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Individual Channel Design Control of an Induction Motor

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Abstract— **In this paper a novel control strategy is applied to an induction motor. Usual Park transformations render a decoupled 2x2 system. Nevertheless, the control based on this representation requires measurement of key parameters in order to maintain the system decoupled. Using the Park transformation the motor can also be represented as a coupled 2x2 linear system. In this representation parameter variations appear as a structured uncertainty. This fact allows the development of linear robust decoupling control systems. In practice this control strategy will not require the measurement of parameter and states, thus, reducing the cost of vector control motors. As follows a Park transformation is proposed together with a linear design for a typical induction motor. The design is obtained by applying Individual Channel Design (ICD).**

Keywords— **Induction Motor, Multivariable Linear Control, Individual Channel Design, Multivariable Structure Function, Robustness**

List of Symbols

v_{qs}, v_{ds} = voltage q, d components of stator state vector

i_{qs}, i_{ds} = current q, d components of stator state vector

Ψ_{qrs}, Ψ_{drs} = stationary frame rotor flux q, d components

ω_r = rotor angular frequency

L_{lr}, L_{ls} = rotor, stator self inductances

L_r, L_s, L_m = rotor, stator, mutual inductances

σ = disperssion coefficient

R_r, R_s = rotor, stator resistances

I. Introduction

In this paper a novel control of an induction motor through Individual Channel Design (ICD) is presented. Different control techniques for induction motors exist nowadays. One of the most common techniques used is Vector Control. It provides separate control over field and torque components of total stator current to give DC machine performance capabilities. The inherent coupling effect is solved as vector control creates independent channels for electromagnetic flux and electromagnetic torque control [2]. This is accomplished by means of a rotatory reference frame model which requires the knowledge of the flux position and magnitude. The rotor flux is the most common reference used. One problem associated to this approach is its high sensitivity to parameter variation, in particular the rotor time constant (τ_R), so its value needs to be updated in order to maintain performance [14].

Another method is Direct Torque Control (DTC). It uses a stationary reference frame model that decouples electromagnetic flux from electromagnetic torque channels throughout a table involving 8 voltage vectors and it only depends on one parameter, the stator resistance R_S [15]. Although in this case sensitivity to parameters variation is not a disadvantage the ripple found in the response both in flux and torque poses the major disadvantage in DTC. Thus, it is very difficult to achieve a successful motor control at low velocities and at a starting operation [17].

ICD allows the use of a coupled stationary reference frame induction motor model. Decoupling is accomplished due to the nature of the design process, which involves the definition of individual input-output channels, which are determined in terms of the multivariable structure function [8,9]. Classical control techniques (Bode and Nyquist) can be used in order to achieve a multivariable control design robust to parameters variation [11,12] and without rippled responses. In practice this control strategy will not require the measurement of parameter and states, thus, reducing the cost of vector control motors.

II. Induction Motor Model

After applying the Park transformation to the induction motor model found in [7], the d-q representation was obtained. The following system of equations can be formed

$$\begin{aligned}
\dot{i}_{ds} &= -\frac{L_r^2 R_s + L_m^2 R_r}{\sigma L_s L_r^2} i_{ds} + \frac{L_m R_r}{\sigma L_s L_r^2}\Psi_{drs} + \frac{L_m \omega_r}{\sigma L_s L_r}\Psi_{qrs} + \frac{1}{\sigma L_s} v_{ds} \\
\dot{i}_{qs} &= -\frac{L_r^2 R_s + L_m^2 R_r}{\sigma L_s L_r^2} i_{qs} - \frac{L_m \omega_r}{\sigma L_s L_r}\Psi_{drs} + \frac{L_m R_r}{\sigma L_s L_r^2}\Psi_{qrs} + \frac{1}{\sigma L_s} v_{qs} \\
\dot{\Psi}_{drs} &= -\frac{R_r}{L_r}\Psi_{drs} - \omega_r \Psi_{qrs} + \frac{L_m R_r}{L_r} i_{ds} \\
\dot{\Psi}_{qrs} &= -\frac{R_r}{L_r}\Psi_{qrs} + \omega_r \Psi_{drs} + \frac{L_m R_r}{L_r} i_{qs}
\end{aligned} \tag{1}$$

