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Indirect Field Oriented Control of Induction Motor Drive Using Fuzzy Controller

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ABSTRACT - This paper presents the theory, design and simulation of a fuzzy logic based controller used for an indirect field oriented controlled three phase induction motor (IM). Field Oriented Control (FOC) theory is the base of special control method for induction motor drives. With this theory induction motors can be controlled like a separately excited dc motor. This method enables the control of field and torque of induction machine independently by manipulating the corresponding oriented quantities. Induction motor is modeled in synchronous reference frame in term of *dq* form. Three speed control techniques, Direct, Scalar and conventional PD are used to compare the performance of the control system with fuzzy logic controller. The models are carried out using MATLAB/SIMULINK. The simulation results demonstrate that the performance of the Indirect Field Oriented Control (IFOC) technique with fuzzy logic controller is better, especially with dynamic disturbances than that for other three types of control.

Keywords: *Field Oriented Control, Induction Motor Drive, Fuzzy Logic Controller, MATLAB/SIMULINK*

المستخلص - هذه الورقة تقدم النظري , التصميم والمحاكاة لحاكمة المنطق الغامض التي تستخدم تحكم توجيه المجال غير المباشر, للتحكم في المحرك الحثي ثلاثي الاطوار. نظرية تحكم توجيه المجال المباشر, تمثل الأساس لطرق التحكم الخاصة في المحركات الحثية. بهذه النظرية يمكن التحكم في المحرك الحثي مثل محركات التيار المستمر منفصل الاثارة. هذا الاسلوب يمكن من التحكم في المجال والعزم للمحرك الحثي كلاً على حدا , وذلك بمعالجة الكميات المقابلة لكلٍّ. تمت نمذجة المحرك الحثي في الاطار المرجعي التزامني في صيغة المباشر والمتعامد dq . ثلاث تقنيات للتحكم في السرعة , و هي المباشر , القياسي والمتحكم التقليدي التناسبي التفاضلي استخدمت لمقارنة الآداء مع نظام التحكم ذو حاكمة المنطق الغامض. النماذج تم ايجادها باستخدام الحزمة البرمجية للمحاكاة ماتلاب. نتائج المحاكاة توضح أنّ تقنية تحكم توجيه المجال غير المباشر باستخدام حاكمة المنطق الغامض , خصوصاً عند الخلل الدناميكي أفضل من أنواع التحكم الثلاث الأخرى.

INTRODUCTION

Three phase induction motors are used in industry for converting electrical power into mechanical power. They are considered to be simple, rugged, robust, effcient, and suiTable for applications in hursh environments. However, despite their popularity, their controllability remains a difficult task using conventional control methods. The control difficulty is associated with high nonlinearity of the motor's behaviour, complexity of its analytical model and presence of interactive multivariable structures. Therefore, designing a conventional controller takes significant time and effort and requires the presence of an accurate model of the motor.

In recent years, the advances in power electronics and computing fields have made it possible to use three phase induction machines in high performance applications [1]. Also, more robust and intellignt controllers have been employed for induction motor control. One of those intelligent controller is the Fuzzy Controller. Fuzzy controllers allow the human experience to be incorporated in the control process [2].

Fuzzy controller, unlike conventional ones, can be designed without the need for an accurate model or with less information about the controller system, which applies in the induction motor's case. FLC offers a linguistic approach to develop control algorithms for any system. It maps the input-output relationship based on human expertise and hence, does not require an accurate mathematical model of the system and can handle the nonlinearities that are generally difficult to model. This consequently makes the FLC tolerant to parameter variation and more accurate and robust[3]. The vector control or field oriented control (FOC) theory is the base of a special control method for induction motor drives. With this theory induction motors can be controlled like a separately excited dc motor [4]. This method enables the control of field and torque of the induction machine independently (decoupling) by manipulating the corresponding field oriented quantities. Depending on previous research, Fuzzy logic has variety of applications applied to induction motors. For instance, it is used for motor control, control enhancement, Fault detection and diagnoses. The applications of fuzzy control in motor control performance enhancement include rotor resistance (Rr) and stator resistance (Rs) compensation in addition to torque ripple minimization . The objective of this paper is to test drive system performance (Rising time, overshoot, time to the peak, and settling time) using FLC and compare it with Direct, Scalar, and conventional controller, and also to study the effect of load disturbance.

