Journal of Applied Sciences Research, 8(6): 2881-2887, 2012
ISSN 1819-544X
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# ORIGINAL ARTICLES

## Design and Estimation of Double Side Fuzzy Controlled Wound Rotor Induction Motor

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**ABSTRACT**

In this paper, the fuzzy controller is designed for effective control of doubly fed wound rotor induction motor. This system has two fuzzy controllers, one in stator side and other for rotor side. Double side control leads to a more effective control design objectives such as steady state and transient characteristics of the closed loop system. If the conventional controllers are used the performance may depreciate. Fuzzy logic is integrated to overcome the problems with uncertainties in the machine parameters more effectively. The proposed controller gives better performance comparing with Fuzzy-PID controller. The modified fuzzy logic controller reduces the number of membership function there by the program complication is reduced during implementation. The effectiveness of the proposed controllers for different operating conditions of the drive system using MATLAB / Simulink is presented.

***Key words:*** Wound Rotor Induction Motor (WRIM), Fuzzy Logic Controller, Field Oriented Control (FOC)

### Introduction

In modern industrial applications the requirement of accurate dynamic control of motor has been ever increasing the recent past. The thyristor based control of DC machines has been used to satisfy the requirement. However the DC machine are found to be more expensive over the rotating machines and expected to have frequent maintenance. This has motivated the induction motor drives for wide range of applications requiring variable speed (P.C. Krause, 1988). In particular, the Wound Rotor Induction Motor has high starting torque and high performance and its applications are increased rapidly. The slip power can either be mechanically or electronically controlled for WRIM speed control. The researches developed various speed control techniques in the recent years.

Reference (P.C. Sen and K.H. Ma, 1975) shows the rotor side control of WRIM using chopper controlled external resistance technique. The chopper duty cycle is varied for the purpose of controlling the speed of the WRIM. A three phase-controlled rectifier is used in the rotor circuit to feed the external resistance, the effective rotor impedance is controlled by varying the firing angle of thyristors. Slip energy recovery drives were developed with several improvements as in (Gautam Poddar and V. T. Ranganathan 2004) and different schemes were designed to enhance the line power factor (Gautam Poddar and V. T. Ranganathan, 2006.). The position sensorless method was developed for rotor side FOC of WRIM as in (Rajib Datta and V.T. Ranganathan, 2001).

The stator and rotor side control of WRIM was developed. The fuzzy and PID controllers were used for speed regulation of the machine (I.Thangaraju and M.Madheswaran, 2010). Later, The rotor side control of WRIM using Neruo fuzzy controller was developed. The results were compared with PI controller and open loop responses. It is observed that the peak percentage overshoot is more in the controller performance (K. Naga Sujatha and K. Vaisakh J., 2010). In the present work the control of WRIM has been considered using stator and rotor side inverters with Field Oriented Control (FOC) based fuzzy controllers.

*II. Model Of The Proposed System:*

The block diagram of the proposed system is shown in Figure1. The system consists of uncontrolled rectifier with filter capacitor and the doubly fed Wound Rotor Induction Motor (WRIM). This system has the following Salient advantages. Machine current is almost sinusoidal hence it reduces the harmonic copper loss. Line side power factor is unity with no harmonic current injection. Continuous slip power recovery for all speed of the machine is possible. Power can flow in either direction of the inverters and permitting the machine to run on both directions. Similarly, regenerative braking can quickly stop the machine. Super synchronous speed of operation is possible.

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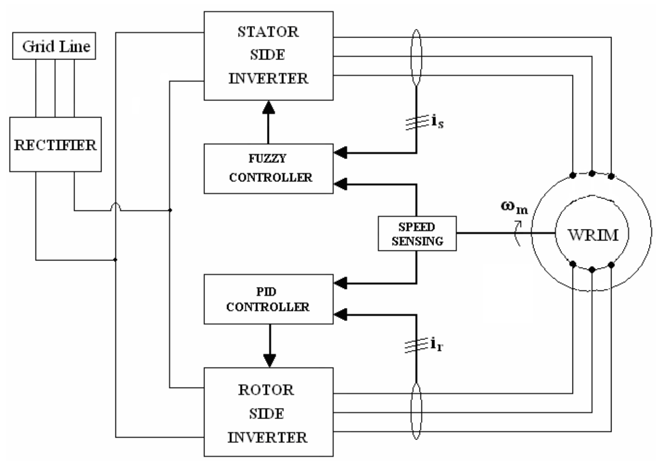


**Fig. 1:** Block diagram of the proposed system

The stator and rotor side converters are controlled by the modified fuzzy based field oriented controller which utilizes the actual speed and the stator currents.

