COMPARISON OF SCALAR AND VECTOR CONTROL STRATEGIES OF INDUCTION MOTORS

G. Kohlrusz[✉], D. Fodor

University of Pannonia, Faculty of Engineering, Institute of Mechanical Engineering,
Automotive Systems Engineering Group, H-8200, Veszprem, Egyetem str. 10., HUNGARY
[✉]E-mail: kohlrusz.gabor@chello.hu

Currently the use of three-phase induction machines is widespread in industrial applications due to several methods available to control the speed and torque of the motor. Many applications require that the same torque be available at all revolutions up to the nominal value.

In this paper two control methods are compared: scalar control and vector control. Scalar control is a relatively simple method. The purpose of the technique is to control the magnitude of the chosen control quantities. At the induction motor the technique is used as Volts/Hertz constant control. Vector control is a more complex control technique, the evolution of which was inevitable, too, since scalar control cannot be applied for controlling systems with dynamic behaviour. The vector control technique works with vector quantities, controlling the desired values by using space phasors which contain all the three phase quantities in one phasor. It is also known as field-oriented control because in the course of implementation the identification of the field flux of the motor is required.

This paper reports on the changing possibilities of the revolution – torque characteristic curve, and demonstrates the results of the two control methods with simulations. The simulations and the applied equivalent circuit parameters are based on real measurements done with no load, with direct current and with locked-rotor.

Keywords: speed-torque characteristics, scalar control, vector control, Volts/Hertz constant control, field-oriented control.

Introduction

The control methods for induction motors can be divided into two parts: vector control and scalar control strategies. In this research on three phase squirrel-cage induction motors the closed loop Volts/Hertz voltage-fed inverter drive as scalar control technique and the rotor flux oriented control with voltage-fed inverter drive as vector control technique were compared.

Speed changing opportunities of induction motors

Many applications require that the speed of the motor be variable without changing the torque. The speed of induction motors can be changed in three different ways [1]:
– changing the number of pole pairs,
– vary the magnitude of supplied voltage or
– vary the frequency of the supplied voltage.

Changing the number of pole pairs causes huge curve shifting, and varying the magnitude of supplied voltage gives solution only in a small range.

The most promising possibility to change the speed of the motor is the varying of the frequency *(Fig. 1)*.

However, this is not the best solution, because the impedances increase and the currents decrease with growing frequency.
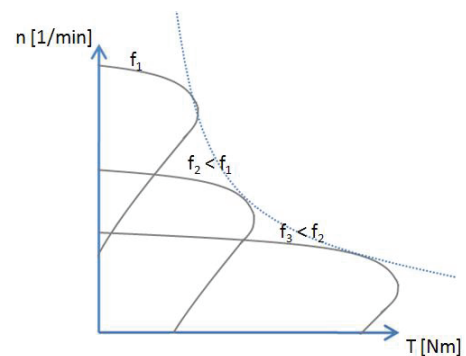

Figure 1: Speed vs. torque curves as functions of frequency

Current can also be controlled by voltage. This offers a possibility of control through both the voltage and the frequency changing.

This idea was the basis of the evolution of a control method which is capable of controlling both speed and torque of induction motors, the so-called Volts/Hertz constant method.

Basics of scalar control

The scalar control method is based on varying two parameters simultaneously. The speed can be varied by increasing or decreasing the supply frequency, but this results in change of impedances. The change of impedances eventuates the increase or decrease of current. If the current is small, the torque of motor decreases. If the frequency decreases or the voltage increases, the coils can be burned or saturation can occur in the iron of coils. To avoid these problems, it is necessary to vary the frequency and the voltage at the same time. In this way, the occurring disadvantages of changing frequency and voltage can be compensated. According to the equation of induced voltage the V/Hz constant control gives constant flux in the stator (Eq. 1).

$$\frac{V_{e,RMS}}{f} = 4.44 \cdot N \cdot \psi_s \cdot \xi \tag{1}$$

where

$V_{e,RMS}$ – the induced voltage in the stator,
f – the frequency of the supplied voltage,
N – the number of turns,
Ψ_s – magnetic flux-linkage in the stator,
ξ – constant of coil.