INDUCTION MOTOR MODEL

The motor equation in the d-q reference frame can be obtained by linking Park's and Clark's transformation [4, 5] in the form of :

$$v_{s\_\alpha\beta} = v_{s\_dq} e^{j\theta_s} \quad (1)$$

$$i_{s\_\alpha\beta} = i_{s\_dq} e^{j\theta_s} \quad (2)$$

$$\lambda_{s\_\alpha\beta} = \lambda_{s\_dq} e^{j\theta_s} \quad (3)$$

The substitution of equations (1) – (3) into the below voltage equation of induction motor :

$$v(t) = Ri(t) + \frac{d}{dt}\lambda(t) \quad (4)$$

Results in the following equations :

$$v_{sd} = R_s i_{sd} + \frac{d}{dt}\lambda_{sd} - \omega_s \lambda_{sq} \quad (5)$$

$$v_{sq} = R_s i_{sq} + \frac{d}{dt}\lambda_{sq} + \omega_s \lambda_{sd} \quad (6)$$

The same method can be applied to obtain the rotor voltage equations:

$$v_{rd} = R_r i_{rd} + \frac{d}{dt}\lambda_{rd} - \omega_{sl} \lambda_{rq} \quad (7)$$

$$v_{rq} = R_r i_{rq} + \frac{d}{dt}\lambda_{rq} + \omega_{sl} \lambda_{rd} \quad (8)$$

Hence,

$$\lambda_{sd} = L_s i_{sd} + L_m i_{rd} \quad (9)$$

$$\lambda_{sq} = L_s i_{sq} + L_m i_{rq} \quad (10)$$

$$\lambda_{rd} = L_r i_{rd} + L_m i_{sd} \quad (11)$$

$$\lambda_{rq} = L_r i_{rq} + L_m i_{sq} \quad (12)$$

The mathematical model of the induction motor in term of d-q reference can be obtained by substituting equations (9)-(12) into (5)-(8) [6]:

$$\begin{bmatrix} v_{sd} \\ v_{sq} \\ v_{rd} \\ v_{rq} \end{bmatrix} = \begin{bmatrix} R_s + pL_s & -\omega_s L_s & pL_m & -\omega_s L_m \\ -\omega_s L_s & R_s + pL_s & -\omega_s L_m & pL_m \\ pL_m & -\omega_{sl} L_m & R_r + pL_r & -\omega_{sl} L_r \\ -\omega_{sl} L_m & pL_m & -\omega_{sl} L_r & R_r + pL_r \end{bmatrix} x \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{bmatrix} \quad (13)$$

FIELD ORIENTED CONTROL

Direct field orientation was introduced by Blaschke. Two Hall Effect sensors mounted in the air gap are used to estimate the rotor flux based on the air gap measurement. Since it was not desirable to install flux sensors in the motor air gap, the Indirect Field Orientation Control (IFOC) approach is introduced. This approach estimates the rotor flux from the measured currents and speed without the need for flux measuring sensors. In the indirect field orientation (IFO), the angular position, θ_r, of the rotor flux vector is determined indirectly as [4,7,8]:

$$\theta_r = \int_0^t \omega_r^* dt + p_p \theta_M \quad (14)$$

where ω_r^* denotes the rotor frequency required for field orientation and θ_M is the angular displacement of the rotor, measured by a shaft position sensor, typically a digital encoder. The required rotor frequency can be computed directly from motor equations under the field orientation condition. With $\lambda_r^e = \lambda_{DR}$,

$$i_r^e = \frac{1}{L_r}(\lambda_{DR} - L_m i_S^e), \quad (15)$$

The rotor voltage equation

$$\frac{d\lambda_r^e}{dt} = -R_r i_r^e - j\omega_r \lambda_r^e \quad (16)$$

which, when substituted (15) in (16) yields

$$\lambda_{DR}[1 + \tau_r(p + j\omega_r)] = L_m i_S^e, \quad (17)$$

where τ_r denotes the rotor time constant, L_r/R_r. and $p = \frac{d}{dt}$, Splitting (17) into the real and imaginary parts gives

