



Sensorless Speed Control Scheme for Induction Motor Drive Using DC link Measurements

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ABSTRACT:

The controlled induction motor drives without mechanical speed sensors at the motor shaft have the attractions of low cost and high reliability. To replace the sensor, the information on the rotor speed is extracted from measured stator voltages and currents at the motor terminals. Vector controlled drives requires estimating the magnitude and spatial orientation of the fundamental magnetic flux waves in the stator or in the rotor. Open loop estimators or closed loop observers are used for this purpose. They differ with respect to accuracy, robustness and sensitivity against model parameter variations. This paper presents a new control strategy for three-phase induction motor which includes independent speed & torque control loops and the current regulation thereby overcoming the limitation (i.e. sluggish response) of volts per hertz controlled industrial drives.

For closed-loop control, the feedback signals including the rotor speed, flux and torque are not measured directly but are estimated by means of an algorithm. The inputs to this algorithm are the reconstructed waveforms of stator currents and voltages obtained from the dc link and not measured directly on stator side. The proposed drive thus requires only one sensor in the dc link to implement the close-loop speed and torque control of a three-phase induction motor.

I.INTRODUCTION:

In recent years, a large number of speed sensorless vector control systems for induction motor (IM) have been proposed. Speed information is generally provided by a speed transducer on the motor shaft; recently, low cost and high performance digital signal processors (DSP) become available allowing obtaining speed by means of digital estimators integrated with motor control. This solution represents an advantage in terms of costs, simplicity and mechanical reliability of the drive. Several schemes of speed estimators have been proposed in the literature; among them, the model reference adaptive system (MRAS) approach is very attractive and gives good performance. The classical MRAS method is based on the adaptation of the

rotor flux; with this scheme, some difficulties in terms of precise and robust speed estimation arise, especially at low speed. The need of a pure integration in the speed estimator represents a drawback in the low speed region, due to drift and low frequency disturbances; moreover, parameter sensitivity (in particular to stator resistance) represents a usual disadvantage for all model-based estimators. To overcome these problems, alternative MRAS schemes based on back-EMF or reactive power has been presented, but it seems that they don't solve troubles at low speed. The common approach to increase dynamic performance and stability of speed sensorless field oriented control systems is the on-line parameter adaptation. The different methods of types of control strategies are clearly shown in below figure 1.

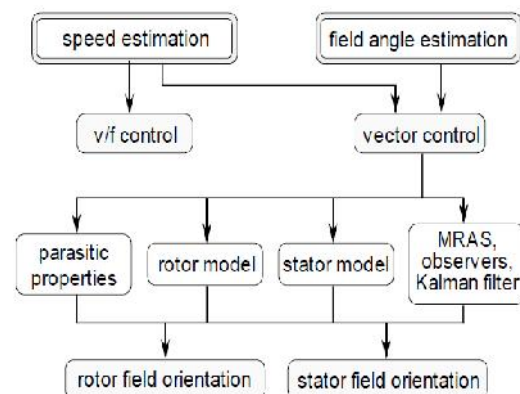


Fig 1: Methods of sensorless speed control

The controlled induction motor drives without mechanical speed sensors at the motor shaft have the attractions of low cost and high reliability. The control of IM variable speed drives often requires control of machine currents, which is normally achieved by using a voltage source inverter. A large number of control strategies have been registered so far. The volts per hertz (v/f) IM drives with inverters are widely used in a number of industrial applications promising not only energy saving, but also improvement in productivity and quality. The low cost applications usually adopt v/f scalar control when no particular performance is required Variable-speed pumps, fans are the

examples. For those applications which require higher dynamic performance than v/f control, the dc motor like control of IM that is called, the field oriented control (FOC) is preferred. During the last few years, a particular interest has been noted on applying speed sensor less FOC to high performance applications that is based on estimation of rotor speed by using the machine parameters, instantaneous stator currents and voltages. The benefits of speed sensor less control are the increased reliability of overall system with the removal of mechanical sensors, thereby reducing sensor noise and drift effects as well as cost and size. However to exploit the benefits of sensor less control, the speed estimation methods must achieve robustness against model and parameter uncertainties over a wide speed range.

