is bulky in literature, some problem associated with low speed performance and parameters mismatch still need careful attention by the researchers. Nevertheless the invention of speed sensorless estimation strategies has greatly increased the popularity and performance of the induction motor drives.

The open-loop speed estimation methods, reviewed in this chapter, are simple to implement. However, it should be noted once more that the accuracy of open-loop speed estimators depends greatly on the accuracy of the machine parameters used. In general, at low speed the accuracy of open-loop speed estimators is reduced. Furthermore, the integration problem makes application of these schemes at zero and very low speed impossible.

The performance of speed estimator is judged by parameter \( (R_s, R_r, L_s, L_r, and J) \) variation and fault analysis (single phasing) in terms of tracking capability. It found that under parameter variation and fault condition the estimator behavior is satisfactorily.