$$\lambda_{DR}(1 + p\tau_r) = L_m i_{DS} \quad (18)$$

and

$$\omega_r \tau_r \lambda_{DR} = L_m i_{QS} \quad (19)$$

Replacing ω_r with ω_r^*, λ_{DR} with λ_r^*, and i_{QS} with i_{QS}^* in the last equation, and solving for ω_r^*, yields

$$\omega_r^* = \frac{L_m}{\tau_r} \frac{i_{QS}^*}{\lambda_r^*}, \quad (20)$$

in the steady state of the motor (p = 0),

$$\lambda_r^* = \lambda_{DR}^* = L_m i_{DS}^*, \quad (21)$$

which, when substituted in (20), gives

$$\omega_r^* = \frac{1}{\tau_r} \frac{i_{QS}^*}{i_{DS}^*}, \quad (22)$$

Variables i_{DS}^* and i_{QS}^* represent the required flux-producing and torque-producing components of the stator current vector, i_S^*. The reference current i_{DS}^* corresponding to a given reference flux, λ_r^*, can be found from (18) as

$$i_{DS}^* = \frac{\tau_r p + 1}{L_m} \lambda_r^* = \frac{1}{L_m}\left(\tau_r \frac{d\lambda_r^*}{dt} + \lambda_r^*\right) \quad (23)$$

while the other reference current, i_{QS}^*, for a given reference torque, T_M^*, can be obtained

$$T_M = k_T \lambda_{DR} i_{QS}, \quad (24)$$

Then

$$i_{QS}^* = \frac{1}{k_T} \frac{T_M^*}{\lambda_r^*}. \quad (25)$$

A drive system with indirect rotor flux orientation is shown in Figure (1) [4]. In accordance with (14), the angle, θ_r, of the rotor flux vector used in the DQ → dq transformation is determined as

$$\theta_r = \theta^* + \theta_o, \quad (26)$$

where θ^* denotes the time integral of the reference rotor frequency, ω_r^*, and $\theta_o = p_p\theta_M$ is the angular displacement of the rotor in an equivalent two-pole motor [4].

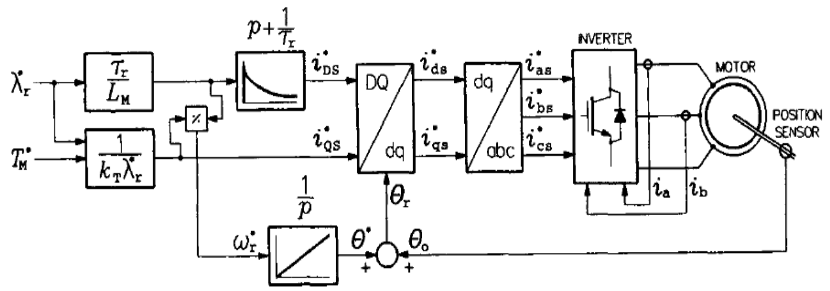

Figure 1: Block diagram of the ASD with indirect rotor flux orientation

FUZZY CONTROLLER ARCHITECTRE

The fuzzy controller has four main components [9,10]:

- ✓ The fuzzification interface simply modifies the inputs so that they can be interpreted and compared to the rules in the rule-base.converts the crisp input into fuzzy variables.
- ✓ The Rule-base holds the knowledge, in the form of a set of rules, of how best to control the system.
- ✓ The inference mechanism evaluates which control rules are relevant at the current time and then decides what the input to the plant should be.
- ✓ The defuzzification interface converts the conclusions reached by the inference mechanism into the inputs (crisp) to the plant. In this work, Center Of Area (COA) is used as a defuzzification method.

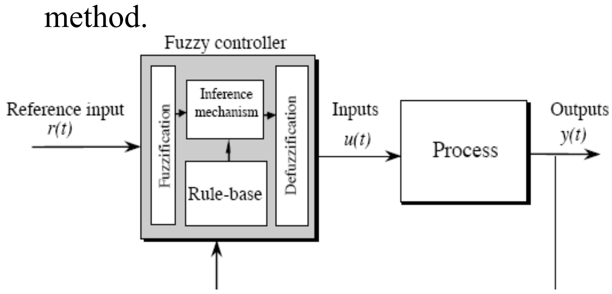

Figure 2: Fuzzy controller architecture

In this paper the fuzzy controller uses both the speed error (e) and its rate of change (ce) as inputs, and the change in electromagnetic torque (ΔTe) as output. In motor control system, the function of fuzzy controller is to convert linguistic control rules into control strategy based on heuristic information or expert knowledge.