III. Control Model

The system of equations in (1), which represents the induction motor dynamics, can be represented by the linear state space model [3]

$$\begin{aligned}
\dot{X} &= AX + Bu \\
Y &= CX + Du
\end{aligned} \tag{2}$$

where

$$X = \left[i_{ds}, i_{qs}, \Psi_{drs}, \Psi_{qrs}\right]^T \text{ and } u = \left[v_{ds}, v_{qs}\right]^T \tag{3}$$

Matrices A, B, C, and D are expressed as follows after substituting motor parameters

$$A = \begin{bmatrix} -127.4 & 0 & 90.1 & 3051.9 \\ 0 & -127.4 & -3051.9 & 90.1 \\ 4.97 & 0 & -11.13 & -377 \\ 0 & 4.97 & 377 & -11.13 \end{bmatrix},$$

$$B = \begin{bmatrix} 9.15 & 0 \\ 0 & 9.15 \\ 0 & 0 \\ 0 & 0 \end{bmatrix},$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}, \text{ and } D = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$$

In the frequency domain the induction motor model can be represented as

$$\begin{bmatrix} i_{ds}(s) \\ i_{qs}(s) \end{bmatrix} = G(s) \begin{bmatrix} v_{ds}(s) \\ v_{qs}(s) \end{bmatrix} \tag{4}$$

where the elements of G(s) are

$$\begin{aligned} g_{11}(s) &= \frac{9.1459(s+89.05)(s^2+60.63s+1.392\times10^5)}{(s^2+176.2s+7852)(s^2+100.9s+1.376\times10^5)} \\ g_{12}(s) &= \frac{138827.43934s}{(s^2+176.2s+7852)(s^2+100.9s+1.376\times10^5)} \\ g_{21}(s) &= \frac{-138827.43934s}{(s^2+176.2s+7852)(s^2+100.9s+1.376\times10^5)} \\ g_{22}(s) &= \frac{9.1459(s+89.05)(s^2+60.63s+1.392\times10^5)}{(s^2+176.2s+7852)(s^2+100.9s+1.376\times10^5)} \end{aligned} \tag{5}$$

IV. ICD & THE MULTIVARIABLE STRUCTURE FUNCTION

ICD is an analytical framework in which it is possible to investigate the potential and limitations for feedback design of any multivariable linear time invariant control system. Although ICD is in principle a feedback structure based on diagonal controllers, it can be applied to any cross coupled multivariable system such as the induction motor, irrespective of the degree of coupling. Another important aspect of ICD is that the influence of transmission zeros on the control design and closed loop performance is clearly revealed. ICD is based on the definition of individual transmission channels. In general the input-output channels arise from design specifications. In this context the control design is an interactive process involving the required specifications, plant characteristics, and the multivariable feedback design process itself. Once the channels are defined, that is, the pairing of every output signal to a reference input is established, it is possible to form, with each channel, a feedback loop with a compensator which must be designed to meet costumer specifications. In this manner the multivariable control design problem is reduced to the design of a single-input single-output control for every channel. For further details and motivation of ICD the reader is referred to [8], [9], [10], [11], and [16].

The induction model analysis is done investigating the dynamical structure of the input-output channels. Pairing the inputs and outputs as follows can form the individual input-output channels:

(a) Ch1. $v_{ds} - i_{ds}$ with $\gamma_a(s)=g_{12}g_{21}/g_{11}g_{22}$
    Ch2. $v_{qs} - i_{qs}$
(b) Ch1. $v_{qs} - i_{qs}$ with $\gamma_b(s)=g_{11}g_{22}/g_{12}g_{21}$
    Ch2. $v_{ds} - i_{ds}$