*II.1. General WRIM model:*

In order to simplifie the WRIM, we apply the 3/2 transformation (P.C. Krause, 1988). Then we obtain expressions in terms of the two-axis coordinate system as used in DC motor control.

This leads to consider:

$$v_{sd}(t) = R_s i_{sd}(t) + \frac{d\lambda_{sd}(t)}{dt} - \frac{d\theta_s(t)}{dt}\lambda_{sq}(t) \quad (1)$$

$$v_{sq}(t) = R_s i_{sq}(t) + \frac{d\lambda_{sq}(t)}{dt} + \frac{d\theta_s(t)}{dt}\lambda_{sd}(t) \quad (2)$$

$$v_{rd}(t) = R_r i_{rd}(t) + \frac{d\lambda_{rd}(t)}{dt} - \frac{d\theta_r(t)}{dt}\lambda_{rq}(t) \quad (3)$$

$$v_{rq}(t) = R_r i_{rq}(t) + \frac{d\lambda_{rq}(t)}{dt} + \frac{d\theta_r(t)}{dt}\lambda_{rd}(t) \quad (4)$$

Where,

$v_{sd}$ and $v_{sq}$ are stator d-q axis voltages
$v_{rd}$ and $v_{rq}$ are rotor d-q axis voltages
$i_{sd}$ and $i_{sq}$ are stator d-q axis currents
$i_{rd}$ and $i_{rq}$ are rotor d-q axis currents
$R_s$ and $R_r$ are stator and rotor resistances
$\lambda_{sd}$ and $\lambda_{sq}$ are stator d-q axis flux linkages
$\lambda_{rd}$ and $\lambda_{rq}$ are rotor d-q axis flux linkages

The stator and rotor angular velocities $d\theta_s/dt$ and $d\theta_r/dt$ are expressed such as:

$$\frac{d\theta_s}{dt} = \omega_s \quad \text{and} \quad \frac{d\theta_r}{dt} = \omega_r$$

with the angular relationship:

$$\theta_s = \theta_r + \theta$$

The flux-linkage equations between currents and fluxes can be written as follows:

$$\lambda_{sd}(p) = L_s i_{sd}(p) + L_m i_{rd}(p) \quad (5)$$

$$\lambda_{sq}(p) = L_s i_{sq}(p) + L_m i_{rq}(p) \quad (6)$$

$$\lambda_{rd}(p) = L_r i_{rd}(p) + L_m i_{sd}(p) \quad (7)$$

$$\lambda_{rq}(p) = L_r i_{rq}(p) + L_m i_{sq}(p) \quad (8)$$

Where,

$L_s$ and $L_r$ are stator and rotor inductances
$L_m$ is mutual inductance
The electromagnetic torque $T_e$ can be written as follows

$$T_e = \frac{2pL_m}{3L_r}\left(i_{qs}^s \phi_{dr}^s - i_{ds}^s \phi_{qr}^s\right) \tag{10}$$

Where, p = Pairs of Poles

$$\phi_{ds}^s = L_r i_{dr}^s + L_m i_{ds}^s$$

$$\phi_{qr}^s = L_r i_{qr}^s + L_m i_{qs}^s$$

$\Phi_{dr}^s$ and $\Phi_{qr}^s$ are the rotor flux linkage components expressed in the stator reference frame.
The $qd_e$ - $qd_s$ transformation is shown in eq. (11) and (12).

$$i_{qs}^* = i_{qs}^{r*} \cos\theta_{rf}^* + i_{ds}^{r*} \sin\theta_{rf}^* \tag{11}$$

$$i_{ds}^* = -i_{qs}^{r*} \sin\theta_{rf}^* + i_{ds}^{r*} \cos\theta_{rf}^* \tag{12}$$

Here $\theta_{rf}$ represents the sum of slip and rotor angles.
The eq. from (13) to (15) shows the $qd_s$ - $abc$ transformation.

$$i_a^* = i_{qs}^* \tag{13}$$

$$i_b^* = -\frac{1}{2} i_{qs}^* - \frac{\sqrt{3}}{2} i_{ds}^* \tag{14}$$

$$i_c^* = -\frac{1}{2} i_{qs}^* + \frac{\sqrt{3}}{2} i_{ds}^* \tag{15}$$

A sinusoidal current source of variable magnitude and frequency is used to represent the fundamental component of the actual PWM inverter waveform. This avoids lengthy simulation times caused by the PWM switching.

