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Classical Controller with Intelligent Properties for Speed Control of Vector Controlled Induction Motor

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ABSTRACT

This paper presents a classical speed controller (CSC) for vector controlled induction motors. The controller explores the use of a Fuzzy Logic controller in a classical form. The controller combines the advantages of the classical controller and the properties of intelligent controllers. The Fuzzy Logic controller idea is used to obtain the CSC output equation, whereby the CSC equation is based on the speed error and its change. The CSC parameters are calculated based on the motor mechanical equation and a predefined system performance. Once the CSC parameters are obtained, the defined speed performance can be achieved at all operating conditions. The application of the CSC to control the speed of a vector controlled induction motor is presented. Different induction motor ratings are used. Simulation results in all possible o1perating conditions are presented. Results show that the CSC behaves as an expert controller to provide the predefined speed performance in all possible operating conditions. Based on the results obtained in this paper, the CSC is expected to become the ultimate solution for high-performance drives of the next generation.

Keywords: Speed controller, Fuzzy Logic, Induction motor

1. Introduction

The development of high performance motor drives is very important in industrial applications. Many techniques [1-4] have been developed and applied to the speed control of induction motor drives so that very good control performance can be obtained. The standard approach for speed control in industrial drives is to use a proportional plus integral (PI) controller. But the PI controller does not provide a good regulating performance instantaneously because the controller parameters do not adaptively change according to the induction motor parameters. Moreover, its control performance is sensitive to the system parameters variations [5]. Recent developments in artificial intelligent based control have brought into focus the possibility of replacing a PI speed controller with a Fuzzy Logic equivalent [6]. Fuzzy Logic (FL) speed control appears to be the ultimate solution for high-performance drives of the next generation [7]. Such a prediction of future trends is based on a comparison of drive response under PI and FL speed control, which has been compared on a number of occasions. But simulation and experimental results in [8] show that there are speed regions where either PI or FL offer better behavior, as well

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as a region where the two controllers yield essentially the same response.

This present paper introduces a proposed controller which explores the use of a Fuzzy Logic controller in a classical form. So, the proposed controller can combine the advantages of classical controllers and the properties of intelligent controllers.

The FL controller can be regarded as a set of heuristic decision rules that include the experience of a human operator. The fuzzy controller relates significant and observable variables to the control actions, and consists of a fuzzy relationship or algorithm [9]. In the case of speed control, the speed error signal e(k) and its rate of change Δe(k) are selected as inputs to Fuzzy Logic controller. As a FL controller on its own is a PD (proportional plus derivative) controller equivalent [8], output of the speed FL controller is integrated in order to yield PI like behavior. Based on this fact, the CSC is designed.

2. The Proposed Controller (CSC) Design

The following equation is suggested to represent the FL controller output in a classical form as follows:
The controller output = integration of

$$[k_1(e(k)+k_2\Delta e(k))] \tag{1}$$

Where: k_1 and k_2 are scaling factors.

$$e(k)=\omega_m^*-\omega_m \tag{2}$$

$$\Delta e(k)=(\omega_m^*-\omega_m)-(\omega_{mo}^*-\omega_{mo}) \tag{3}$$

If ω_m^* is constant then:

$$de(k)=-(\omega_m-\omega_{mo}) \tag{4}$$

The controller output = integration of

$$[k_1[(\omega_m^*-\omega_m)-k_2(\omega_m-\omega_{mo})]] \tag{5}$$

2.1 The controller model

The CSC output equation can be represented in z-domain and s-domain using a MATLAB/SIMULINK program as shown in Fig.1 and Fig.2 respectively. T is the sampling time in the z-domain model.