Figure 3. shows the fuzzy sets and corresponding triangular MF description of each signal, the membership function of the associated input and output linguistic variables is generally predefined on a common universe of discourse : NL (Negative Large), NM (Negative Medium), Z (Zero), PM (Positive Medium), PL (Positive Large)[11].

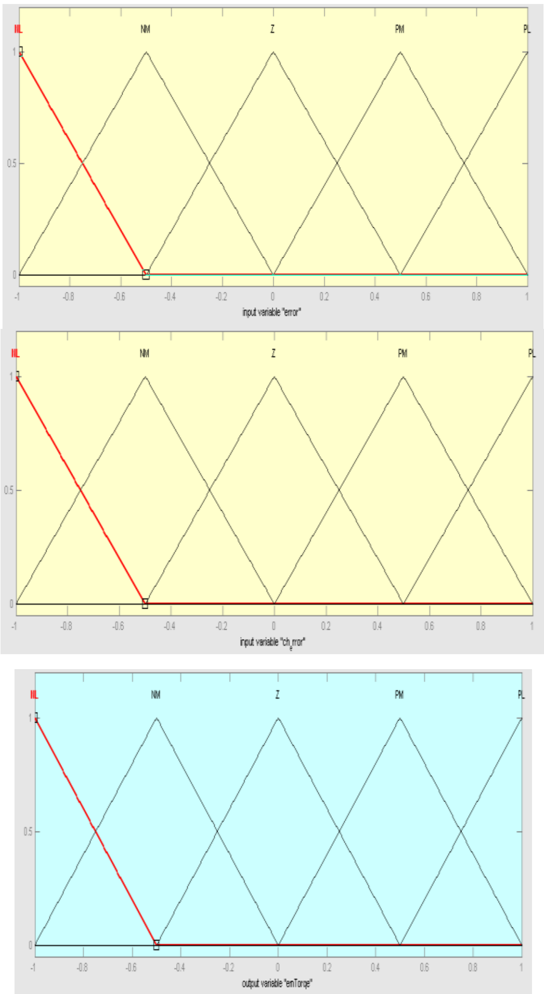

Figure 3: Triangular membership functions for fuzzy controller input (e and ce) and output (ΔTe)

The rules are drived by help of fuzzy inference systems in the Matlab/Fuzzy Logic Toolbox as in Figure 4., then rules represented in rule Tables [11].