### *III. Fuzzy Logic Controller:*

Here the modified fuzzy logic controller is used for both stator and rotor side controller. The controller structure is illustrated in figure.2 and the Fuzzy logic Rules used in the controller is shown in table I.

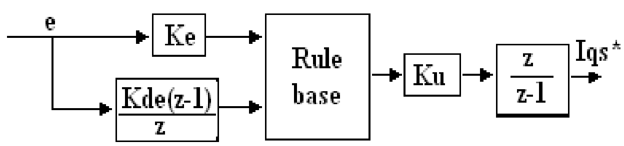


**Fig. 2:** Structure of the Fuzzy Logic Controller

The simulation of the proposed system is done based on simulink-block set and equation modeling technique, using MATLAB/simulink toolbox.

The effective and efficient control using fuzzy logic has emerged as a tool to deal with uncertain, imprecise or qualitative decision making problems. The FLC involves four stages namely Fuzzification, Rule-Base, Inference engine and Defuzzification. In this work the Mamdani type controller is used. This controller has the membership function in the output variable which will give accurate result.

In this work, the motor variables are speed ($\omega_m$) and stator current ($i_{sabc}$). The stator and rotor side converters are controlled by FLC. The reference speed and the actual speed are given as input to the FLC. The error is found by comparing the actual speed $\omega_m$ with reference speed $\omega_r$. From the error e the stator quadrature current $i_{qs}$ and the stator change in quadrature current $di_{qs}$ is calculated. Then the $i_{qs}$ error and $di_{qs}$ are fuzzified.

Here five linguistic variables are used for the input variable $i_{qs}$ and $di_{qs}$. That are negative big (NB), negative small (NS), zero (Z), positive small (PS), and positive big (PB). There are many types of membership functions, such as triangular-shaped, Gaussian, sigmoidal, pi-shaped trapezoidal-shaped, bell-shaped etc. the triangular membership function is used for simplicity and also to reduce the calculations. The reverse process of fuzzification is called defuzzification. The linguistic variables are converted in to a numerical variable. As the centroid method is considered to be the best well-known defuzzification method, it is utilized in the present model.