The torque–speed equation of induction motors (Eq. 2) can be used to determine the voltage–torque and frequency–torque functions [2].

$$T_{air-gap} = \frac{3}{2\omega_m} I_r^2 \frac{R_r}{s} \tag{2}$$

where

$T_{air\text{-}gap}$ – the torque of the motor in the air-gap,
ω_m – the mechanical angular speed,
I_r – the rotor current,
R_r – the resistance of rotor,
s – the slip.

It can be seen from equation (2) that the relationship between torque and frequency is inverse, while voltage is directly proportional to torque.

Torque–speed control can be solved by the linear variaton of the two parameters (Eq. 3).

$$\frac{T}{\omega} \sim \frac{V^2}{2\pi \cdot f^2} \sim \frac{V}{f} \tag{3}$$

With this control method the torque is accessible in all operating points up to the nominal value of speed and the motor can operate over the nominal speed *(Fig. 2)*.

In the overspeed range, the torque of the motor will decrease in inverse proportion to the increasing frequency because voltage cannot be higher than the value at which the driver electronics is able to operate [3].
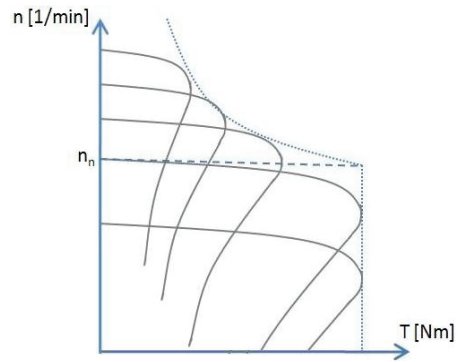

Figure 2: Torque-speed curves with V/Hz constant control

Open-loop scalar control

The open-loop Volts/Hertz control of induction motors is widely used in industry *(Fig. 3)*. For this strategy, feedback signals are not required. This type of motor control has some advantages:
– low cost,
– simplicity and
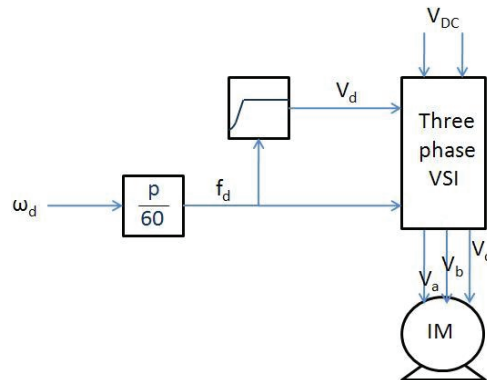– immunity to errors of feedback signals.

Figure 3: Open-loop V/Hz constant control

Closed-loop scalar control

The closed-loop method offers a more precise solution to controlling the speed than the open-loop method. Furthermore, the closed-loop technique controls the torque, too. A major disadvantage of the open-loop control method is that this technique does not control the torque, so the desired torque is only accessible at the nominal operating point. If the load torque changes, the speed of the motor will change, too [4].

The closed-loop method contains a slip control loop, because the slip is proportional to the torque. The speed feedback signal from the tachogenerator is compared to the desired speed value. The difference is decreased to zero by the PI controller, so the motor will reach the desired speed.

Typical applications of this method are in the winder drives [5]. A disadvantage of the method is uncontrolled magnetic flux.
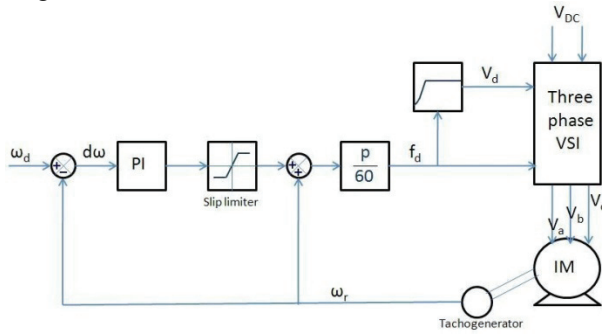

Figure 4: Closed-loop V/Hz constant control

There are some methods which use current control. Current controlling solves the problem of uncontrolled flux, but these methods are more complex, e.g. in the case of current regulated voltage-fed inverter drive.

