# Open Loop Control for AC Drives

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**ABSTRACT**

Over recent years many control schemes have been suggested to improve the behaviour of high performance induction motor drives. Many such schemes require relatively complex electronics and feed-back transducers. They are restricted in their application due to their complexity and cost. There are other methods which are relative simple to implement, which are therefore very attractive for typical industrial applications. The method that is described in [1] is one such. There the authors suggest an open loop compensation scheme, which utilises the voltage drop on the stator resistance to make the model stable. The critical issue for such methods is how well they behave relative to more complex closed-loop control. This paper describes an investigation of the method using Simulink as the main means to verify its operation. The stability check that appears in [1] was also studied and a corrected form is shown to have been obtained.

## INDUCTION MOTOR MODELLING

According to [2] the equation for the stator voltage vector expressed in a General Reference Frame (GRF) is:

$$\bar{u}_{sg} = R_s \bar{i}_{sg} + \frac{d\bar{\psi}_{sg}}{dt} + j\omega_g \bar{\psi}_{sg} \quad (1)$$

where $\bar{u}_{sg}$ is the stator voltage vector in the GRF, $\bar{i}_{sg}$ is the stator current vector in the GRF, $\bar{\psi}_{sg}$ is the stator flux linkage vector in the GRF, $R_s$ is the stator resistance and $\omega_g$ is the angular speed of the reference frame. If this general frame is now locked to the stator flux, it rotates with the supply frequency and if $\rho_s$ is the angle of the stator flux to the Stator Reference Frame (SRF) then

$$\theta_g = \int \omega_g dt = \rho_s = \int \omega_{ms} dt \quad (2)$$

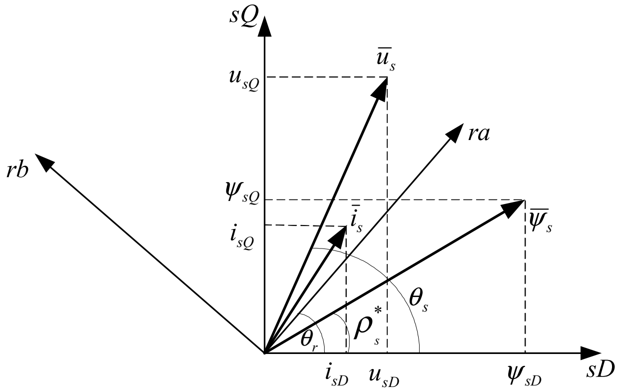


Fig. 1 Space Vectors

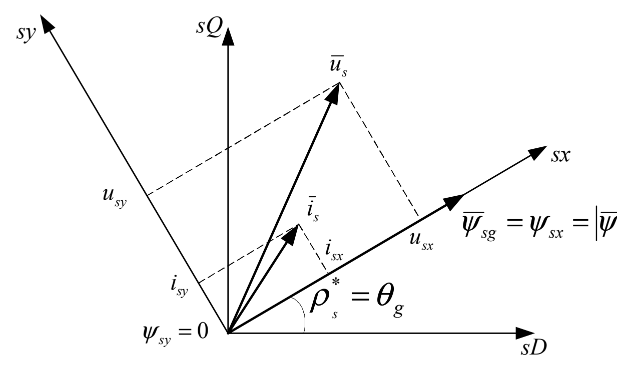


Fig. 2 Stator flux orientation

Since the general reference frame is locked to the stator flux then the imaginary component of $\overline{\psi}_{sg}$ is zero: $\overline{\psi}_{sg} = |\overline{\psi}_s| = \psi_{sx}$ (3)

Hence eqn. 1 can be written as: $\overline{u}_{s\psi_s} = R_s \overline{i}_{s\psi_s} + \frac{d\psi_{sx}}{dt} + j\omega_{ms}\psi_{sx}$ (4)

By splitting eqn. 4 to its orthogonal components: $\begin{Bmatrix} u_{sx} = i_{sx}R_s + \frac{d\psi_{sx}}{dt} \\ u_{sy} = i_{sy}R_s + \omega_{ms}\psi_{sx} \end{Bmatrix}$ (5)

In the steady state eqn. 5 can be written as: $\begin{Bmatrix} u_{sx} = i_{sx}R_s \\ u_{sy} = i_{sy}R_s + \omega_{ms}\psi_{sx} \end{Bmatrix}$ (6)