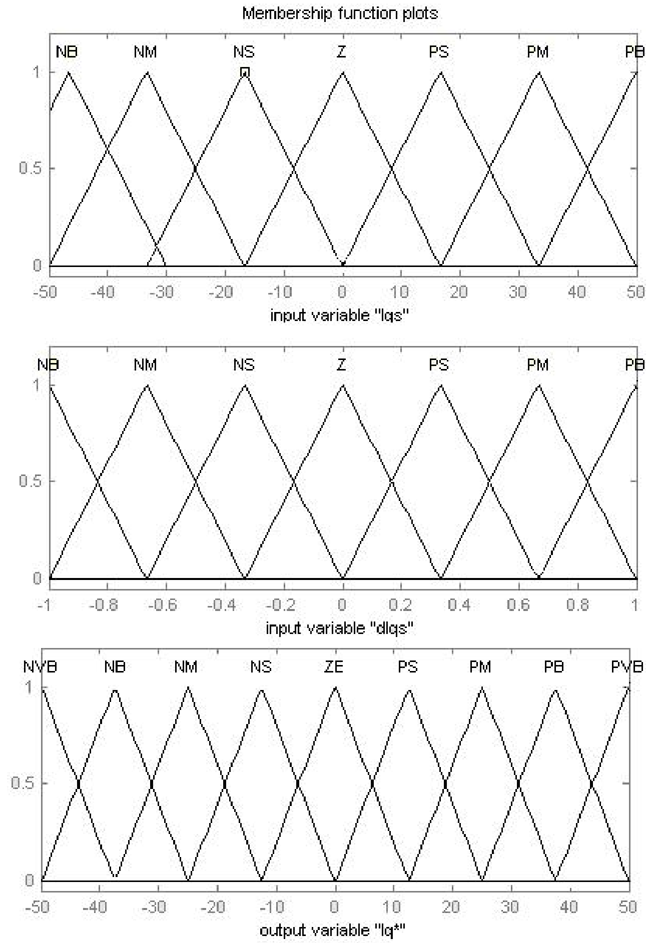


**Fig. 3:** Fuzzy memberships used for simulation

**Table 1:** fuzzy Rules

| | | | | | | |
|---|---|---|---|---|---|---|
| | $i_{qs}$ | | | | | |
| | | NB | NS | Z | PS | PB |
| | NB | NB | NB | NB | NS | Z |
| $di_{qs}$ | NS | NB | NB | NS | Z | PS |
| | Z | NB | NS | Z | PS | PB |
| | PS | NS | Z | PS | PB | PB |
| | PB | Z | PS | PB | PB | PB |

The defuzzified output is the reference quadrature current $i_q$*. The reference stator current $i_{sabc}$* is calculated from the $i_q$*, $i_d$* and theta. This reference stator current is utilized for generating the PWM signals for the stator side inverter. The input and output fuzzy membership functions are shown in Figure 3.

The control rules that relate the fuzzy output to the fuzzy inputs are derived from general knowledge of the system behavior, also the perception and experience.

## Results and Discussion

The proposed model has been simulated using Matlab/simulink toolbox. The Variation of speed from standstill to 100 rad/sec is shown in figure 5. The graph shows that the rise time is 0.04 sec and there is no peak overshoot. The corresponding torque variation is shown in figure 6.

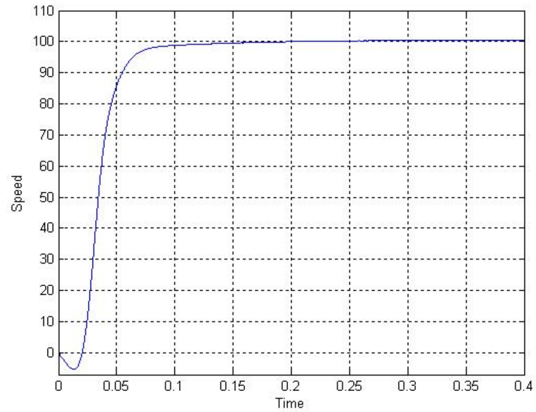


**Fig. 5:** Speed Variation with respect to Time Response

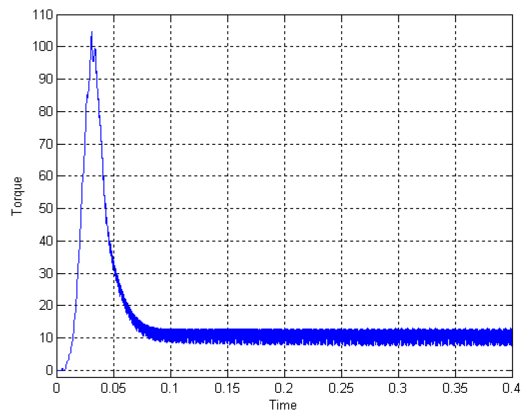


**Fig. 6:** Torque Variation with respect to Time Response

The Variations of three phase stator and rotor currents for the step speed change is shown in figure 7 and 8. The magnitude of current during starting is high then comes to low when speed settles at 100 rad/sec.

