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Sensorless Speed Control of 3-Phase Induction Motors by using several techniques

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Abstract: In this paper, a sensorless controller for induction motor is presented. Induction motors derive their name from the way the rotor magnetic field is created. The rotating stator magnetic field induces currents in the short circuited rotor. These currents produce the rotor magnetic field, which interacts with the stator magnetic field, and produces torque, which is the useful mechanical output of the machine. The three phase squirrel cage AC induction motor is the most widely used motor. The bars forming the conductors along the rotor axis are connected by a thick metal ring at the ends, resulting in a short circuit as shown in Figure 1. The sinusoidal stator phase currents fed in the stator coils create a magnetic field rotating at the speed of the stator frequency (ωs). The changing field induces a current in the cage conductors, which results in the creation of a second magnetic field around the rotor wires. As a consequence of the forces created by the interaction of these two fields, the rotor experiences a torque and starts rotating in the direction of the stator field. The authors have concluded the various techniques of Sensor less Control of Induction Motors. Full-order model of the induction motor is considered and no simplifying assumptions on the speed dynamics (as negligibility of the speed time-derivative) are introduced. The load torque is assumed constant but unknown.

I. INTRODUCTION

Making an induction or asynchronous motor is an AC electric motor in which the electric current in the rotor needed to produce torque is obtained by electromagnetic induction from the magnetic field of the stator winding. An induction motor therefore does not require mechanical commutation, separate-excitation or self-excitation for all or part of the energy transferred from stator to rotor, as in universal, DC and large synchronous motors. An induction motor's rotor can be either wound type or squirrel-cage type.

Three-phase squirrel-cage induction motors are widely used in industrial drives because they are rugged, reliable and economical. Single-phase induction motors are used extensively for smaller loads, such as household appliances like fans. Although traditionally used in fixed-speed service, induction motors are increasingly being used with variable-frequency drives (VFDs) in variable-speed service. VFDs offer especially important energy savings opportunities for existing and prospective induction motors in variable-torque centrifugal fan, pump and compressor load applications. Squirrel cage induction motors are very widely used in both fixed-speed and VFD applications.

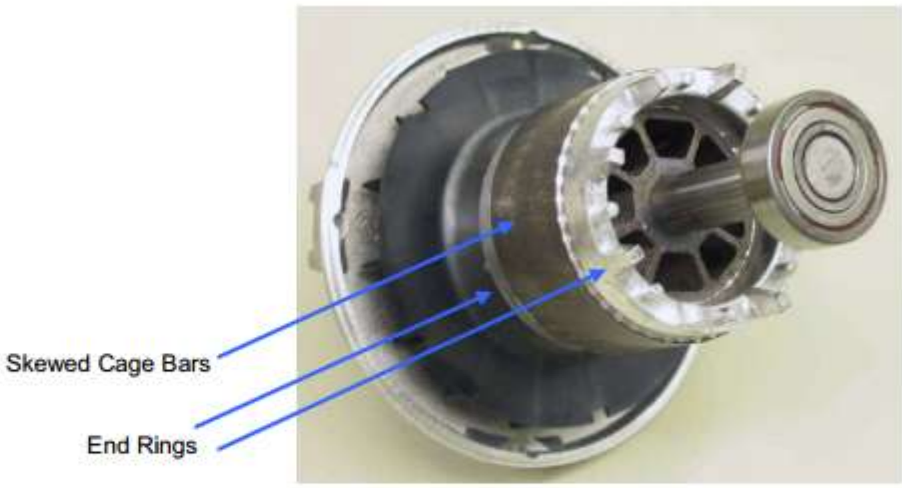

Figure 1: Induction Motor Rotor

As the rotor begins to speed up and approach the synchronous speed of the stator magnetic field, the relative speed between the rotor and the stator flux decreases, decreasing the induced voltage in the stator and reducing the energy converted to torque. This causes the torque production to drop off, and the motor will reach a steady state at a point where the load torque is matched with the motor torque. This point is an equilibrium reached depending on the instantaneous loading of the motor. In brief:

- Since the induction mechanism needs a relative difference between the motor speed and the stator flux speed, the induction motor rotates at a frequency near, but less than, that of the synchronous speed.
- This slip must be present, even when operating in a field-oriented control regime.
- The rotor in an induction motor is not externally excited. This means that there is no need for slip rings and brushes. This makes the induction motor robust, inexpensive and need less maintenance.
- Torque production is governed by the angle formed between the rotor and the stator magnetic fluxes.