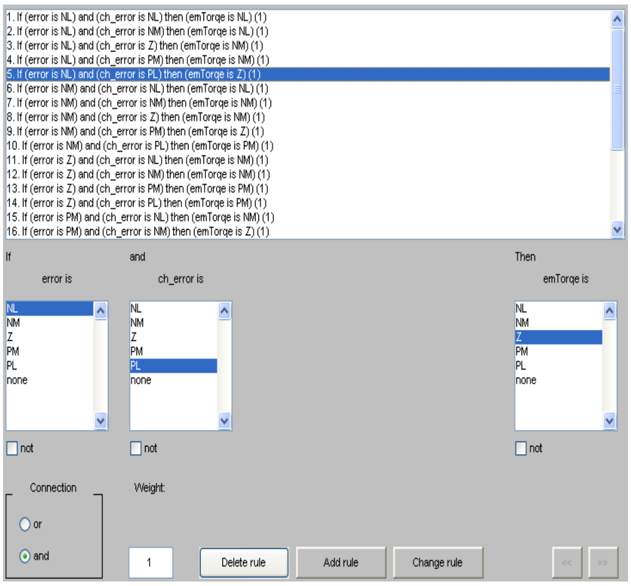

Figure 4: Constructor of rules

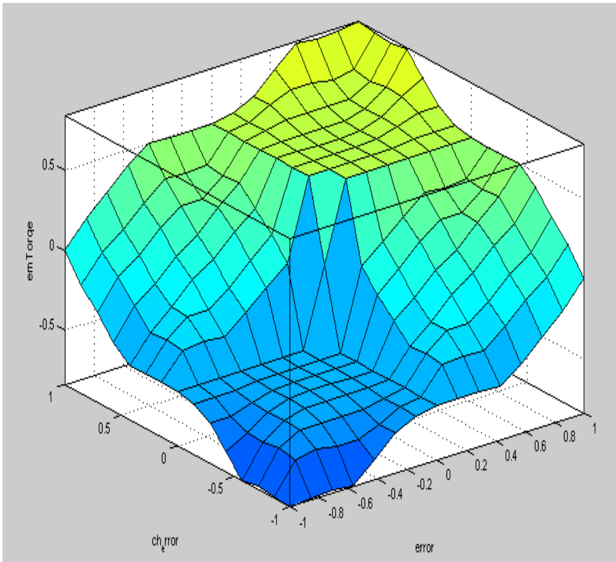

Figure 5: Surface viewer fuzzy rules

Table 1: Fuzzy rules Table of FC

e / ce	NL	NM	Z	PM	PL
NL	NL	NL	NM	NM	Z
NM	NL	NM	NM	Z	PM
Z	NM	NM	Z	PM	PM
PM	NM	Z	PM	PM	PL
PL	Z	PM	PM	PL	PL

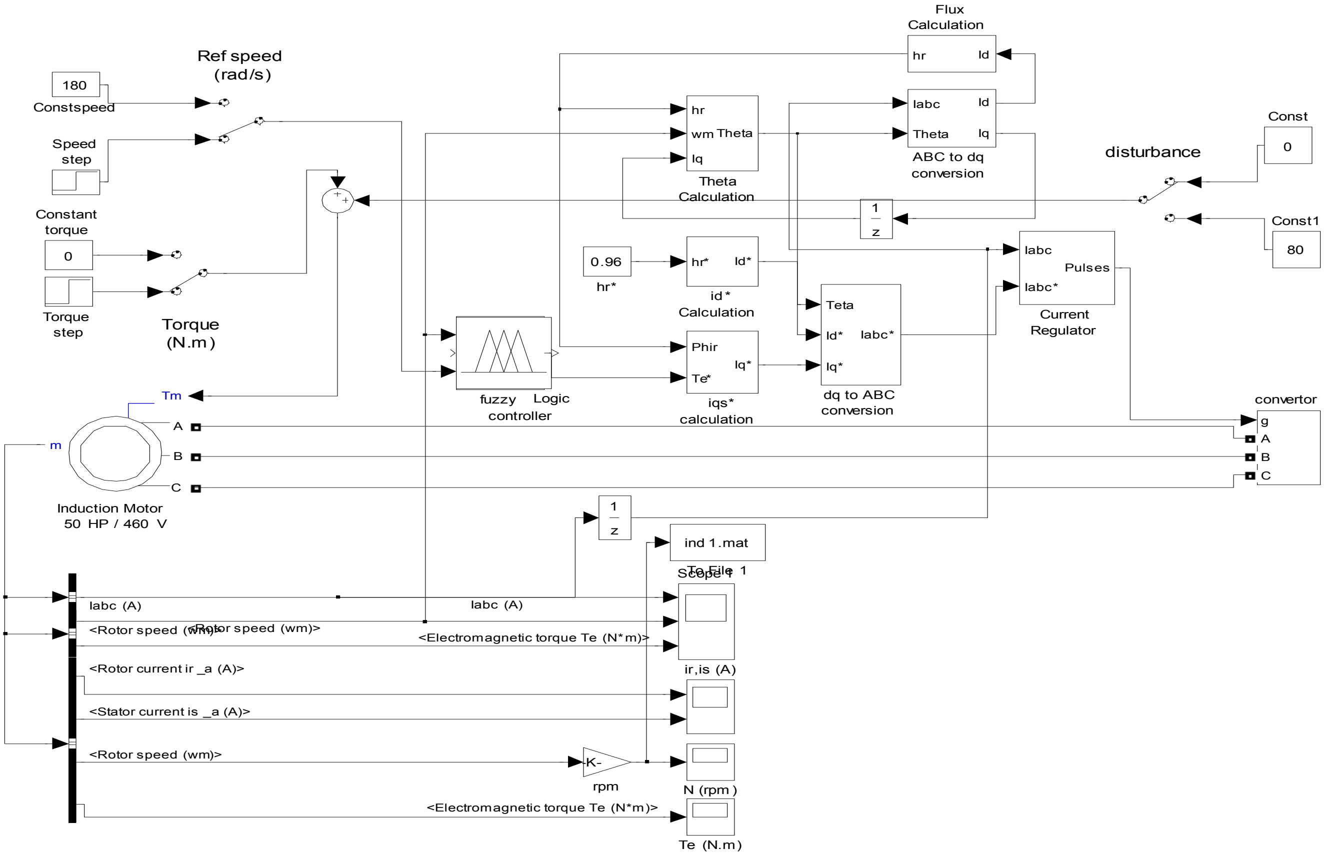

Figure 6: Indirect Field Oriented Control of Induction Motor Drive Using PD Fuzzy Controller in Matlab/Simulink