The coupling characteristic of each input-output configuration is determined from $\gamma_a(s)$ and $\gamma_b(s)$ -their associated multivariable structure function [8]. The multivariable structure function associated with channels in (a) is

$$\gamma_a(s) = \frac{-230408106.0591s^2}{(s^2+178.1s+7929)(s^2+60.63s+1.392\times10^5)} \tag{6}$$

Using $\gamma_a(s)$ and assuming a diagonal controller, the closed-loop system can be represented by

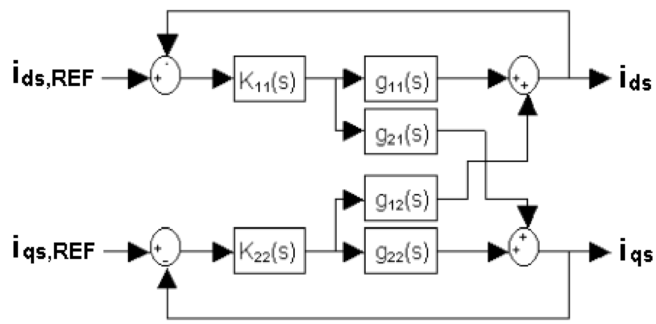

Fig. 1. Closed loop system associated with $\gamma_a(s)$

The existence and design of stabilizing compensators $K_{11}(s)$ and $K_{22}(s)$ can be determined from the characteristics of $\gamma_a(s)$, revealed by its Nyquist and Bode plots shown in Fig. 2 following the analysis presented in [11].

From Fig. 1, two input-output channels can be identified, whose open loop transfer functions are given by

$$C_i(s) = K_{ii}g_{ii}(1-\gamma_a(s)h_j(s)) \tag{7}$$

where

$$h_j(s) = \frac{K_{ii}(s)g_{ii}(s)}{1+K_{ii}(s)g_{ii}(s)}, \quad i \neq j \tag{8}$$

Similarly, the multivariable structure function associated with channels in (b) is

$$\gamma_b(s) = \frac{-4.3\times10^{-9}(s+89.1)(s+89)(s^2+60.6s+1.4\times10^5)}{s^2} \tag{9}$$

From (9) it can be seen that the control design can turn into a very difficult task. The coupling associated with $\gamma_b(s)$, which is strictly non-proper, indicates that this channels definition is highly coupled for almost all frequencies. The design using $\gamma_b(s)$ is avoided.

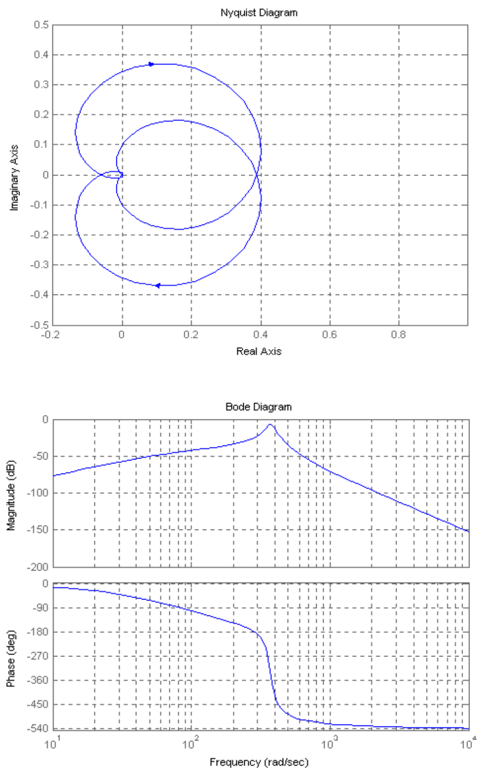

Fig. 2. Assessing $\gamma_a(s)$ structure

V. Control System Design Specifications

The final design should meet the following specifications:

Bandwidth:

$i_{ds}(s) \Rightarrow 100 rad/s$

$i_{qs}(s) \Rightarrow 60 rad/s$

Stability Margins:

$G_M(s) > 10dB$

$P_M(s) > 60°$

Both margins should be accomplished in both channels.

Coupling: The design should provide a completely decoupling between the channel associated to magnetic flux and the channel associated to torque.