In Figure 2 the rotor speed is denoted by Ω. Stator and rotor frequencies are linked by a parameter called the slip s, expressed in per unit as $s = (\omega s - \omega r) / \omega s$

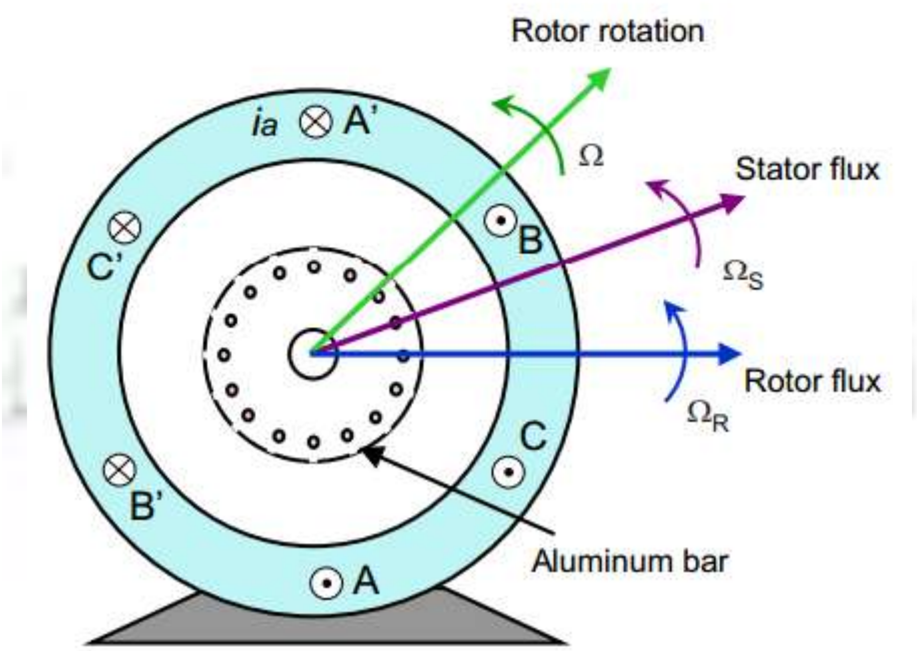

Figure 2: Squirrel Cage Rotor AC Induction Motor Cutaway View

High performance drives based on induction motor (IM) can be implemented by means of a speed/flux controller which relies on field orientation concepts [1, 7]. This control algorithm is an output feedback controller based on the measured currents and rotor speed/position, normally obtained with a shaft encoder. The position sensor reduces the robustness and reliability of the IM drive and increases its cost. Hence, in recent years speed sensorless controllers for IM (i.e. without the speed/position measure) have become an attractive task from the industrial perspective and as a benchmark for different nonlinear control techniques. In recent years, the vector control theory has been receiving much attention because of the better steady and dynamic performance over conventional control methods in controlling motors torque and speed. In various vector control schemes, the speed sensorless vector control has been a relevant area of interest for many researchers due to its low drive cost, high reliability and easy maintenance. There are two main parameters which are required in speed sensorless vector control of induction motor, those are, the motor flux and speed estimation. These parameters are necessary for establishing the outer speed loop feedback and also in the flux and torque control algorithms. . In order to get good performance of sensorless vector control, different speed estimation methods have been proposed. Such as direct calculation method, model reference adaptive system(MRAS), Observers (extended Kalman filter, luenberger etc), Estimators using artificial intelligence etc .