The adaptive observers (AO) like Luenberger observer or the extended Kalman filter, gets accurate estimates under detuned operating conditions but these solutions are computationally intensive, require more memory space and are difficult to tune because the initial values of three covariance matrices have to be assumed and selected after much trial and error. So their application in low cost drives is limited. The model reference adaptive system is also an AO technique, where the same quantity is calculated by two different ways. One of them is independent of variable to be estimated while the other one is dependent on it. The two computed quantities are used to formulate the error signal. The error signal is then fed to an adaptation mechanism which in most cases is a PI controller. The output of the adaptation mechanism is the estimated quantity. While the entire speed sensor less techniques eliminates the use of mechanical speed sensor, they require the stator current and stator voltage signals as input. This requires at-least two current sensors and two voltage sensors on the stator side. It is difficult to get current sensors with equal gains over the wide range of frequencies, voltages and currents used in a practical inverter. The problem is exacerbated if the motor windings are not perfectly balanced or if the current sensors have some dc offset. Over last few years, techniques of stator current reconstruction from the dc link current have been suggested in literature.

In this paper, a new speed sensor less control strategy for IM is proposed that includes the speed control, torque control and current regulation. Unlike conventional close loop estimators, it involves less computation and is less dependent on machine parameters. The stator currents and stator voltages are reconstructed from dc link quantities and the inverter switching signals. For faithful reconstruction of currents, use of adaptable gain band-pass filter is proposed in the scheme. The simulation results of proposed scheme shows fast performance as compared to v/f control and

therefore can be regarded as an improvement. For the close loop speed control, a single current sensor in the dc link is sufficient. Thus it is suitable for low-cost, moderate performance, sensor less IM drive applications. The proposed systems are clearly verified with simulation results shown below.

II. PROPOSED SCHEME:

Fig. 2 shows the block diagram of the proposed scheme. It consists of a speed (frequency loop), a torque loop, and a current regulator. The output of speed/frequency regulator represents the torque reference for the torque loop. The torque regulator generates the q-axis current command i_{qe}^* . The d-axis current command i_{de}^* is directly generated from the reference rotor flux Ψ_r^* as given by (1). This eliminates an additional PI controller and reduces the computational burden. These dc commands expressed in synchronously rotating reference after transformation to the three phase current commands are then compared with the actual three phase currents (reconstructed waveforms) to generate the switching signals for the inverter. In the proposed scheme, all the feedback signals including the stator currents and stator voltages are estimated/reconstructed from the dc link quantities.

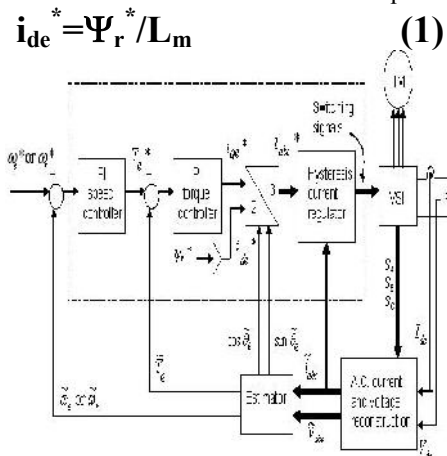


Figure 2: Block diagram of the proposed scheme

1. RECONSTRUCTION OF STATOR VOLTAGES AND CURRENTS FROM DC-LINK:

As indicated in the stator flux, torque and speed can be derived from the stator voltages and currents expressed in d-q reference frame. The phase currents and voltages are related to the dc link current and voltage by inverter switching states. A voltage source inverter-IM drive is shown in Fig 3. Where V_{dc} is the dc link voltage, I_{dc} is the instantaneous dc link current and i_a, i_b, i_c are the instantaneous three-phase winding currents. Generally, IGBTs associated with snubber protection and feedback diode are used as switch in inverters. When a switch is being turned-on and the

conducting diode at the same leg is being blocked off by this turn-on, because of the reverse recovery effect of diode, this leg is in fact shorted through at this moment such that a positive current spike will appear at the dc link side. To establish the basic relationship between dc link current, winding currents and inverter switching pattern, the switches shown in Fig. 3 are considered as ideal; the diode recovery effect and the snubber action are not considered.