Overshoot: It should be avoided. It can be limited with prefiltering action.

Parameter Variation: The controller design should be robust to variation of parameters in rotor inductance and resistance.

VI. Results

Using the toolbox presented in [13], the following controller was obtained

$$K_{11}(s) = \frac{2839(s+90)^3(s+50)}{s(s+130)(s+120)(s+110)(s+100)} \tag{10}$$

$$K_{22}(s) = \frac{1451.4(s+90)^2(s+50)(s+40)(s^2+77s+1.5\times10^5)}{s(s+110)^2(s+80)(s+70)(s^2+30.16s+1.4\times10^5)}$$

Notice that the controller is diagonal with stable minimum phase elements and of relatively low order.

The definition of channel stability margins is possible if their dynamical structure is preserved - the robustness of the multivariable system can be stated in these terms, as the Nyquist paths of $\gamma_a(s)h_j(s)$ do not pass near the point (1,0) and the functions $K_{ii}g_{ii}$ have adequate phase and gain margins. The controller performance and robustness measures are shown next:

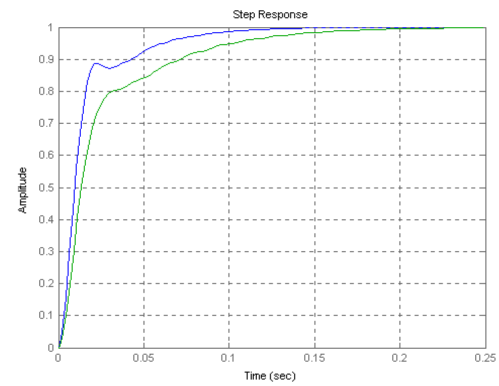

Fig 3. Channel 1 vs Channel 2 step response

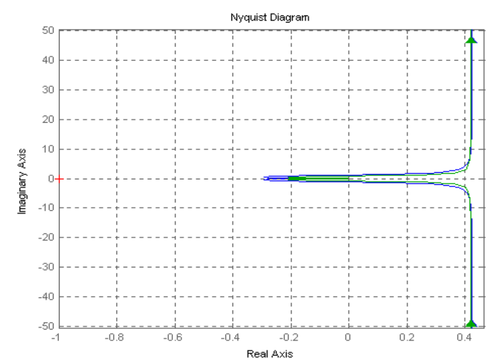

Fig 4. Channel 1 vs Channel 2 Nyquist plot

Fig. 3 shows the step response of each channel. Fig 4. shows there is no encirclement of the point (-1,0) in either channels. Table 1 summarizes the resulting structural robustness of the channels and the control system, obtained from Figs. 5, 6, and 7 [10].

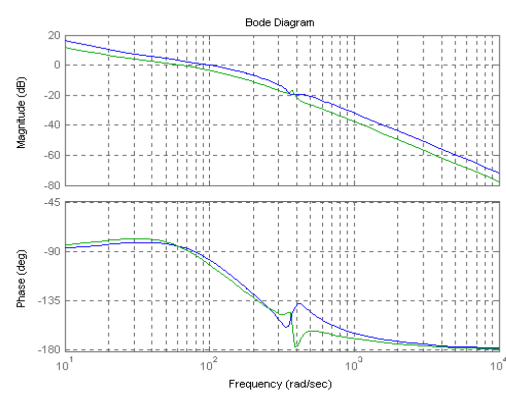

Fig 5. Channel 1 vs Channel 2 Bode diagram

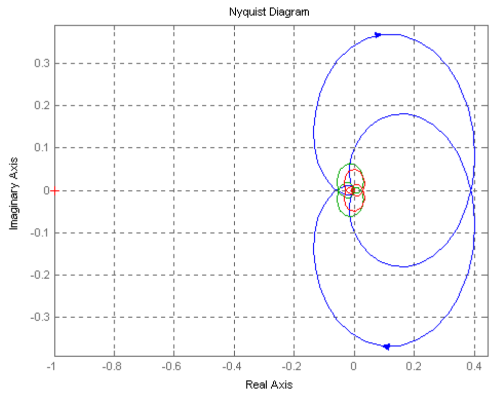

Fig. 6. Channel 1 & 2 structural robustness assessment. γ_a vs $\gamma_a h_2$ vs $\gamma_a h_1$