Out of various speed estimation methods, MRAS-based speed sensorless estimation has been commonly used in AC speed regulation systems due to its good performance and ease of implementation. In order to design MRAS for sensorless speed estimation, first we have to model the induction motor. In induction motor, inputs to motor are stator currents and voltages and output is rotor speed. That's why while choosing reference model for MRAS, we have to form rotor flux equation in the form of stator side parameters. In adaptive model, speed is the adaptive parameter.

II. INDUCTION MOTOR MODEL

In an arbitrary reference frame, the induction motor model is described by the equations below:

$$\vec{v}_s = R_s\vec{i}_s + \dot{\vec{\lambda}}_s + j\omega_e\vec{\lambda}_s \qquad (1)$$

$$\vec{0} = R_r\vec{i}_r + \dot{\vec{\lambda}}_r + j(\omega_e - \omega_r)\vec{\lambda}_r \qquad (2)$$

$$\vec{\lambda}_s = L_s\vec{i}_s + L_m\vec{i}_r \qquad (3)$$

$$\vec{\lambda}_r = L_m\vec{i}_s + L_r\vec{i}_r \qquad (4)$$

where

$\vec{v}_s$	Stator voltage vector (V)
$\vec{i}_s$, $\vec{i}_r$	Stator and rotor current vectors (A)
$\vec{\lambda}_s$, $\vec{\lambda}_r$	Stator and rotor flux vectors
L_s, L_r, L_m	Stator, rotor and mutual inductances (H)
R_s, R_r	Stator and rotor resistances (Ω)
ω_e, ω_r	Reference frame and rotor speeds (elect. rad/s)

III. REVIEW OF SENSORLESS STRATEGIES

In this section, some of the methods based on the dq model for speed estimation in sensorless induction motor drives will be presented and discussed. A. Speed Calculation from State-Space Equations Two of these methods will be presented. In the first one [4], the rotor flux vector is first estimated. In order to make the flux computation independent from the speed, the stator voltage equation (voltage model) in a stator fixed reference frame is usually preferred:

$$\vec{\lambda}_r = \frac{L_r}{L_m}\left[\int\left(\vec{v}_s - R_s\vec{i}_s\right)dt - \sigma L_s\vec{i}_s\right] \qquad (5)$$

where σ is the leakage coefficient.

Rotor equation (2) can then be used to obtain rotor speed.

$$\omega_r = \begin{cases} -\dfrac{\dfrac{\lambda_{rd}}{\tau_r} - \dfrac{L_m}{\tau_r}i_{sd} + \dot{\lambda}_{rd}}{\lambda_{rq}} \\[2ex] \dfrac{\dfrac{\lambda_{rq}}{\tau_r} - \dfrac{L_m}{\tau_r}i_{sq} + \dot{\lambda}_{rq}}{\lambda_{rd}} \end{cases} \qquad (6)$$

The author proposed the use of the first equation only to estimate the speed. It should be noted however that the d and q axis flux components will be generally sinusoidal quantities. Thus, in order to avoid dividing by zero, we suggest using the second equation whenever

$$|\lambda_{rd}| > |\lambda_{rq}|.$$

For low speed operation, when the frequency is also low, the integral in Eqn. is difficult to implement due to offsets and drifts. A filter is often implemented to allow the strategy to be used in moderate and high speeds. A good measuring scheme, such as the one presented in the next section can be used to reduce the minimum speed for which the method can be applied. Fig. 1 shows simulation results in low and high-speed operation of a sensorless drive with this strategy. No offsets or drifts in the measured signals were considered. The stator voltage was considered to be measured by using the scheme described in the next section. The good results show that it is ideally possible to implement a sensorless induction motor drive for zero speed operation, since the offsets and drift problems are solved for the integral in Eqn. to be stable. Another alternative to calculate flux and speed from the induction motor equations can be derived from the stator flux vector speed and slip speed expressions.