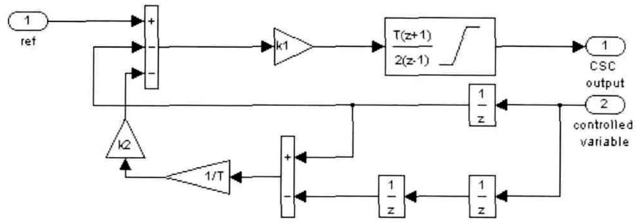

Fig. 1 CSC model in z-domain

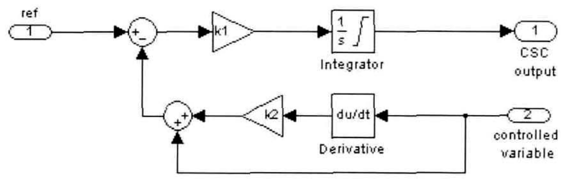

Fig. 2 CSC model in s-domain

3. The Induction Motor Model

In this model the electrical part of the machine is represented by a fourth-order state-space model and the mechanical part by a second-order system. All electrical variables and parameters are referred to the stator. This is indicated by the prime signs (') in the machine equation given below. All stator and rotor quantities are in the arbitrary two-axis reference frame (q-d frame)[10].

$$\begin{aligned}
V_{qs} &= R_s i_{qs} + p\varphi_{qs} + \omega\varphi_{ds} \\
V_{ds} &= R_s i_{ds} + p\varphi_{ds} - \omega\varphi_{qs} \\
V'_{qr} &= R'_r i'_{qr} + p\varphi'_{qr} + (\omega-\omega_r)\varphi'_{dr} \\
V'_{dr} &= R'_r i'_{dr} + p\varphi'_{dr} - (\omega-\omega_r)\varphi'_{qr} \\
T_e &= 1.5P(\varphi_{ds} i_{qs} - \varphi_{qs} i_{ds}) \\
\varphi_{qs} &= L_s i_{qs} + L_m i'_{qr} \;;\; \varphi_{ds} = L_s i_{ds} + L_m i'_{dr} \\
\varphi'_{qr} &= L'_r i'_{qr} + L_m i_{qs} \;;\; \varphi'_{dr} = L'_r i'_{dr} + L_m i_{ds} \\
L_s &= L_{ls} + L_m \;;\; L'_r = L'_{lr} + L_m
\end{aligned} \tag{7}$$

$$\frac{d}{dt}\omega_m = \frac{1}{2J}(T_e - B\omega_m - T_L) \tag{8}$$

$$\frac{d}{dt}\theta_m = \omega_m \tag{9}$$

Fig.3 shows the MATLAB/SIMULINK model of the induction motor drive system, where the vector control equations are{10}:

$$Phir = L_m i_d /(1 + T_r s) \quad (10)$$

$$T_r = L_r / R_r \quad (11)$$

$$\omega_r = L_m i_q /(T_r * Phir) \quad (12)$$

$$i_q = (2/3)(2/P)(L_r / L_m)(T_e / Phir) \quad (13)$$

$$I_d = Phir^* / L_m \quad (14)$$

4. Determination of the CSC Parameters

To get the CSC parameters, the following equation is used to describe the motor operation:

$$T_e(t) = J\frac{d\omega_r(t)}{dt} + B\omega_r + T_L(t) \quad (15)$$

Simulating this equation with the CSC in s-domain, as shown in Fig. 4, reveals that the characteristic equation is given by (B is set to zero):

$$Js^2 + k_1 k_2 s + k_1 = 0 \quad (16)$$

and for a certain damped response for a reference speed step change, the following equation is valid:

$$k_2 = 2\sqrt{\frac{J\eta}{k_1}} \quad (17)$$

Where η is the damping ratio.

The relation between the motor speed and load torque, as shown in Fig. 5, can be obtained as follows:

$$\omega_r(s) = \frac{\frac{1}{k_1 * k_2}}{\frac{J}{k_1 * k_2}s + 1} T_L(s) \quad (18)$$