The open loop compensating scheme represented in [1] utilises these two eqns. The values of $\omega_{ms}$ and $\psi_{sx}$ can be set by the user. In [1] two different methods were suggested to calculate the angles $\rho_s$ and $\theta_s$, ($\theta_s$ is the angle of the stator voltage vector in the SRF). Only the first approach is studied here, the second method is very similar. The integral of the desired speed is used to give the angle $\rho_s$ and the angle $\theta_s$ is calculated from: $\theta_s = \rho_s + \tan^{-1}\left(\frac{u_{sy}}{u_{sx}}\right)$ (7)

## STABILITY ANALYSIS

The previous stability analysis [1] had an error that made result verification impossible. According to the paper the state space model description was:

$$A = \begin{bmatrix} 0 & 0 & -R_s & 0 \\ 0 & 0 & 0 & -R_s \\ -\frac{R_r}{L_m^2\sigma} & -\frac{\omega_r L_r}{L_m^2\sigma} & \frac{R_r L_s + R_s L_r}{L_m^2\sigma} & -\omega_r \\ \frac{\omega_r L_r}{L_m^2\sigma} & -\frac{R_r}{L_m^2\sigma} & \omega_r & \frac{R_r L_s + R_s L_r}{L_m^2\sigma} \end{bmatrix}, \quad B = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ -\frac{L_r}{L_m^2\sigma} & 0 \\ 0 & -\frac{L_r}{L_m^2\sigma} \end{bmatrix}, u = \begin{bmatrix} u_{sD} \\ u_{sQ} \end{bmatrix}, X = \begin{bmatrix} \psi_{sD} \\ \psi_{sQ} \\ i_{sD} \\ i_{sQ} \end{bmatrix} \quad (8)$$

where $R_r$ is the rotor resistance, $L_r$ is the rotor self inductance, $L_s$ is the stator self inductance, $L_m$ is the mutual inductance between the stator, rotor coils and $\sigma$ is the resultant leakage factor and $\omega_r$ is the rotor angular velocity: $\int \omega_r dt = \theta_r$

if $\rho_s=0$ then $\begin{cases} u_{sx} = u_{sD} = i_{sD}\widetilde{R}_s \\ u_{sy} = u_{sQ} = i_{sQ}\widetilde{R}_s + \omega^*_{ms}\psi^*_s \end{cases}$ (9)

$\widetilde{R}_s$ is the value of stator resistance used in the compensator. It can be assumed that the control strategy can be fitted into a linear state feedback control system where the input signal is:

$$\overline{u} = -KX + u_{ref} \text{ and } K = \begin{bmatrix} 0 & 0 & -\widetilde{R}_s & 0 \\ 0 & 0 & 0 & -\widetilde{R}_s \end{bmatrix}, \quad u_{ref} = \begin{bmatrix} 0 \\ \omega_r^{\ *} \psi^{*}{}_s \end{bmatrix} \tag{10}$$

And hence:

$$A_c = A - BK = \begin{bmatrix} 0 & 0 & \widetilde{R}_s - R_s & 0 \\ 0 & 0 & 0 & \widetilde{R}_s - R_s \\ -\dfrac{R_r}{L_m^2 \sigma} & -\dfrac{\omega_r L_r}{L_m^2 \sigma} & \dfrac{R_r L_s + R_s L_r - \widetilde{R}_s L_r}{L_m^2 \sigma} & -\omega_r \\ \dfrac{\omega_r L_r}{L_m^2 \sigma} & -\dfrac{R_r}{L_m^2 \sigma} & \omega_r & \dfrac{R_r L_s + R_s L_r - \widetilde{R}_s L_r}{L_m^2 \sigma} \end{bmatrix} \tag{11}$$

To check the stability of the system the eigenvalues of $A_c$ where plotted for various speeds and $\widetilde{R}_s$ resistances. The matrix from eqn. 11 gives Figs. 3 & 4 which are not the same as in [1]:

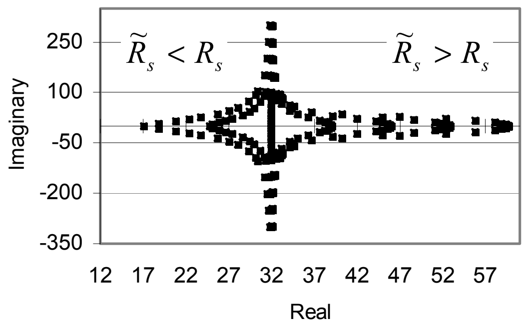


Fig. 3 Root locus for stator currents

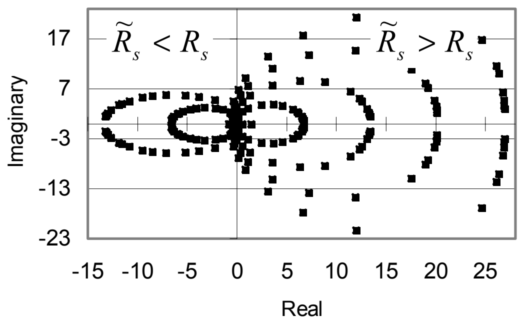


Fig. 4 Root locus for stator fluxes

The error is in the matrix *A,* in the denominator of the factors that contain the term $L_m{}^2\sigma$ where $\sigma = 1 - \dfrac{L_m{}^2}{L_r L_s}$ (for more information see [3] or [4]). The correct factor was found to be $\left(L_m{}^2 - L_r L_s\right)$. So the correct state matrix is:

$$A = \begin{bmatrix} 0 & 0 & -R_s & 0 \\ 0 & 0 & 0 & -R_s \\ -\dfrac{R_r}{\left(L_m{}^2 - L_r L_s\right)} & -\dfrac{\omega_r L_r}{\left(L_m{}^2 - L_r L_s\right)} & \dfrac{R_r L_s + R_s L_r}{\left(L_m{}^2 - L_r L_s\right)} & -\omega_r \\ \dfrac{\omega_r L_r}{\left(L_m{}^2 - L_r L_s\right)} & -\dfrac{R_r}{\left(L_m{}^2 - L_r L_s\right)} & \omega_r & \dfrac{R_r L_s + R_s L_r}{\left(L_m{}^2 - L_r L_s\right)} \end{bmatrix} \tag{12}$$

Following the same steps as before the matrix $A_c$ was calculated and its eigen-values are:

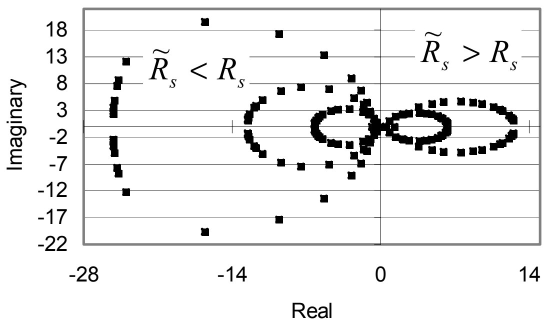


Fig. 5 Root locus for stator fluxes

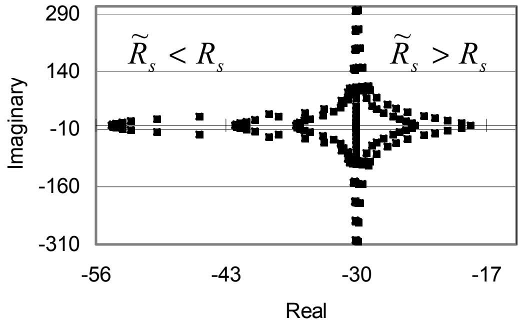


Fig. 6 Root locus for stator currents

A very interesting characteristic of the system can be deduced from Figs. 5 & 6. This is that the system will be unstable for values of the resistance $\tilde{R}_s$ bigger than $R_s$.

Another error is the assumption in [1] that $\rho_s = 0$ this gives the correct gain matrix *K* apparently by luck. The first indication of this is that if $\rho_s = 0$ then the machine would not turn. If $\rho_s \neq 0$ and the state space model of the control scheme is derived, the *K* matrix will be the same, so the stability analysis is not influenced. On the other hand the input matrix $u_{ref}$ should be $u_{ref} = \begin{bmatrix} -\sin(\rho_s)\omega_r^* \psi_s^* \\ \cos(\rho_s)\omega_r^* \psi_s^* \end{bmatrix}$. This statement can easily be verified from the Simulink model that appears in Fig. 7.