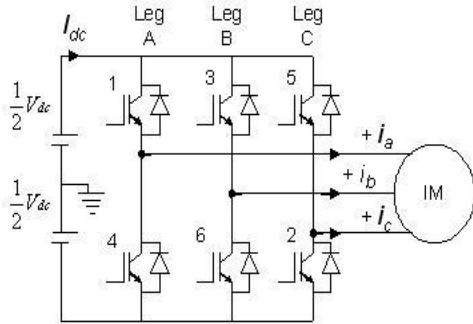


Figure 3: Voltage source inverter fed induction motor drive

A. Space-Vectors: During normal state, there are eight switching states of inverter which can be expressed as space voltage vector (SA,SB,SC) such as (0,0,0), (0,0,1), (0,1,0), (0,1,1), (1,0,0), (1,0,1), (1,1,0) and (1,1,1). SA =1 means upper switch of leg A is on while the lower one is off, and vice versa. The same logic is applicable to SB and SC also. Amongst above eight voltage vectors, (0,0,0) and (1,1,1) are termed as zero vectors while the other six as active vectors. The switching vectors describe the inverter output voltages.

B. Basic Principle of Phase Voltage & Line Current Reconstruction: For different voltage vectors, the phase voltage that will appear across stator winding can be determined by circuit observation. This is summarized in Table 1. It is assumed that the stator winding is star connected. From this table, the expressions for the reconstruction of three phase voltages are as follows (assuming no dwelling time):

$$\tilde{v}_a = \frac{V_{dc}}{3}(2S_A - S_B - S_C) \quad (2)$$

$$\tilde{v}_b = \frac{V_{dc}}{3}(-S_A + 2S_B - S_C) \quad (3)$$

$$\tilde{v}_c = \frac{V_{dc}}{3}(-S_A - S_B + 2S_C) \quad (4)$$

The stator voltages as expressed in stationary d-q frame are,

$$\tilde{v}_{qs}^s = \tilde{v}_a = \frac{V_{dc}}{3}(2S_A - S_B - S_C) \quad (5)$$

$$\tilde{v}_{ds}^s = \frac{1}{\sqrt{3}}(\tilde{v}_b - \tilde{v}_c) = \frac{V_{dc}}{\sqrt{3}}(S_B - S_C) \quad (6)$$

Table I: dc link current & phase voltages

Voltage Vector (SA,SB,SC)	va(V)	vb(V)	vc(V)	Idc(A)
(0,0,0)	0	0	0	0
(0,0,1)	-Vdc/3	-Vdc/3	2Vdc/3	+ia
(0,1,0)	-Vdc/3	2Vdc/3	-Vdc/3	+ib
(0,1,1)	-2Vdc/3	Vdc/3	Vdc/3	-ia
(1,0,0)	2Vdc/3	-Vdc/3	-Vdc/3	+ia
(1,0,1)	Vdc/3	-2Vdc/3	Vdc/3	-ib
(1,1,0)	Vdc/3	Vdc/3	-2Vdc/3	-ic

The relationship between the applied active vectors and the phase currents measured from the dc link is also shown in Table 1. It is clear that at-most, one phase current can be related to the dc-link current at every instant. The reconstruction of phase currents from the dc-link current can be achieved easily only if two active vectors are present for at least enough time to be sampled. Fortunately, as indicated in [10], for most PWM strategies, two phase currents can be sampled by looking at the dc link current over every PWM period. If the PWM frequency is high enough, the phase current does not change much over one PWM period. Hence, a reconstructed current derived from the dc link current gives a reasonable approximation of the actual current. In terms of switching states and Idc, the three ac line currents can be derived as follows:

$$\tilde{i}_a = I_{dc}(S_A - \frac{S_B}{2} - \frac{S_C}{2}) \quad (7)$$

$$\tilde{i}_b = I_{dc}(\frac{S_A}{2} + S_B - \frac{S_C}{2}) \quad (8)$$

$$\tilde{i}_c = I_{dc}(-\frac{S_A}{2} - \frac{S_B}{2} + S_C) \quad (9)$$

The stator currents as expressed in stationary d-q frame are,

$$\tilde{i}_{qs}^s = \tilde{i}_a; \quad \tilde{i}_{ds}^s = \frac{1}{\sqrt{3}}(2\tilde{i}_b + \tilde{i}_a) \quad (10)$$

$$\text{or } \tilde{i}_{qs}^s = \tilde{i}_a; \quad \tilde{i}_{ds}^s = \frac{-1}{\sqrt{3}}(2\tilde{i}_c + \tilde{i}_a) \quad (11)$$

$$\text{or } \tilde{i}_{qs}^s = -(\tilde{i}_b - \tilde{i}_c); \quad \tilde{i}_{ds}^s = \frac{1}{\sqrt{3}}(\tilde{i}_b + \tilde{i}_c) \quad (12)$$