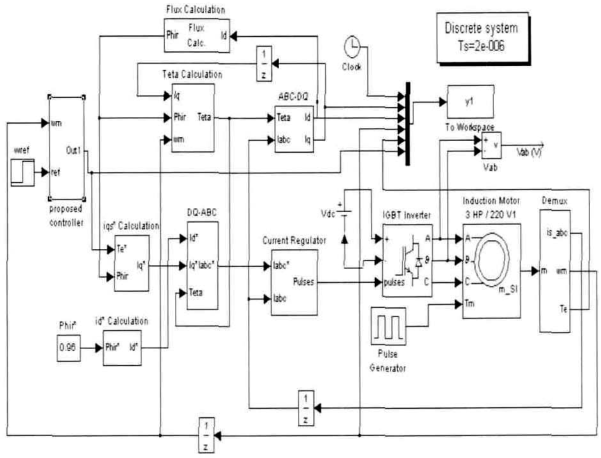

Fig. 3 Model of the induction motor drive system with CSC

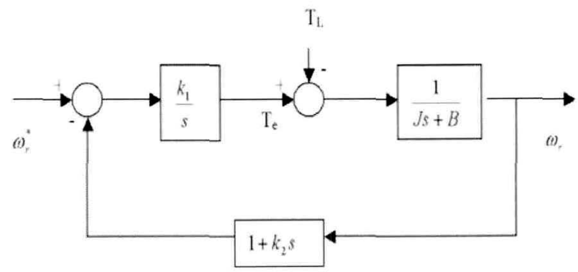

Fig. 4 Relation between command speed and motor speed

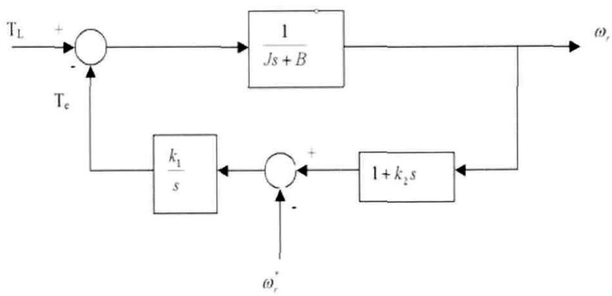

Fig. 5 Relation between load torque and motor speed

For a step change of load torque the motor speed can be calculated as:

$$\omega_r(s) = \frac{\frac{1}{k_1 * k_2}}{\frac{J}{k_1 * k_2}s + 1} \frac{T_L(s)}{s} \quad (19)$$

This represents a first order equation with a gain equal to;

$$M_{dip} = \frac{T_L}{k_1 * k_2} \tag{20}$$

This represents the maximum dip in motor speed at a load torque change from no load to full load. During transient in this case, the controller tries to reject this disturbance. So, the dip should be less than the value in (20). Based on equations (17) and (20) the CSC parameters can be calculated to provide a motor speed with a certain damped response and a full load torque rejection with a predefined maximum dip.

In equation (19) as $(k_1 * k_2)$ increases, the load torque disturbance rejection is faster and its maximum dip is smaller.

5. The CSC Application to 3hp Induction Motor

To analyze the CSC performance, it is applied to control the speed of a 3hp induction motor having an inertia of J=0.089 $kg.m^2$ and 12 Nm full load torque.

5.1 Defining required system performance

When defining a 2rad/sec maximum dip for a 12Nm full load disturbance and a critically damped speed response for reference speed step change, the CSC parameters can be calculated as follows:

$$k_1 * k_2 = \frac{T_L}{M_{dip}} = \frac{12}{2} = 6$$

$$k_2 = 2\sqrt{\frac{J}{k_1}} = 2\sqrt{\frac{Jk_2}{6}}$$

$$k_2 = \frac{4 * J}{6} = \frac{4 * 0.089}{6} = 0.0593$$

$$k_1 = \frac{6}{k_2} = \frac{6}{0.0593} = 101.1$$

Using these values of the CSC parameters, Fig.6 shows the controller output and the motor output speed response to a 120rad/sec step change of speed reference for different values of maximum allowable torque (controller output T_{max}).

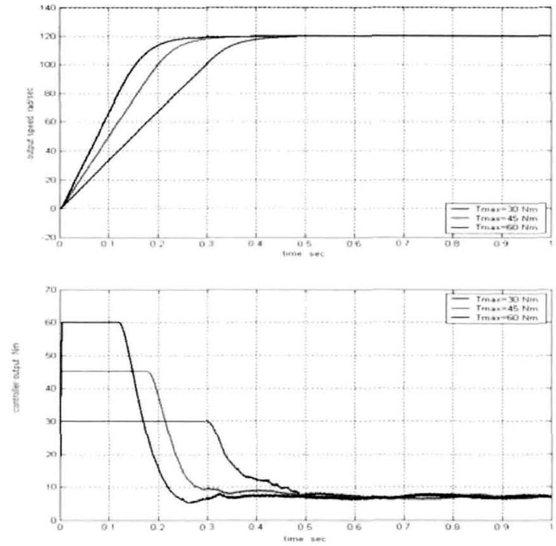

Fig. 6 Responses to step change of speed reference at different values of T_{max}

Fig.6 shows that the calculated CSC parameters can ensure a fast and critically damped response for the motor output speed even with different maximum acceleration of the system.