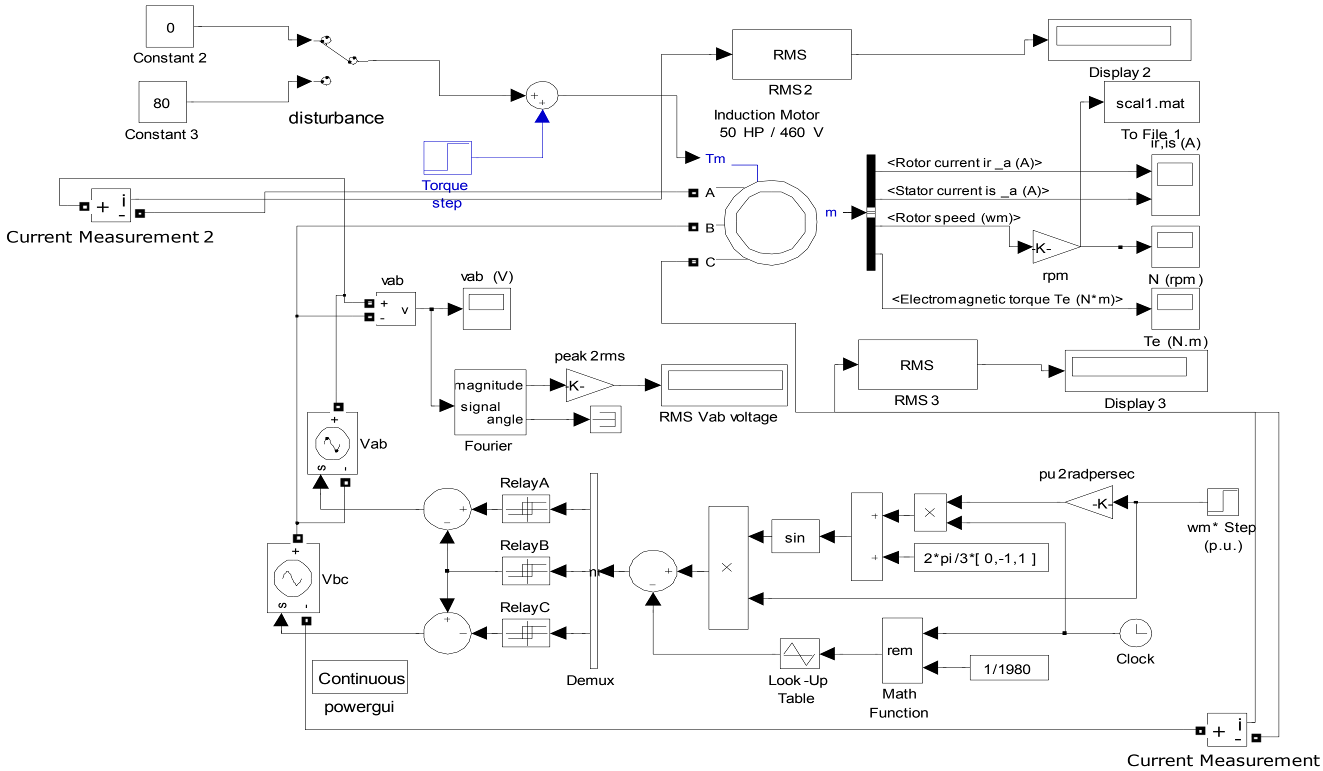

Figure 7: Scalar Control of Induction Motor Drive in Matlab/Simulnk

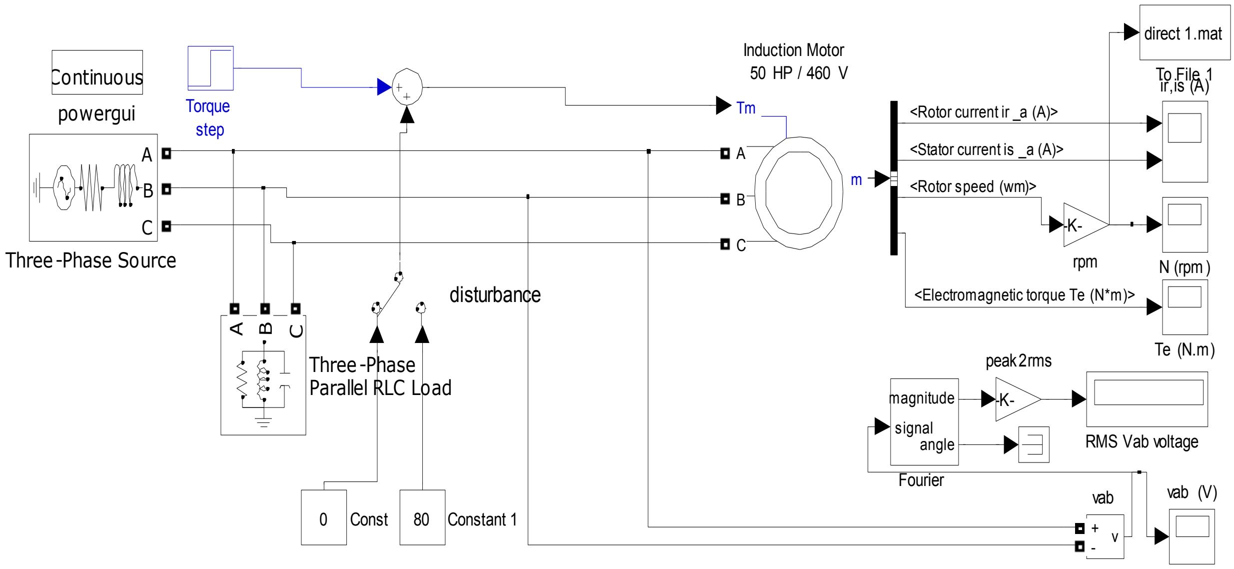

Figure 8. direct operation of Induction Motor Drive in Matlab/Simulink

DESIGN OF SYSTEM CONTROL SIMULINK

Figure 6 shows the Indirect Field Oriented Control of Induction Motor Drive Using PD Fuzzy Controller, and the same Figure represents Indirect Field Oriented Control of Induction Mo-tor Drive Using conventional PD Controller, when replace the fuzzy controller by conventional controller. Figures 7 and 8, show the Scalar Control of Induction Motor Drive and direct operation of Induction Motor Drive respectively.

SIMULATION RESULTS AND DISCUSSIONS