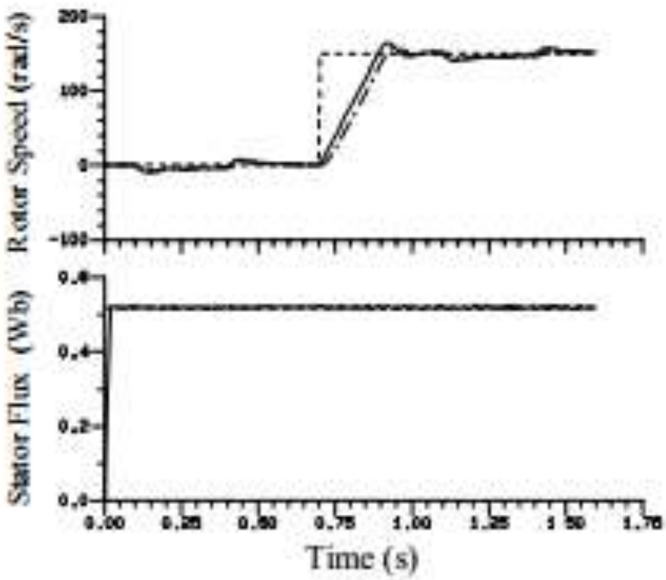

Fig. 3: Sensorless strategy according to eqn. 5 & 6

$$\omega_e = \frac{\lambda_{sd}\dot{\lambda}_{sq} - \lambda_{sq}\dot{\lambda}_{sd}}{\lambda_{sd}^2 + \lambda_{sq}^2} \qquad (7)$$

$$\omega_s = \frac{L_m}{\tau_r}\frac{\lambda_{sd} i_{sq} - \lambda_{sq} i_{sd}}{\lambda_{sd}^2 + \lambda_{sq}^2} \qquad (8)$$

Rotor speed is obtained by subtracting Eqn. The same problems associated to the low frequency integration necessary to compute the stator flux vector arise here. Simulation results without considering dc errors in the measuring signals are presented in Fig. 2. The results show again that the flux and speed calculation scheme would suffice, even for low speed operation, if no dc measurement errors were present. For high-speed operation the velocity became oscillatory and a digital filter was used.

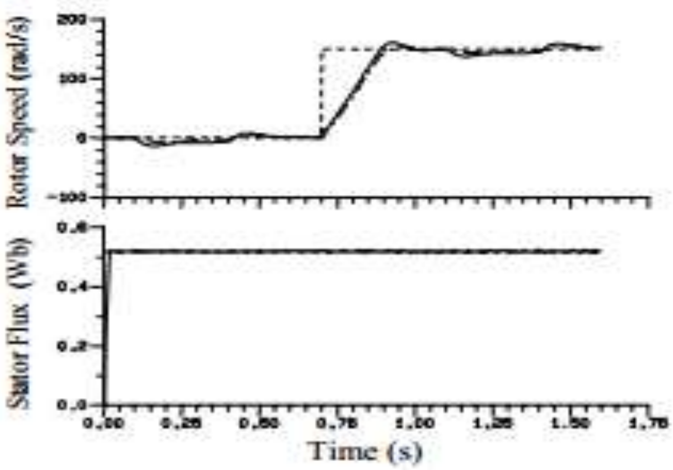

Fig. 4: Sensorless strategy using Eqs (7) and (8)

Model Reference Adaptive Systems (MRAS) techniques were applied in order to estimate rotor speed. Schauder used the induction motor voltage model as in Eqn. (5), and the current model, derived from the rotor equation, to obtain two estimates for the rotor flux. The voltage model was considered to be the reference, once it does not depend on the speed. Then, from the two rotor flux estimates, an adaptive mechanism to generate the rotor speed to be used in the current model was developed. The current model and the adaptive mechanism are described by Eqns. (9) and (10) below.

$$\dot{\vec{\lambda}}_r = -\left(\frac{1}{\tau_r} - j\omega_r\right)\vec{\lambda}_r + \frac{L_m}{\tau_r}\vec{i}_s \qquad (9)$$

$$\hat{\omega}_r = k_p\left(\hat{\vec{\lambda}}_r^v \times \hat{\vec{\lambda}}_r^i\right) + k_i\int\left(\hat{\vec{\lambda}}_r^v \times \hat{\vec{\lambda}}_r^i\right)dt \qquad (10)$$

Simulation results using this speed estimation technique are shown in Fig. 3.