C. Filter Stage: The dc link current Idc consists of a train of short duration pulses and has information about the stator currents of all the three phases. By using (7)-(9), these pulses can be segregated into three ac line currents. Generally, an active or passive-type low-pass filter (LPF) with narrow bandwidth is used to filter out the high frequency components in the ac current waveform thus obtained from Idc. This filter actually works as an integrator. However, a LPF causes phase lag and amplitude attenuation that vary with fundamental

frequency. In this paper, we propose the use of band-pass filter with adaptable gain to overcome this problem. The transfer function of the filter is given below:

$$y = \left[\left(\frac{sT}{1+sT} \right) \left(\frac{T}{1+sT} \right) \right] x \quad (13)$$

Where x,y and T are input constants and time constant of the band pass filter. For

$$sT \gg 1; (1+sT) \cong 1. \text{ Therefore,} \\ y = \frac{1}{s} x \quad (14)$$

2. ESTIMATION OF FEEDBACK SIGNALS FROM RECONSTRUCTED QUANTITIES:

The feedback signals required to simulate the proposed scheme i.e., flux, torque and rotor speed are estimated as:

A. Estimation of Flux: The stator flux in stationary d-q frame:

$$\psi_{ds}^s, \psi_{qs}^s \text{ and thus } \psi_s$$

It can be obtained on integration of the phase voltage minus voltage drop in the stator resistance R_s .

$$\psi_{ds}^s = \int (\tilde{v}_{ds}^s - R_s \tilde{i}_{ds}^s) dt \quad (15)$$

$$\psi_{qs}^s = \int (\tilde{v}_{qs}^s - R_s \tilde{i}_{qs}^s) dt \quad (16)$$

$$|\tilde{\psi}_s| = \sqrt{\tilde{\psi}_{ds}^s{}^2 + \tilde{\psi}_{qs}^s{}^2} \quad (17)$$

$$\cos \tilde{\theta}_e = \frac{\tilde{\psi}_{ds}^s}{|\tilde{\psi}_s|}; \sin \tilde{\theta}_e = \frac{\tilde{\psi}_{qs}^s}{|\tilde{\psi}_s|} \quad (18)$$

where $\tilde{\theta}_e$ is the stator flux angle with respect to the q-axis of the stationary d-q frame.

B. Estimation of Torque: The electromagnetic torque can be expressed in terms of stator currents and stator flux as follows:

$$\tilde{T}_e = \frac{3P}{4} (\tilde{\psi}_{ds}^s \tilde{i}_{qs}^s - \tilde{\psi}_{qs}^s \tilde{i}_{ds}^s) \quad (19)$$

C. Estimation of Synchronous Speed & Rotor Speed:

The synchronous speed ω_e can be calculated from the expression of the angle of stator flux as:

$$\tilde{\omega}_e = \tan^{-1} \frac{\tilde{\psi}_{ds}^s}{\tilde{\psi}_{qs}^s} \quad (20)$$

$$\tilde{\omega}_r = \frac{d\tilde{\theta}_e}{dt} \quad (21)$$

To obtain the rotor speed ω_r , simple slip compensation can be derived using the steady-state torque speed curve for the machine being used.

$$\tilde{\omega}_{sl} = K_s \tilde{T}_e \quad (22)$$

Where K_s is the rated slip frequency/rated torque and it can be derived from the name plate of the machine. Alternately, if the rotor flux ψ_r is assumed as constant, the slip speed can also be calculated as:

$$\tilde{\omega}_{sl} = \frac{R_r \tilde{i}_{qs}^s}{L_r \tilde{i}_{ds}^s} \quad (23)$$