To show the influence of load torque on speed, a load torque change from no load to 12Nm full load is applied to the motor at time=0.75sec then removed after 0.5sec at time=1.25sec. The system performance is shown in Fig.7. The speed response in this figure shows that a fast load torque compensation is achieved with a maximum dip of 2rad/sec.

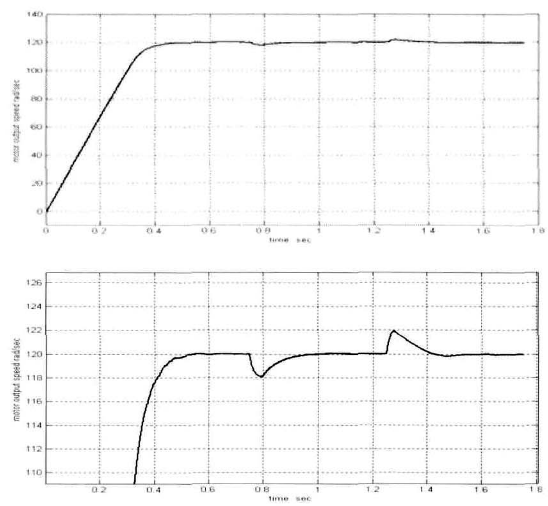

Fig. 7 Speed responses to full load disturbance (without and with zooming)

As shown in Fig.7, the CSC with its calculated parameters behaves as an expert controller providing fast and critically damped speed response with a maximum dip of 2rad/sec (as defined) and also a fast load disturbance rejection.

6. The CSC Application to 50hp Induction Motor

To demonstrate the effectiveness of the CSC, it is applied to control the speed of a 50hp induction motor having an inertia of J = 1.662 kg. m^2 and full load torque 200 Nm and a 300 Nm maximum allowable torque of the CSC output.

The controller parameters k_1 and k_2 can be calculated based on equations. (17) and (20) to provide a critically damping speed response with a maximum full load disturbance dip of 2.5rad/sec as follows:

$$k_1 * k_2 = \frac{T_L}{M_{dip}} = \frac{200}{2.5} = 80$$

$$k_2 = \frac{4*J}{80} = \frac{4*1.662}{80} = 0.0831$$

$$k_1 = \frac{80}{k_2} = \frac{80}{0.0831} = 962.7$$

A proposal for a set of benchmark tests for evaluation of the speed controller performance is suggested in [8]. The tests would need to be performed for a number of reference speed settings, ideally, for all of the following transient operating regimes:

- Large step speed commands from standstill, under rated inertia and with an increased inertia;
- Small reference step changes, with rated and with increased inertia;
- Step load torque application;
- Reversing transient;
- Robustness to rotor resistance variation.

Using the calculated values of the CSC parameters, all the above mentioned tests will be conducted to evaluate the CSC performance. Fig.8 shows the performance of the drive system to a 120rad/sec step change of speed reference and a 200Nm full load torque is applied to the motor at time=0.75sec then removed after 0.5sec at time=1.25sec. Fig.8 shows that the CSC satisfies the required performance; fast and critically damped speed response with a maximum speed dip less than 2.5rad/sec for a full load disturbance. The same test shown in Fig.8 is repeated but at different step changes of reference speed. The full load torque disturbance is the same. Fig.9 shows the responses of the drive system. As shown in Fig.9, the system behavior is the same in all cases which ensures the intelligent properties of the CSC.

Increased inertia of 3 times is achieved to test the CSC performance at this condition. Fig.10 shows the drive system responses to a step change of reference speed (160rad/sec and 80rad/sec) followed by a step reduction of 40rad/sec. Even with this effective increase of inertia, the CSC still has the same performance at all cases.