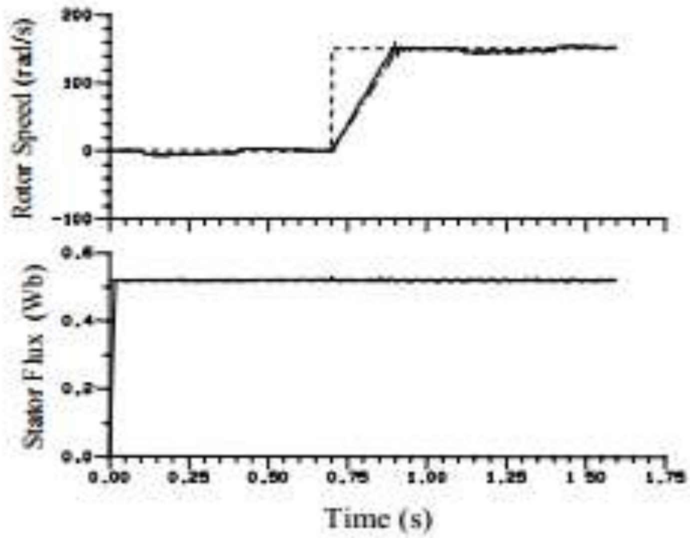

Fig. 5: Simulation results. Sensorless strategy according to Schauder

All the alternatives presented make use of the voltage model in some way for the speed estimation and have problems for low speed operation. Other techniques for speed estimation have been proposed recently. Rotor position and velocity can be estimated by injecting a high frequency signal in the machine terminals and tracking the rotor magnetic saliencies [8]. In a wye connected machine, the sum of the three stator voltages is dominated by the third harmonic component and a high frequency rotor slot ripple. Assuming a balanced operation, it can be shown [9], [10] that the amplitude and position of the air gap flux can be obtained from the third harmonic air gap voltage. In low speed operation, however, the signal/noise relation is very low and the third harmonic voltage is difficult to be precisely measured.

DIRECT VECTOR CONTROL

The direct vector control depends on the generation of unit vector signals from rotor flux signals. The principle vector control parameters ids*, and iqs* , which are dc values in synchronously rotating frame, are converted to stationary frame with the help of a unit vectors cosθe and sinθe which are generated from flux vector signals .The resulting stationary frame signals are then converted to phase current commands for the inverter. The flux signals and are generated from the machine terminal voltages and currents.

$$\Psi_{dr}^{s} = \hat{\Psi}_r \cos\theta_e, \quad \Psi_{qr}^{s} = \hat{\Psi}_r \sin\theta_e$$

$$\cos\theta_e = \frac{\Psi_{dr}^{s}}{\Psi_r}; \quad \sin\theta_e = \frac{\Psi_{qr}^{s}}{\Psi_r}$$

Eqn. (11) & (12)

Where vector Ψr is represented by magnitude r ^Ψ the unit vector signals (cosθe and sinθe), when used for vector rotation. The generation of a unit vector signal from feedback flux vectors gives the name "direct vector control. The schematic diagram of control strategy of induction motor with sensor less control is shown in Sensor less control induction motor drive essentially means vector control without any speed sensor [5]. The inherent coupling of motor is eliminated by controlling the motor by vector control, like in the case of as a separately excited motor. The inverter provides switching pulses for the control of the motor. The flux and speed estimators are used to estimate the flux and speed respectively. These signals then compared with reference values and controlled by using the PI controller.

FIELD ORIENTED CONTROL (VECTOR CONTROL)

A simple control such as the V/Hz strategy has limitations on the performance. To achieve better dynamic performance, a more complex control scheme needs to be applied, to control the induction motor. With the mathematical processing power offered by the microcontrollers, we can implement advanced control strategies, which use mathematical transformations in order to decouple the torque generation and the magnetization functions in an AC induction motor. Such decoupled torque and magnetization control is commonly called rotor flux oriented control, or simply Field Oriented Control (FOC).