Many simulation tests were carried out on the four types of control, and their results were compared. Figure 9, and Table 2 show the speed response of induction motor on full load.

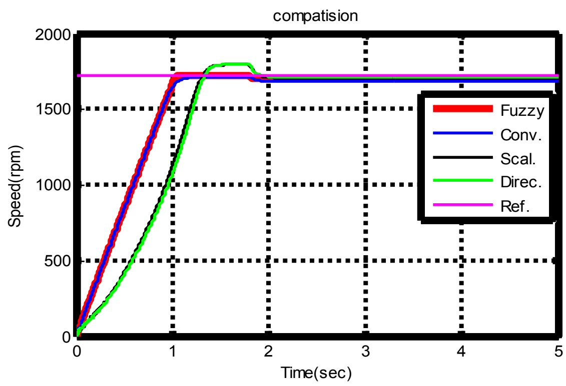

Figure 9: Speed response comparison at full load

Table 2 summarizes numerical values of rising time, peak overshoot, time to the peak and settling time.

Table 2 : Speed response comparison at full load

Type of control	Property			
	Rising time (10%-90%) (sec)	Settling time ±2(sec)	Overshoot (%)	Time to the peak (sec)
Direct on line	1.020	2.20	4.272	1.65
Scalar control	0.985	2.2O	4.285	1.74
PD conv. IFOC	0.825	2.35	-	1.37
PD fuz. IFOC	0.820	1.90	-	1.10

Figure 10-12 and Table 3 show the speed response copmarison and stator current and rotor current changes with load disturbance.