The rotor speed is given by,

$$\tilde{\omega}_r = \tilde{\omega}_e - \tilde{\omega}_{sl} \quad (24)$$

3. PROPOSED CONTROL STRATEGY:

Majority of IM drives are of open-loop, constant-v/f, voltage source-inverter type. These drives are cost effective but they offer sluggish response. Due to high current transients during the torque changes, they are subject to undesirable trips. To avoid the un-necessary trips, the control parameters like acceleration/deceleration rate has to be adjusted (reduced) according to the load. This results in underutilization of torque capability of the motor. Thus the drawback of v/f drive can be attributed to lack of torque control. This is the reason why open-loop, constant-v/f drives are mostly used in low performance fan and pump type loads. In this paper, we propose a modified control scheme that includes the torque control and a current regulated PWM inverter to avoid the undesirable trips due to transient currents.

As shown in Fig.2, the feedback signals i.e. torque and rotor speed are obtained from the dc link quantities and hence from the reconstructed line currents and phase voltages. The accuracy of reconstructed waveforms depends upon the sampling rate. Higher the sampling rate less is the error between the actual and reconstructed waveforms. In a hard switching inverter, the switching frequency is limited to a typical value of a few kHz. This limits the sampling rate of dc current and hence the update rate of torque and rotor speed. Consequently, closing the loop directly on the instantaneous value of the estimated torque now becomes difficult because estimation error during a PWM cycle could become significantly high. In order to use the estimated torque in a more robust manner, a control strategy should use the averaged torque instead of the instantaneous value. This leads to the control strategy depicted in Fig.2. In this system, two PI controllers are used to regulate the average value of torque and speed. The output of the P-I regulators forms the q-axis reference in a synchronously rotating reference frame.

III. SIMULATION CIRCUIT:

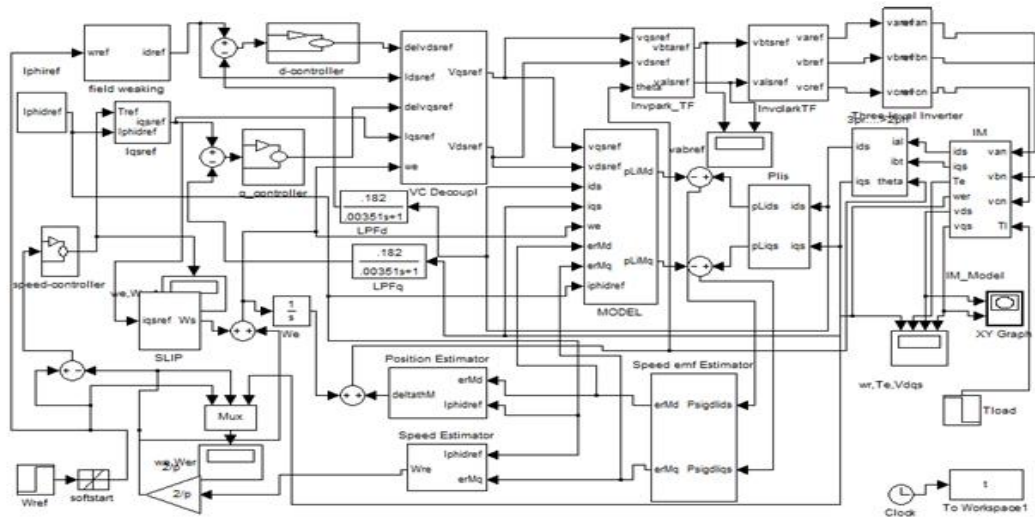


Figure 4: Simulink model of control strategy

IV. SIMULATION RESULTS:

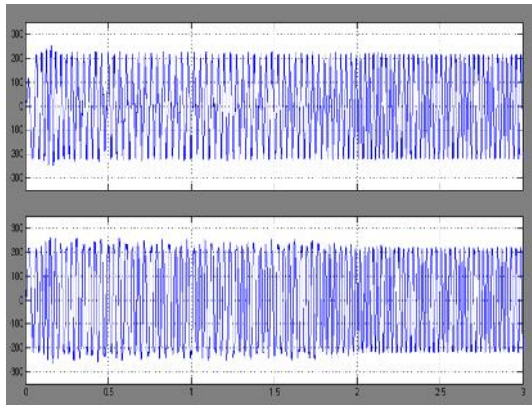


Fig 5: (a) three phase voltages and (b) three line currents separated from the dc link current