Vector control method

Field oriented control is one of the vector control methods. There are other well-known methods like direct torque control and direct self-control that work with vectors, as well. The field oriented control ensures good and robust control in case of transients.

Field oriented control is based on a mathematical abstraction. This results in an easier model conformation which corresponds the structure of well-controllable DC machine.

The principle of field oriented control works with rotating vectors (or phasors) in a complex coordinate system. The magnitude and the phase of the controlled current change.

With this technique, it is possible to uncouple the field components. Uncoupling establishes two independent and single controlled currents: the flux- producing current and the torque-producing current. Using these currents, the flux and torque can be independently controlled. Moreover, a 90° electric angle is ensured between the uncoupled control currents. As a result, the model of the induction motor loses its complexity, and a high-performance drive can be realized [6].

Field oriented control can be carried out by system- and coordinate transformations of the basic equations of the motor. After applying the transformations the alternating and sinusoidal quantities become non-alternating quantities. Due to uncoupling, the currents can be controlled, and then, after back-transformation it is possible to modify the output of the inverter with three-phase quantities. In this way the magnitude and phase of supplied voltage or current can be modified.

The quantities of the motor are described with a space phasor or a Park-vector (Eq. 4) in a three-phase coordinate system [7].

$$\bar{u} = \frac{2}{3}\left(u_a + \bar{a}u_b + \bar{a}^2 u_c\right) \tag{4}$$

The equations which are valid instantenously can be described from the general voltage and flux phasors of the motor (Eqs. 5 ,6 ,7, 8). It is possible to divide the equations into two parts. The stator equations are valid in the coordinate system fixed to the stator, and the rotor equations are valid in the coordinate system fixed to the rotor [8, 9].

$$\bar{v}_s = \bar{i}_s \cdot R + \frac{d\bar{\psi}_s}{dt} \tag{5}$$

$$\bar{v}_r = \bar{i}_r \cdot R + \frac{d\bar{\psi}_r}{dt} \tag{6}$$

$$\bar{\psi}_s = \bar{i}_s \cdot L_s + \bar{i}_r \cdot e^{j\theta} \cdot L_m \tag{7}$$

$$\bar{\psi}_r = \bar{i}_r \cdot L_r + \bar{i}_s \cdot e^{-j\theta} \cdot L_m \tag{8}$$

where

v_r, v_s – the supplied voltage in rotor and in stator,
i_r, i_s – the current in rotor and in stator,
R – resistance of stator and rotor coils,
Ψ_r, Ψ_s – magnetic flux-linkage in rotor and in stator,
L_r, L_s, L_m – inductance of stator coil, of rotor coil and of the air-gap.

It is necessary to determine the electromagnetic torque to get the equation-of-motion of the motor (Eq. 9) [7].

$$\bar{T}_e = \frac{3}{2}\bar{\psi}_r \bar{i}_r \sin\varphi = -\frac{3}{2}\bar{\psi}_r \times \bar{i}_r \tag{9}$$

where

T_e – the electromagnetic torque of motor,
Ψ_r – the magnetic flux-linkage in rotor,
i_r – the current in rotor.

The purpose is the conversion into a two-phase coordinate system. After this, both the stator and rotor quantities need to be transformed into a common coordinate system. Then, calculations become executable and so the control signals (e.g. currents) are generated *(Fig. 5)*. The system transformation can be performed by the transformation matrix. This calculation results in a real and an imaginary part of the space-phasor. After transformation the equations (5)-(8) become two-phase quantities and need to be handled in a two-phase, complex α-β coordinate system [9, 10].

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \frac{2}{3} \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix}$$

It is expedient to transform the complex, two-phase quantities into a common coordinate system, which is expediently the synchronously rotating d-q coordinate system. As a result of this transformation, the sinusoidal quantities become non-alternating quantities.