## SIMULATION RESULTS

*Simulation model*

The Simulink model that was used to study the above method is given in Fig. 7.

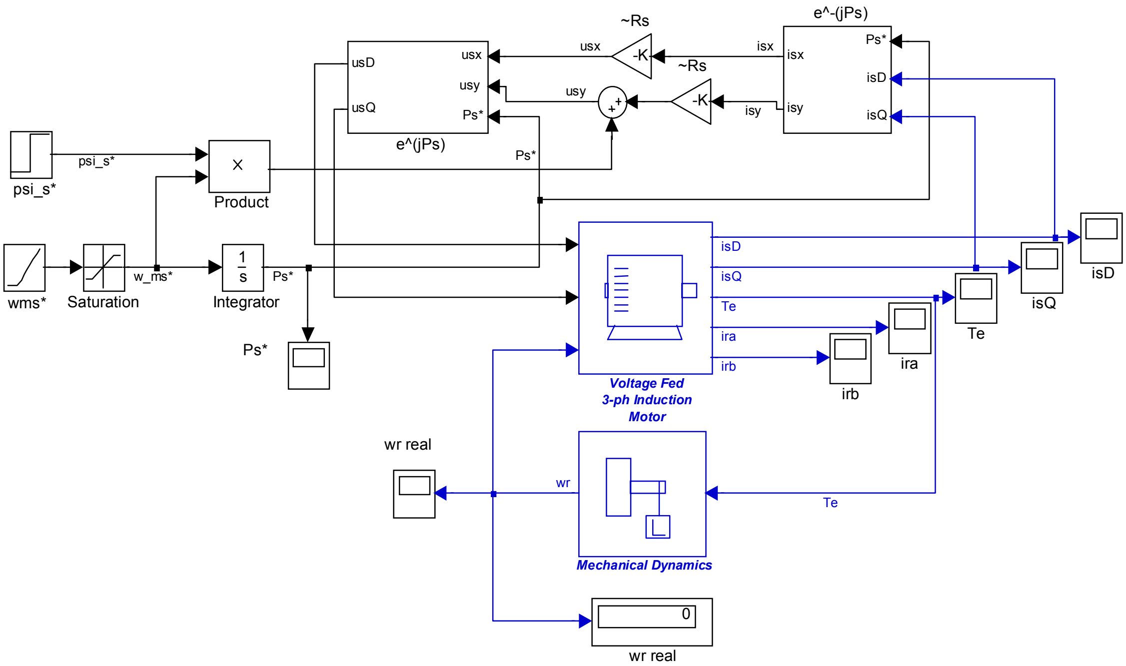


Fig. 7 Simulink model for the Open loop control scheme

The sub blocks defining the compensation method are shown in Figs. 8 & 9:

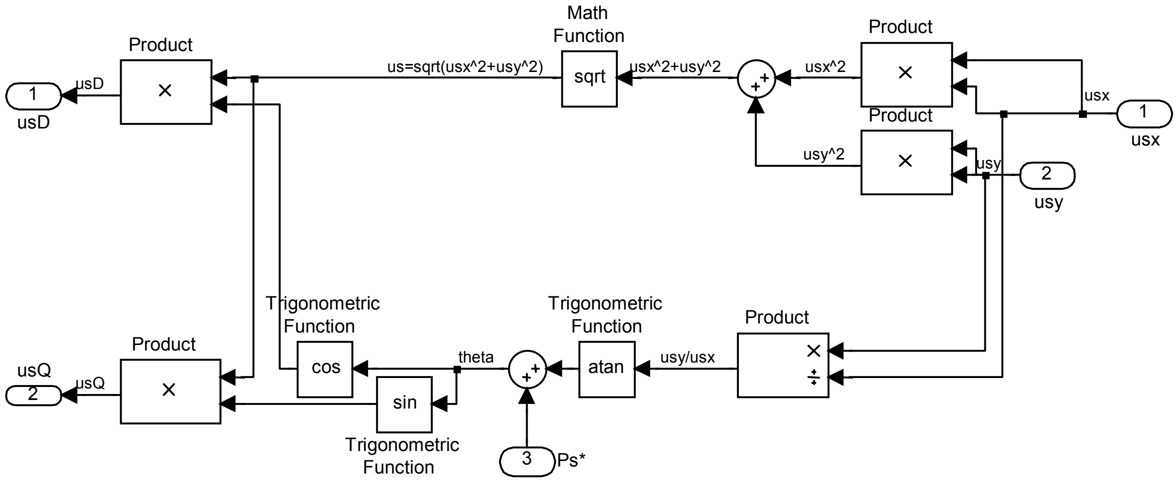


Fig. 8  Sub-block: calculates usD and usQ from usx and usy

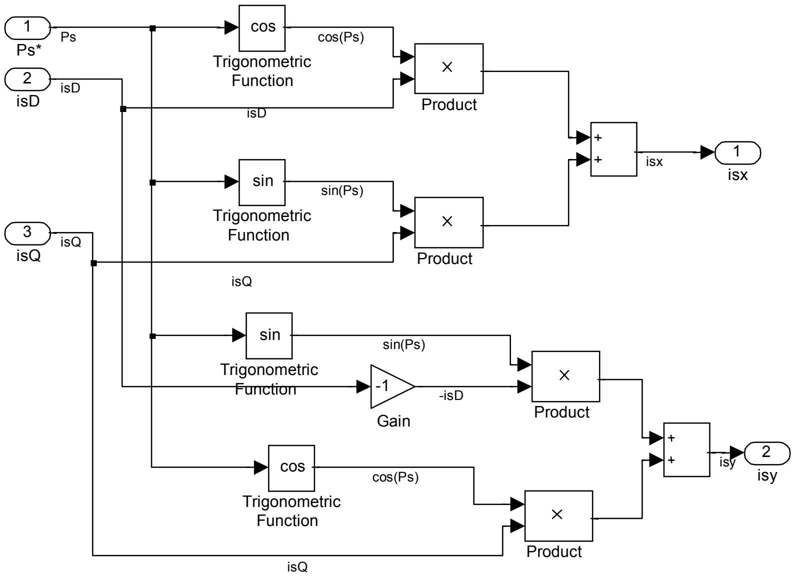


Fig. 9  Sub-block: calculates isx and isy from isD and isQ

*Tests*

In [1] two tests for the above system are described. In the first the motor frequency is ramped from 0 to 37Hz or 235 rad/s in 2 s (the paper states 25Hz but the waveforms of speed shown do not correspond), with a load of 80% of the rated torque. In the second test the motor frequency is ramped from 0 to 5Hz or 31.42 rad/s in 1 s. After four seconds a load of 80% of the rated torque is applied. The value for the desired stator flux unfortunately is not given. From the graphs that appear in [1] an estimated value of 1.6 Wb has been used. Also the inertia has been found by trial and error since it is not given either. The parameters for the delta connected squirrel cage induction motor used are: power 7.5 kW, power factor 0.88, inertia 0.221 kg $m^2$, pole-pair number 1, rated voltage 415 V, rated current 13.5 A, rated torque 25 Nm, rated slip 0.0191, rated frequency 50 Hz. The per phase equivalent parameters are: stator resistance 2.19 Ω, rotor resistance 1.04 Ω, leakage stator and rotor inductance 17.59 mH and stator rotor mutual inductance 0.55 mH.

The system responses for $\widetilde{R}_s = 0.8R_s$ are shown in Figs. 10-15:

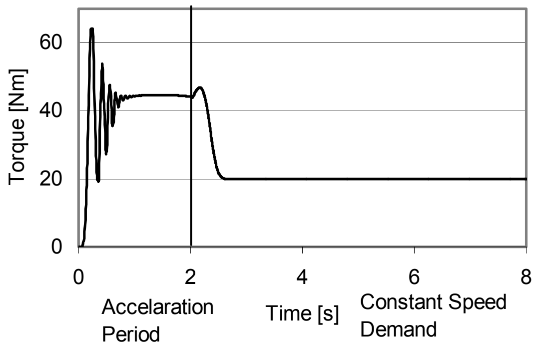


Fig. 10 Torque response for test 1

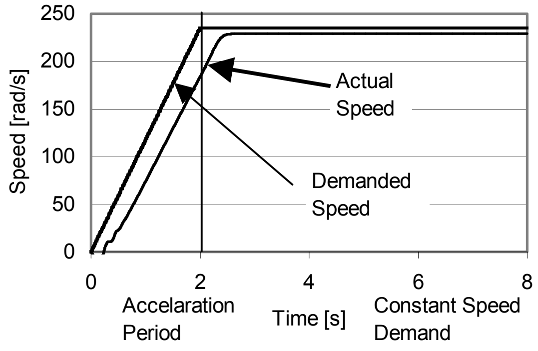


Fig. 11 Speed response for test 1

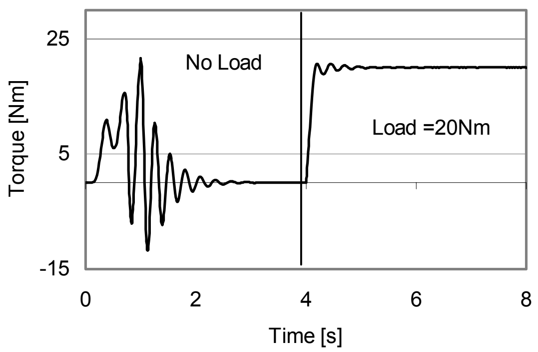


Fig. 12 Torque response for test 2

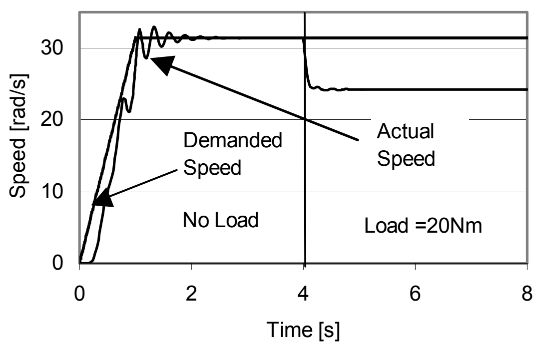


Fig. 13 Speed response for test 2

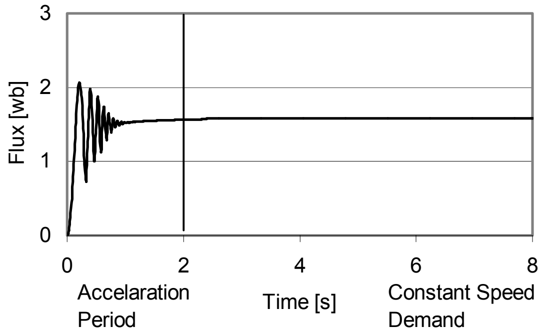


Fig. 14 Stator flux linkage response for test 1

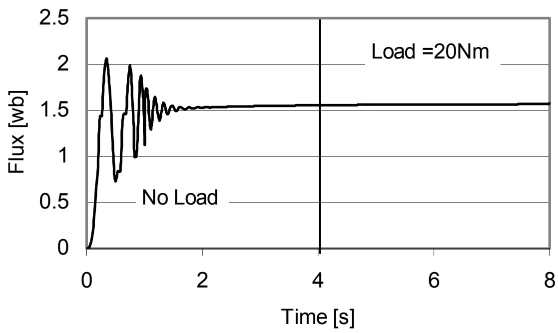


Fig. 15 Stator flux linkage response for test 2

## DISCUSSION OF RESULTS

It has been shown that the response of the simulated system is very similar to the main experimental results [1]. Differences are minor and can be explained. For example ripple exists on the experimental results, due to the power electronic modulation. In the simulations it is assumed that the power electronics are idealised and hence no ripple exists. Furthermore errors were present in the earlier stability analysis of the system [1]; these have been found and corrected. Their location and the influence that they have in the state matrices that model the system are also shown. The correct state space model was finally given and the stability analysis was found to agree with both the experimental and simulation results. Variations on the methods described here are already being widely used with success in industrial drives. Research is continuing to further improve the behaviour of these economical drive schemes.

## REFERENCES


[1] Francis, C.J., and Zelaya De La Parra, H.: "Stator resistance voltage-drop compensation for open loop AC Drives", *IEE Proc.- Electr. Power Appl.,* Vol. 144, No. 1, January 1997, pp. 21-26

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