In order to understand the spirit of the Field Oriented Control technique, let us start with an overview of the separately excited direct current (DC) Motor. In this type of motor, the excitation for the stator and rotor is independently controlled. An electrical study of the DC motor shows that the produced torque and the flux can be independently tuned. The strength of the field excitation (the magnitude of the field excitation current) sets the value of the flux. The current through the rotor windings determines how much torque is produced. The commutator on the rotor plays an interesting part in the torque production. The commutator is in contact with the brushes, and the mechanical construction is designed to switch into the circuit the windings that are mechanically aligned to produce the maximum torque. This arrangement then means that the torque production of the machine is fairly near optimal all the time. The key point here is that the windings are managed to keep the flux produced by the rotor windings orthogonal to the stator field.

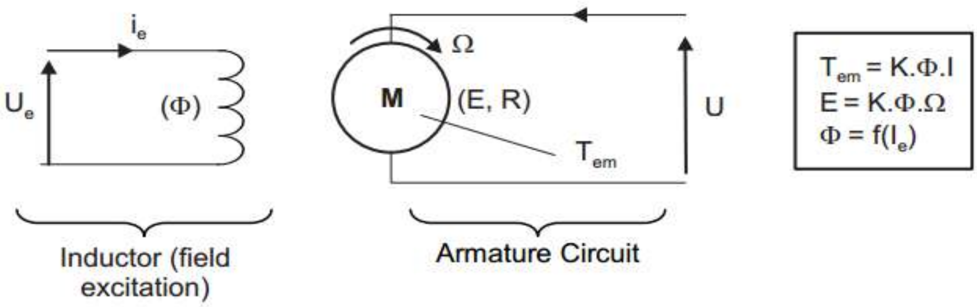

Figure 6: Separated Excitation DC Motor Model

SENSORLESS CONTROL USING MODEL REFERENCE ADAPTIVE SYSTEM (MRAS)

In various vector control schemes, the speed sensorless vector control has been a relevant area of interest for many researchers due to its low drive cost, high reliability and easy maintenance. There are two main parameters which are required in speed sensorless vector control of induction motor, those are, the motor flux and speed estimation. These parameters are necessary for establishing the outer speed loop feedback and also in the flux and torque control algorithms. . In order to get good performance of sensorless vector control, different speed estimation methods have been proposed. Such as direct calculation method, model reference adaptive system (MRAS), Observers (extended Kalman filter, luenberger etc), Estimators using artificial intelligence etc .
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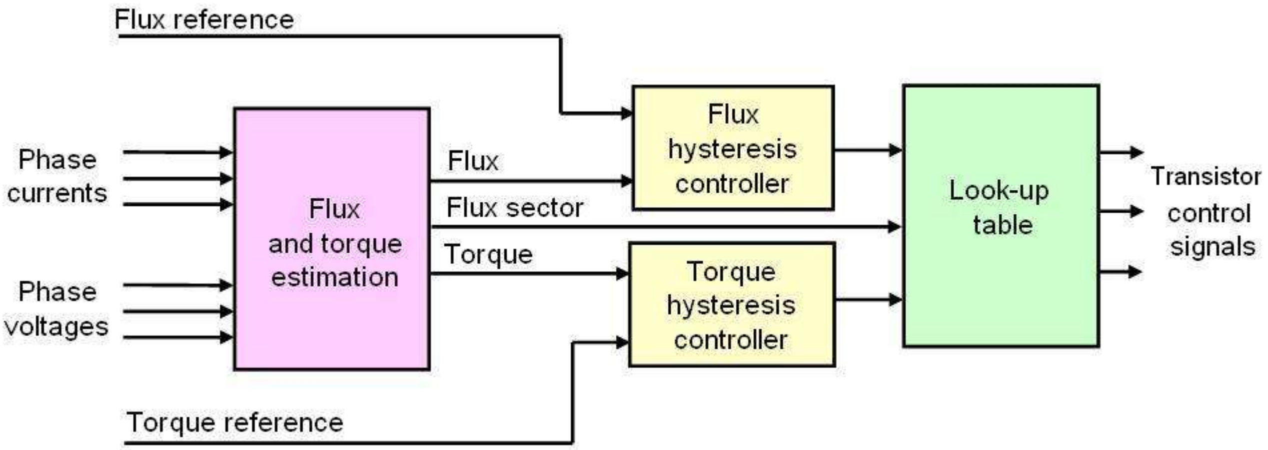
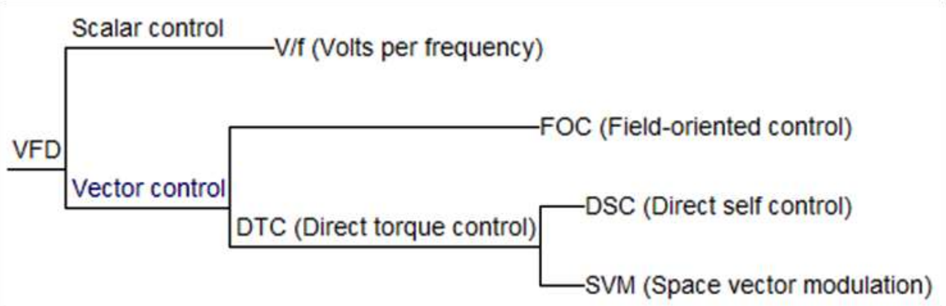
DIRECT TORQUE CONTROL