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} \cos\rho & \sin\rho \\ -\sin\rho & \cos\rho \end{bmatrix} \cdot \begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix}$$

After transformations the quantities have to be handled uncoupled to their d and q components.

It is desirable to control the torque and speed. To achieve rotor flux orientation it is necessary to orient the rotor flux vector to the d axis of the d-q synchronous rotating coordinate system (Fig. 5). Then the d directional component of current can control the rotor flux, while the q directional component controls the torque.
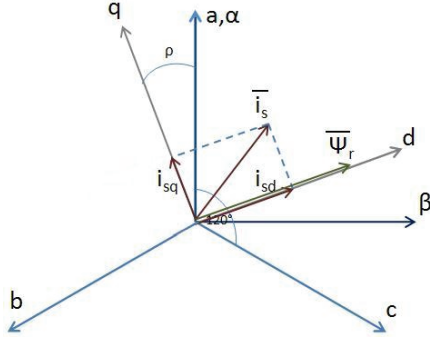

Figure 5: System and coordinate transformation

The equation of torque gets also transformed (Eq. 10).

$$\overline{T} = \frac{3}{2} \cdot p \cdot \psi_{rd} \cdot i_{sq} \tag{10}$$

The reduction of the rotor quantities to the stator gives a simpler model, which is the gamma-model *(Fig. 6)*. Due to this model, the equivalent circuit diagram of the motor can be created [11].
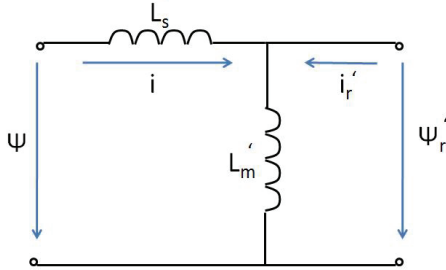

Figure 6: Gamma-model with reduced values

From the uncoupling to d-q components of equations (5)-(8) and from the equation of torque (Eq. 10) it is possible to describe the equations of the motor based on the gamma-model (Eqs. 11-15).

$$\frac{di_{sd}}{dt} = \frac{1}{L_{\sigma s}}\left(u_{sd} - i_{sd} \cdot R_s - \frac{d\psi_{rd}}{dt}\right) + \omega_k \cdot i_{sq} \tag{11}$$

$$\frac{di_{sq}}{dt} = \frac{1}{L_{\sigma s}}\left(u_{sq} - i_{sq} \cdot R_s - \omega_k \cdot \psi_{rd}\right) - \omega_k \cdot i_{sd} \tag{12}$$

$$\psi_{rd} + \tau \frac{d\psi_{rd}}{dt} = L_m \cdot i_{sd} \tag{13}$$

$$\omega_k - \omega_r = \omega_s = \frac{R \cdot i_{sq}}{\psi_{rd}} \tag{14}$$

$$\frac{d\omega_r}{dt} = \frac{3}{2}\frac{p}{J}\psi_{rd} \cdot i_{sq} - \frac{m_l}{J} - \frac{B \cdot \omega}{J} \tag{15}$$

where

i_{sd}, i_{sq} – d and q components of stator current,
$L_{\sigma s}$ – inductance of stator without mutual inductance,
u_{sd}, u_{sq} – d and q components of stator voltage,
ω_k, ω_r – the synchronous and the rotor angular velocity,
Ψ_{rd} – d component of rotor magnetic flux-linkage,
R, R_s – resistance of rotor and stator,
τ – rotor time constant,
J – inertia of rotor,
p – pole pairs of motor,
T_l – shaft load of motor,
B – friction constant.