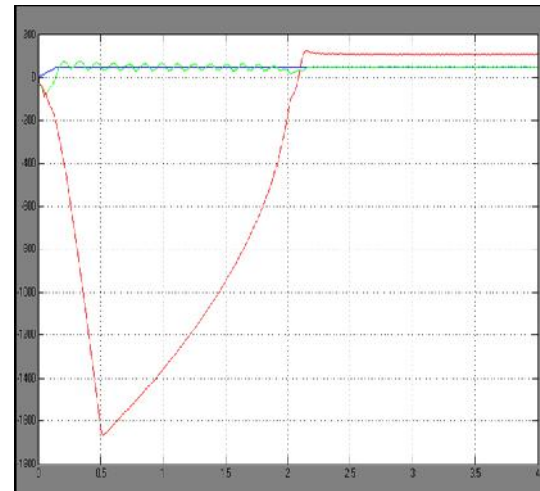


Fig 7: Free-acceleration characteristics of W_e , W_{er}

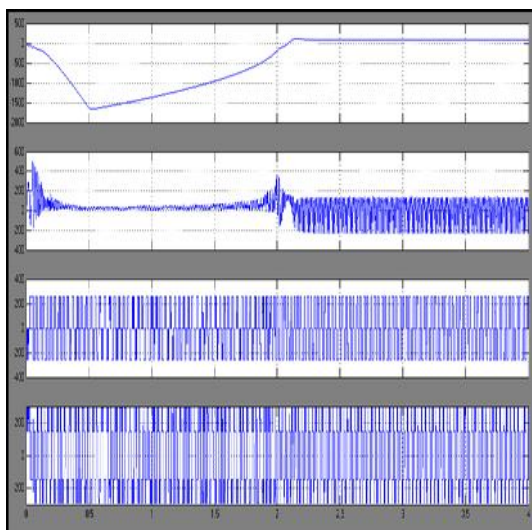


Fig 6: Variation in rotor speed and electro-magnetic torque for step changes in reference speed and three phase voltage, currents

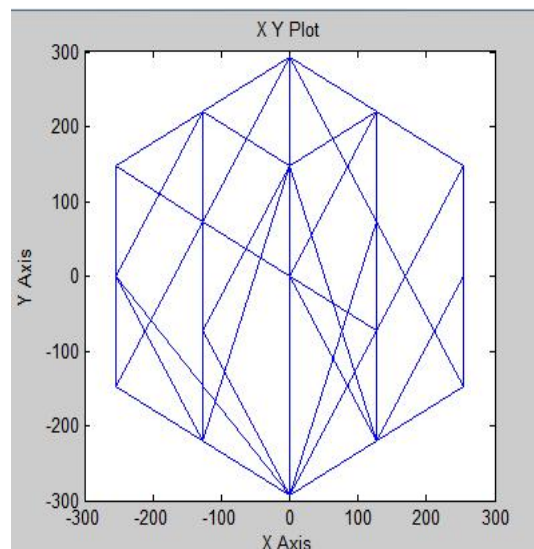


Fig 8: XY plot

V. CONCLUSION:

This paper represents a new control strategy for three-phase induction motor which includes independent speed & torque control loops and the current regulation thereby overcoming the limitation of volts per hertz controlled industrial drives. The controlled induction motor drives without mechanical speed sensors at the motor shaft have the attractions of low cost and high reliability. The drive is operated under torque control with an phase voltages, line currents, flux, torque and rotor speed. If the dc link voltage is assumed as constant, only one current sensor in the dc link is sufficient to give the estimates of all required feedback variables. Moreover, the same current sensor that is already available in the dc link of an open-loop v/f drive for protection purpose can be used. Thus the open-loop control strategy in an existing v/f drive can be replaced by the proposed close-loop control strategy without requiring any additional power components or the physical sensors.

The proposed strategy appears to be a good compromise between the high-cost, high-performance field-oriented drives and the low-cost, low-performance v/f drives.

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