Direct torque control (DTC) is one method used in variable frequency drives to control the torque (and thus finally the speed) of three-phase AC electric motors. This involves calculating an estimate of the motor's magnetic flux and torque based on the measured voltage and current of the motor.
Stator flux linkage is estimated by integrating the stator voltages. Torque is estimated as a cross product of estimated stator flux linkage vector and measured motor current vector. The estimated flux magnitude and torque are then

compared with their reference values. If either the estimated flux or torque deviates from the reference more than allowed tolerance, the transistors of the variable frequency drive are turned off and on in such a way that the flux and torque errors will return in their tolerant bands as fast as possible. Thus direct torque control is one form of the hysteresis or bang-bang control.



Overview of key competing VFD control platforms:



In vector control, an AC induction or synchronous motor is controlled under all operating conditions like a separately excited DC motor. That is, the AC motor behaves like a DC motor in which the field flux linkage and armature flux linkage created by the respective field and armature (or torque component) currents are orthogonally aligned such that, when torque is controlled, the field flux linkage is not affected, hence enabling dynamic torque response.

Vector control accordingly generates a three-phase PWM motor voltage output derived from a complex voltage vector to control a complex current vector derived from motor's three-phase motor stator current input through projections or rotations back and forth between the three-phase speed and time dependent system and these vectors' rotating reference-frame two-coordinate time invariant system.

CONCLUSIONS

In this manuscript, the authors concluded that the Sensorless control gives the benefits of Vector control without using any shaft encoder. In this paper, the principle of vector control and Sensorless control of induction motor are given elaborately. The proposed techniques for induction motor provides local exponential speed tracking and flux regulation proven by means of direct methods, Field Oriented Control, MRAS, Direct Torque Control, Direct Vector Control and the similar techniques. Simulation results show that the controller is effective to track the reference speed and to reject the applied load torque even if relevant errors on the mechanical model are present. In order to achieve these results the only significant requirement is to impose a non null flux reference. This fact is in accordance with the “induction motor physics”: the machine must be excited to produce torque. No restrictions on the speed reference and the load torque are present. This is a very relevant feature since it indicates that the system could work in any condition, provided sufficiently small initial error. It is worth noting that this result seems achievable only if exact knowledge of the fluxes is assumed, i.e. the fluxes are obtained by pure integration of stator equation with known initial conditions, in fact there exist conditions where different speed-flux trajectories are not distinguishable from voltage-current behavior. Anyway it is well known that, from a practical perspective, obtaining reliable pure integration of the stator equations is a very involved task, in particular in condition of constant voltages and currents.

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