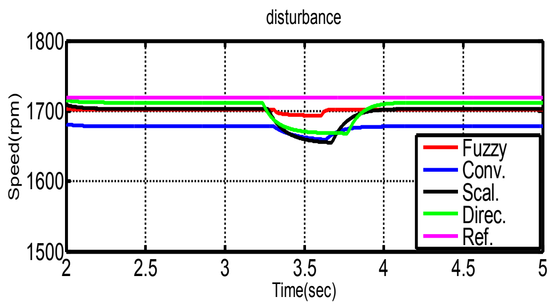

Figure 10: Speed response comparison with load disturbance

Table 3: the effect of disturbance

Type of control	Property		
	Drop in speed (e_{ds}%)	Increase in stator current %	Increase in rotor current %
Direct on line	2.94	39.77	45.00
Scalar control	2.88	36.56	43.02
PD conv. control	1.43	35.63	38.27
PD fuzzy cont.	0.47	34.83	36.14

Figure 11 and Figure 12 show the changes in stator current(Amp) and rotor current with load disturbance.

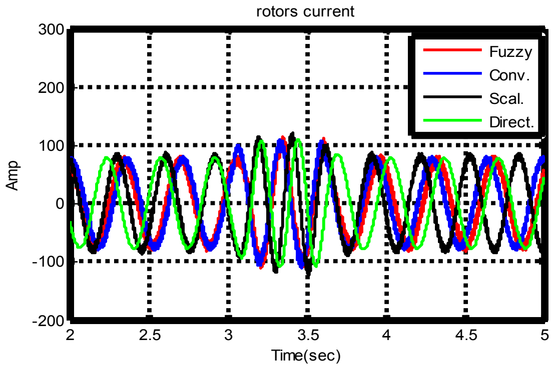

Figure 11: Change in rotor currents at disturbance

FLC performed better with respect to rise time, setting time, overshoot and time to peak compared to conventional, scalar, and direct operation as shown in Figure 9. On the same way, the load disturbance response shown in Figure 10 demonstrates that the FLC produces a better response than the other three systems. Table 2 summarizes the numerical values of rising time, settling time, overshoot and time to peak, the overshoot is the same in FLC and conventional control system, but better than scalar and direct operation systems. FLC shows a shorter rise time, settling time and time to peak. It is found that the FLC is more robust and did not show significant changes in its response due to load disturbance as shown on Table 3.

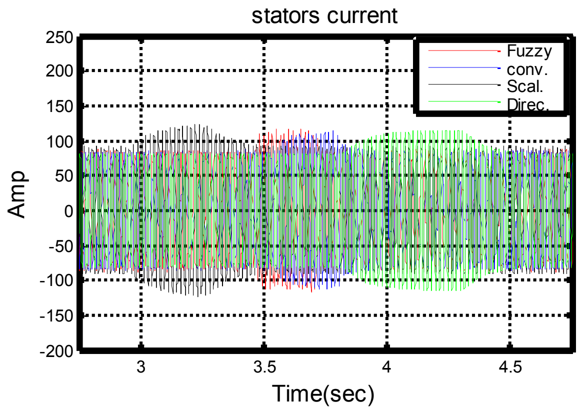

Figure 12: Change in stator currents at disturbance.

CONCLUSION

Indirect Field Oriented Controlled induction motor system has been introduced. The drive system was simulated using fuzzy logic controller, and its performance are compared with conventional PD, scalar, and direct operation. Simulation results showed that the performance of FLC is better than that for other types of controllers. beside that, simulation results showed that the fuzzy logic controller is more robust during load disturbances.

Appendix : Motor specification

Motor type, 3-phase Induction Motor, : Rotor type, Squirrel Cage, 50 hp, 1720 rpm, 460V, 60HZ, 4poles, $R_s = 0.087\Omega$
$R_r = 0.228\Omega$ $L_s = 0.8$mH $L_r = 0.8$mH $L_m = 34.7$mH, $J_n = 1.66$Kg.m^2 f = 0.1N.m.s

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