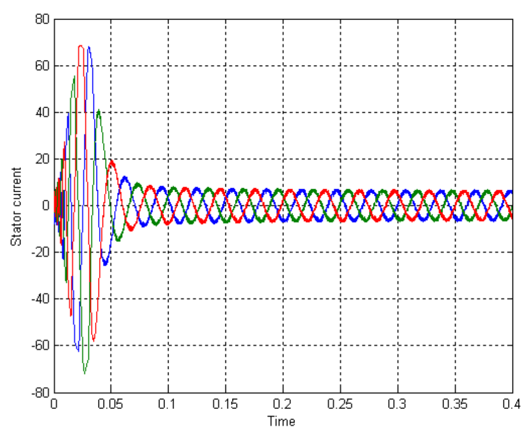


**Fig. 7:** Stator current with respect to Time Response

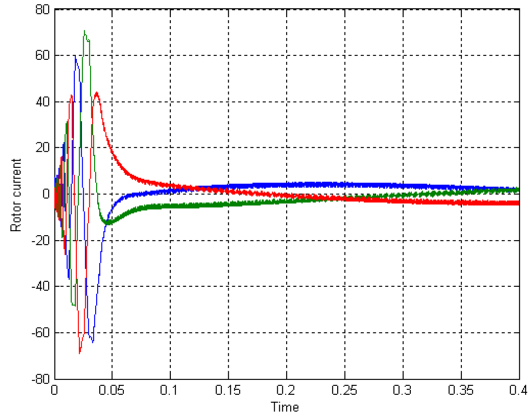


**Fig. 8:** Rotor current with respect to Time Response

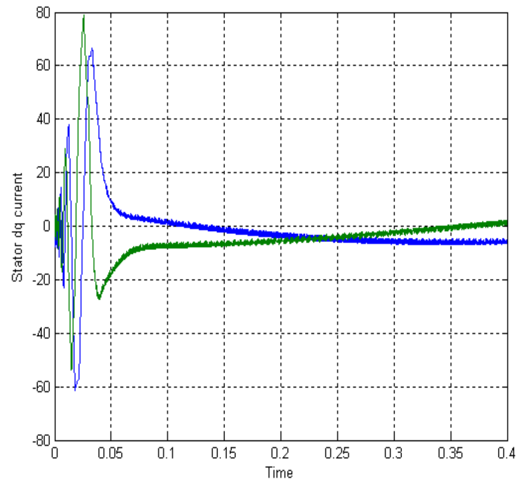


**Fig. 9:** Stator d-q currents with respect to Time Response

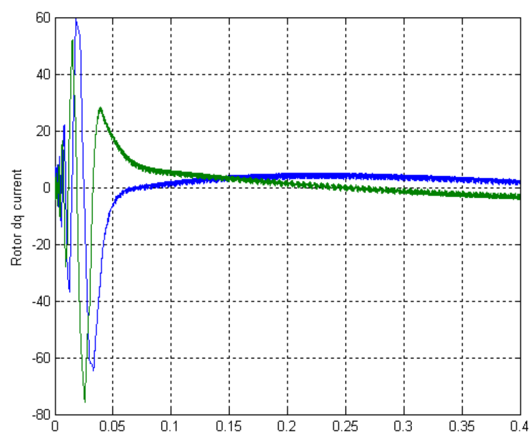


**Fig. 10:** Rotor d-q currents with respect to Time Response

*J. Appl. Sci. Res., 8(6): 2881-2887, 2012*

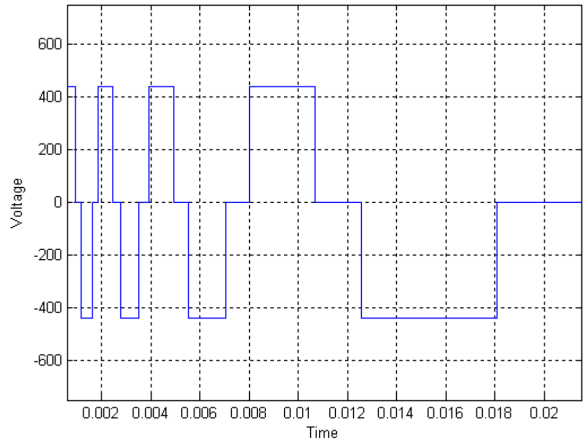


**Fig. 9:** Expanded view of Stator voltages with respect to Time Response

The Variations of d-q axis stator and rotor currents are shown in figure 7 and 8. The table II shows the performance comparison. Double side Fuzzy controller gives superior results then the Fuzzy-PID (I.Thangaraju and M.Madheswaran, 2010) controller.

**Table 2:** Performance Comparison

| Controllers (Stator – Rotor) | Raise Time(sec) | %Over shoot |
|---|---|---|
| Fuzzy – PID [6] | 0.10 | 1.85 |
| Fuzzy – Fuzzy | 0.04 | 0 |

*Conclusions:*

The performance of the two input modified fuzzy logic based FOC for stator and rotor side inverters of Double Inverter Fed WRIM is presented in this paper. The dynamic speed response of WRIM with fuzzy controller was estimated and found that the speed can be controlled effectively with the improved performance. The analysis provides the various useful parameters and the information for effective use of proposed system.

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