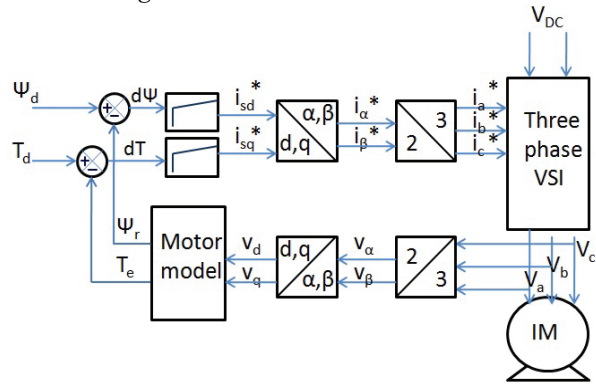The block diagram of rotor flux-oriented control can be seen in *Fig. 7*.

Figure 7: Rotor flux-oriented control without flux calculation (Indirect field-oriented control)

Self-commissioning

To create the motor model it is necessary to determine the unknown parameters of the motor by measuring the phase currents and phase voltages. Moreover, it is necessary to measure the phase difference between voltage and current.

For determining the parameters, three different measurements are needed *(Tables 1-3)* [12] :

– direct current test,
– no-load test,
– locked-rotor test.

The reactances can be calculated from the impedances which are known if the phase difference between the voltage and the current or the power is known.

Table 1: Results of the measurement with direct current

V_{DC} [V]	I_{DC} [A]
5	0.075
15	0.22
25	0.36
35	0.505

From the measured data the stator resistance can be determined. In case of measuring with direct current the reactances are zero, so the measurement of two phase gives only the resistance of the two phase.

$$R_1 = \frac{V_{DC,avg}}{2 \cdot I_{DC,avg}} = 34\,\Omega$$

Table 2: Results of the no-load test

V_{RMS} [V]	I_{RMS} [A]	P [W]	$\cos\theta$
220	1.49	93.54	73.39

In case of no-load test the slip is very small, hence the resistance of the rotor is huge. The results are referring to the stator because of the small input current into the rotor.

$$Z_{nl} = \frac{V_{RMS}}{I_{RMS}} = X_1 + X_m = 147.65\ \Omega$$

Table 3: Results of the locked-rotor test

V_{RMS} [V]	I_{RMS} [A]	P [W]	$\cos\theta$
60.1	0.851	37.08	43.54
61.1	0.895	40.87	41.65
60	0.855	37.42	43.17

The locked-rotor test was implemented by locking the rotor, which is allowed for a short time, only. In this case the slip is equal to one. The impedances and resistances can be measured both for the stator and the rotor. If the phase difference is known, the remaining parameters can also be determined.

$$Z_{lr} = \frac{V_{RMS,avg}}{I_{RMS,avg}} = 69.67\ \Omega$$

$$\theta = arccos\left(\frac{P}{\sqrt{3} \cdot V_t \cdot I_l}\right) = 42.75°$$

$$X_{lr} = Z_{lr} \cdot \sin\theta = 47.29\ \Omega$$

$$X_1 = X_2 = \frac{X_{lr}}{2} = 23.64\ \Omega$$

$$X_m = Z_{nl} - X_1 = 124.01\ \Omega$$

$$R_{lr} = Z_{lr} \cdot \cos\theta = 51.16\ \Omega$$

$$R_2 = R_{lr} - R_1 = 17.16\ \Omega$$

The unknown inductances can be determined from the parameters calculated for modelling.

$$L_m = X_m \cdot \omega = 0.3947$$

$$L_r = L_s = X_1 \cdot \omega = 0.0753$$

Modelling and simulations

The models of the closed-loop V/Hz and the rotor flux-oriented control were implemented in MatLab/Simulink. During the simulations the models were tested with changing speed and torque references. The responses can be seen below.
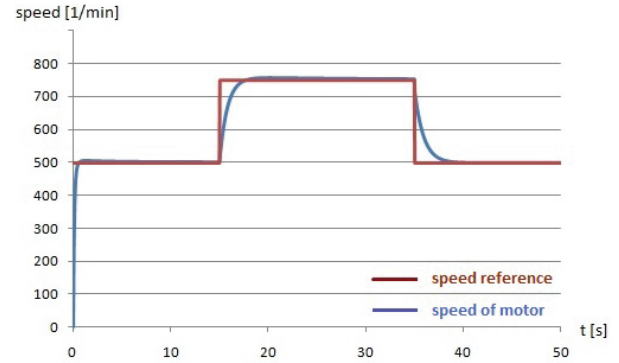
The results in case of speed change are the following:

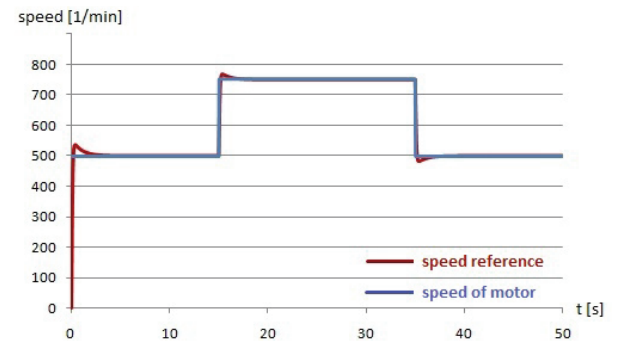*Figure 8:* Closed-loop V/f=constant control

Figure 9: Rotor flux-oriented control

From the results it can be seen that Volts/Hertz control is a sluggish method because it is based on controlling the amplitude of voltage and frequency, instead of current. The rotor flux-oriented method controls the amplitude and phase of current and frequency. Moreover, the controlled currents are decoupled, as it was mentioned earlier. In this way, control can be rapid and very robust.

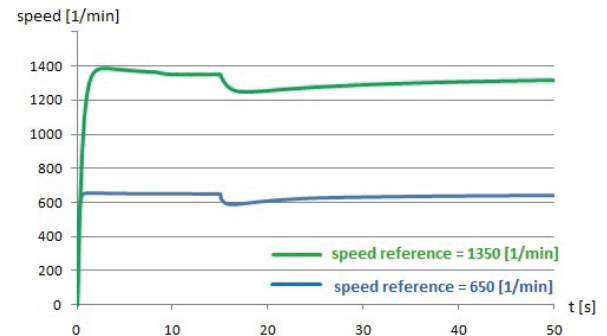The results in case of torque changing are shown in *Figs. 10-11*.

Figure 10: Closed-loop V/f=constant control
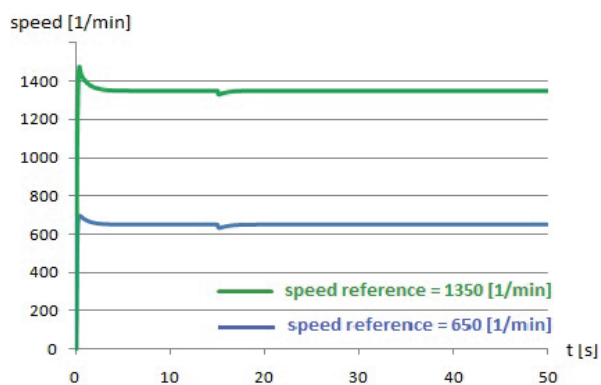
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Figure 11: Rotor flux-oriented control

The response of the model to changing the torque is similar to that in the case of changing the speed reference. The V/Hz constant model controls the torque slowly. The field-oriented control provides constant torque response.

Conclusions

Both control methods have advantages and disadvantages.

Scalar control is a cheap, well-implementable method. Because of these advantages and its simplicity, many applications operate with this control technique in the industry. On the other hand, it is not satisfactory for the control of drives with dynamic behaviour, since it gives slow response to transients. This is because the V/Hz constant method controls the magnitude of voltages and frequency instead of controlling the phase and magnitude of currents.

It is a low-performance, but stable control technique.

The field oriented control method controls the currents so it operates with fast responses. This method satisfies the requirements of dynamic drives, where fast response is necessary. It is an excellent control method to handle transients. Its disadvantage is complexity, and the high price of the driver circuit. Nevertheless, it is a high-performance control technique.

Both techniques are applicable over the nominal speed at the expense of torque.

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