To test the CSC robustness to rotor resistance variation, the rotor time constant is doubled and the performance is compared with the original rotor time constant. Results shown in Fig.11 show the robustness of the CSC to rotor resistance variation. Also, it is clear that the CSC adapts its output as an expert controller to provide the required performance.

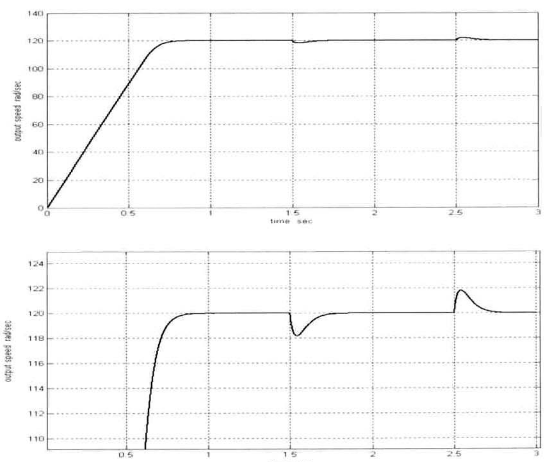

Fig. 8 Responses to step change of speed followed by a full load disturbances (without and with zooming)

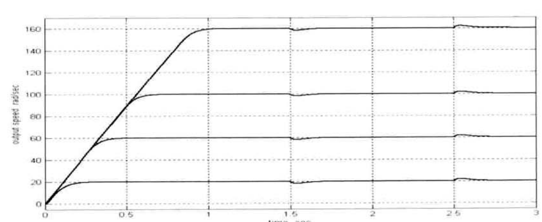

Fig. 9 Responses to different step change of speed reference and full load torque disturbances

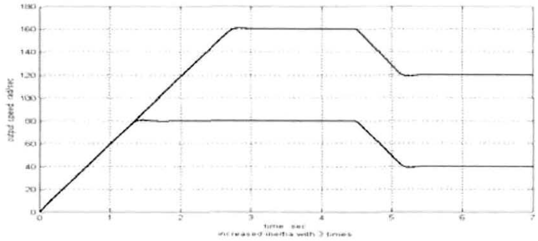

Fig. 10 Responses to a step change of reference speed followed by a step reduction with different inertias

The next section shows the performance of the CSC for a different required performance of the drive system. The case is to obtain a drive system with a critically damped speed response and a maximum full load disturbance dip of 0.5rad/sec. Based on these requirements the CSC parameters can be calculated as follows:

$k_1 = 24067, \quad k_2 = 0.01662$

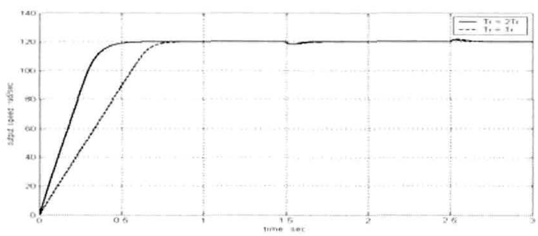

Fig. 11 responses with rotor resistance variations

Fig.12 shows the performance of the drive system to a 120rad/sec step change of speed reference and a 200Nm full load torque is applied to the motor at time=0.75sec then removed after 0.5sec at time=1.25sec. Fig. 12 shows the motor speed without and with zooming; also, it shows the CSC output. It is clear that the motor is running with its maximum acceleration direct to the required reference speed. Also, the influence of full load torque disturbance is as requested (less than 0.5rad/sec).

Fig. 13 shows the drive system responses to a 120rad/sec step change of speed reference, followed by a 200Nm full load disturbances, followed by a 20rad/sec step reduction of reference speed. Fig. 13 shows the motor output speed without and with zooming, as well as the CSC output.

Based on the results shown in Fig.12 and Fig. 13, the CSC is expected to become the ultimate solution for high-performance drives of the next generation.