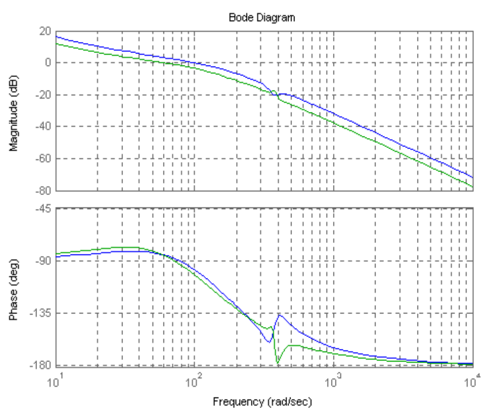

Fig. 7. Channel 1 & 2 structural robustness assessment. $K_{11}g_{11}$ & $K_{22}g_{22}$ stability margins

Table 1. Structural robustness assessment

Measure	Ch 1	$K_{11}g_{11}$	$\gamma_a h_2$	Ch 2	$K_{22}g_{22}$	$\gamma_a h_1$
BW [rad/s]	100.58	100.04	—	60.284	60.217	—
G_M [dB]	∞	∞	33.2	∞	∞	30.7
P_M [deg]	82.201	82.338	∞	95.155	95.015	∞

After performing a sensitivity and coupling between channels analysis, prefilters were designed to avoid sharp responses in control signals (i.e. stator voltages). The designed filters are

$$F_1(s) = \frac{100^2}{s^2 + 200s + 100^2} \quad \text{and} \quad F_1(s) = \frac{80^2}{s^2 + 200s + 80^2}$$

Fig. 8 illustrates the closed loop control system performance. The current references are i_{ds} = 50A and i_{qs} = 50A. Fig 9. illustrates the controller performance considering the same current references as before and under parameter variations ($R_{r1} = 3.5R_r$ and $L_{lr1} = 1.4L_{lr}$). Notice the time response of both simulations.

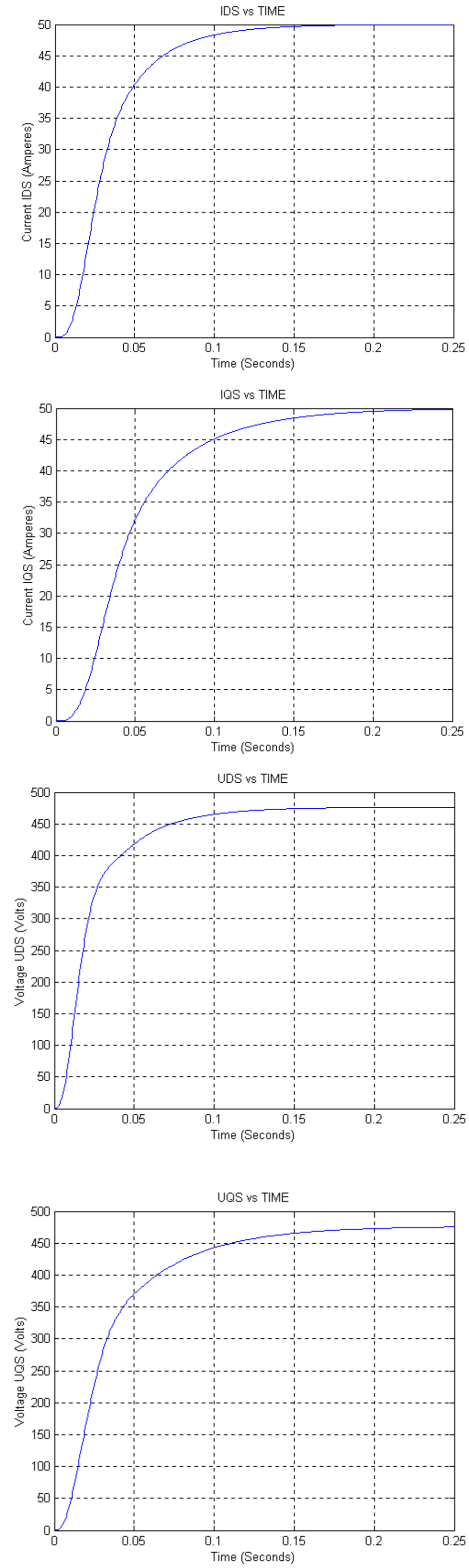

Fig. 8. Closed loop induction motor system simulation

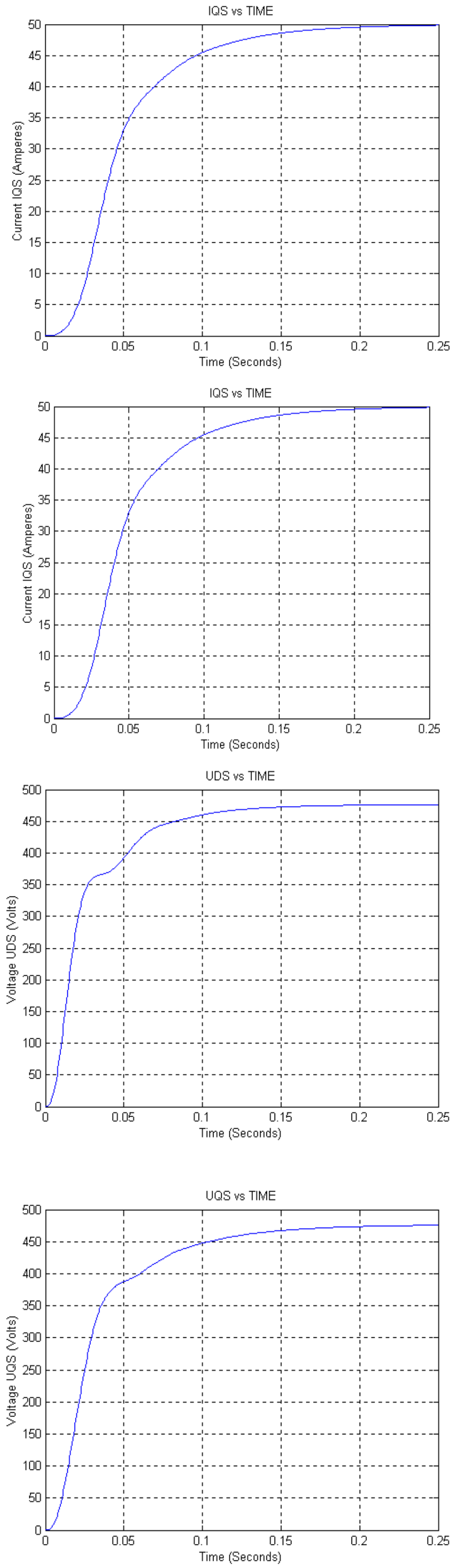

Fig. 9. Closed loop induction motor system simulation under parameter variations

VII. CONCLUSIONS

- Vector control theory is used (input is the stationary frame stator current space vector and output is the stationary frame stator current space vector) to obtain an induction motor model suitable for a control system design via ICD.
- Channel pairing is defined as: Channel 1: $v_{ds} - i_{ds}$ (flux control) and Channel 2: $v_{qs} - i_{qs}$ (torque control), whose multivariable structure function is $\gamma_a(s)$. The alternative channel definition is associated to high coupling and is avoided.
- Channels can be successfully decoupled by means of ICD control.
- A diagonal low order controller with stable minimum phase elements is obtained.
- The control design meets the established performance and robustness requirements.
- Robustness of the multivariable system is assessed through very well proven concepts: gain and phase margins.
- Reference and control signal responses are improved with prefilters.
- Robustness to parameter variation in rotor components is also shown through simulations.

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