7. Conclusions

This paper introduces a classical speed controller (CSC) which combines the advantages of both classical controllers and intelligent controllers in a classical form. The Fuzzy Logic controller idea was used to obtain the CSC output equation, whereby the CSC equation was based on the speed error and its change. The CSC was simulated in a z-domain using the MATLAB/SIMULINK program. The CSC parameters were calculated based on the motor mechanical equation and a predefined system performance. The CSC was applied to control the speed of a field oriented controlled induction motor with different ratings; 3hp and 50hp. Speed responses for a variety of operating conditions were studied. In all the operating conditions, the CSC reacts as an intelligent controller to provide the required system performance. Based on the results obtained in this paper, the CSC is expected to become the ultimate solution for high-performance drives of the next generation.

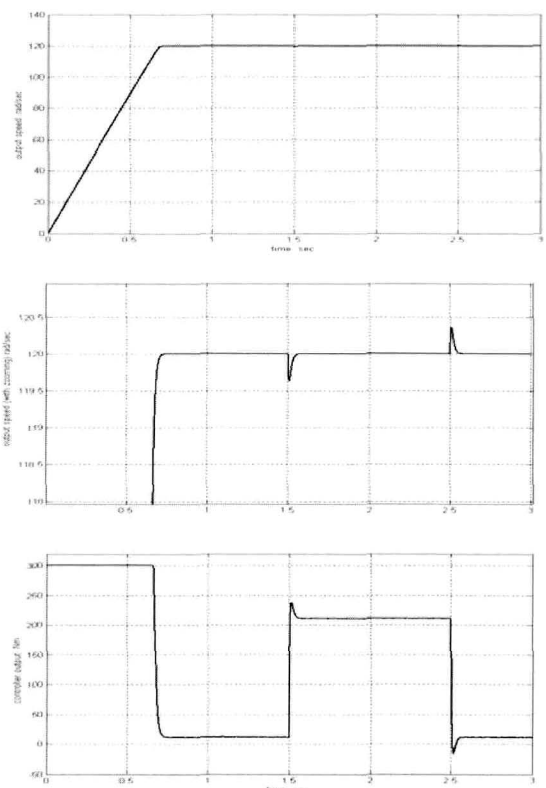

Fig. 12 CSC performance to provide a critically damped speed response and a maximum full load disturbance dip of 0.5rad/sec

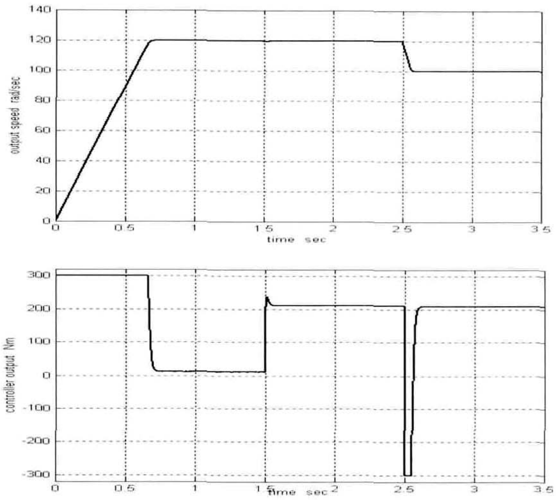

Fig. 13 CSC performance at different operating conditions

Appendix

List of Symbols:

R_s, L_{ls}: stator resistance and leakage inductance
R'_r, L'_{lr}: rotor resistance and leakage inductance
L_m: magnetizing inductance
L_s, L'_r: total stator and rotor inductances
V_{qs}, i_{qs}: q axis stator voltage and current
V'_{qr}, I'_{qr}: q axis rotor voltage and current
V_{ds}, i_{ds}: d axis stator voltage and current
V'_{dr}, I'_{dr}: d axis rotor voltage and current
φ_{qs}, φ_{ds}: stator q and d axis fluxes
φ'_{qr}, φ'_{dr}: rotor q and d axis fluxes
ω_m: angular velocity of the rotor
θ_m: rotor angular position
Phir: d_axis rotor flux
P: number of pole pairs
ω_r: electrical angular velocity (ω_m * P)
θ_r: electrical rotor angular position (θ_m *P)
T_e: electromagnetic torque
T_L: shaft mechanical torque
J: combined rotor and load inertia coefficient
B: combined rotor and load viscous friction coefficient
ω_m^* : reference speed command
ω_{mo}^* : previous sampled speed command
ω_{mo} : previous sampled motor speed

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