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Ziegler-Nichols (Z-N) Based PID Plus Fuzzy Logic Control (FLC) For Speed Control of A Direct Field-Oriented Induction Motor (DFOIM)

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Abstract
The induction motor is having non-linear torque and internal impedance characteristics. In this paper, a Ziegler-Nichols (Z-N) based PID plus fuzzy logic control (FLC) scheme is proposed for speed control of a direct field-oriented induction motor (DFOIM). The Z-N PID is adopted because its parameter values can be chosen using a simple and useful rule of thumb. The FLC is connected to the PID controller for enhancing robust performance in both dynamic transient and steady-state periods. The FLC is developed based on the output of the PID controller, and the output of the FLC is the torque command of the DFCIM. The complete closed-loop speed control scheme is implemented for the laboratory 0.14-hp squirrel-cage induction motor. Experimental results demonstrate that the proposed Z-N PID+FLC scheme can lead to desirable robust speed tracking performance under load torque disturbances.

***Index Terms*:** Induction Motor, Ziegler-Nichols (Z-N) based PID plus fuzzy logic control (FLC), Z-N PID, direct field-oriented induction motor (DFOIM)

I. Introduction

In recent years, field-oriented induction machine (FOIM) drives [1] have been increasingly utilized in motion control applications due to easy implementation and low cost. Besides, they have the advantage of decoupling the torque and flux control, which makes high servo quality achievable. However, the decoupling control feature can be adversely affected by load disturbances and parameter variations in the motor so that the variable-speed tracking performance of an IM is degraded. In general, both conventional PI and PID controllers have the difficulty in making the motor closely follow a reference speed trajectory under torque disturbances. In this regard, an effective and robust speed controller design is needed.

In [2]-[8], fuzzy-logic-based intelligent controllers have been proposed for speed control of FOIM drives. Those intelligent controllers are associated with adaptive gains due to fuzzy inference and knowledge base. As a result, they can improve torque disturbance rejections in comparison with best trial-and-error PI or PID controllers. Nonetheless, no performance advantages of intelligent controllers in combination with a PI or PID controller are investigated in [2]-[8].

Motivated by the successful development and application in [2]-[8], we propose a hybrid PID+ fuzzy controller consisting of a PID controller and a fuzzy logic controller (FLC) in a serial arrangement for speed control of FOIM drives, more specifically, direct field-oriented IM (DFOIM) drives. The Ziegler-Nichols (Z-N)) method in [9] is adopted for designing a PID controller (denoted as "the Z-N PID") because its design rule is simple and systematic. We next design a FLC carrying out fuzzy tuning of the output of the Z-N PID controller to issue adequate torque commands.

Based on a simulation model of the DFOIM drives incorporating the proposed controller, experiments are set up in a Mat lab /SIMULINK environment and implemented in real time using the MRC-6810 analog-to-digital (AD)/ digital-to-analog (DA) servo control card together with a DSP electronic controller. The results show that the incorporation of the proposed controller into the DFOIM drives can yield superior and robust variable-speed tracking performance.

II. Physical Phenomenon of Induction Motor and Control Structure

In this section, we introduce the DFOIM drive shown in Fig. 1. The dynamics of an induction motor can be described by synchronously rotating reference frame direct-quadrature (d-q) equations [10] as

$$\begin{bmatrix} \mathbf{v_{qs}^e} \\ \mathbf{v_{ds}^e} \\ \mathbf{0} \\ \mathbf{0} \end{bmatrix} = \begin{bmatrix} R_s + pL_s & w_e L_s & pL_m & w_e L_m \\ -w_e L_s & R_s + pL_s & -w_e L_m & pL_m \\ pL_m & (w_e - w_r) L_m & R_r + pL_r & (w_e - w_r) L_r \\ -(w_e - w_r) L_m & pL_m & (w_e - w_r) L_r & R_r + pL_r \end{bmatrix} \begin{bmatrix} \mathbf{i_{qs}^e} \\ \mathbf{i_{ds}^e} \\ \mathbf{i_{qr}^e} \\ \mathbf{i_{dr}^e} \end{bmatrix} \quad \text{--- (1)}$$

$$\mathbf{J_m\, p w_{rm} + B_m\, w_{rm} + T_L = T_e} \quad \text{--- (2)}$$

$$\mathbf{T_e = \frac{3N}{4}\, L_m\left(i_{qs}^e \,.\, i_{dr}^e - i_{ds}^e .\, i_{qr}^e\right)}, \quad \text{--- (3)}$$

$$\mathbf{w_{rm} = \frac{2}{N}\, w_r} \quad \text{--- (4)}$$

Where the notational superscript "e" stands for the synchronous reference frame: $\mathbf{v_{ds}^e}$, v_{qs}^e , i_{ds}^e , i_{qs}^e ,and i_{qr}^e stand for the d-axis and the q-axis stator voltages, stator currents and rotor currents; R_s , R_r , L_s and L_r denote the resistances and self-inductances of the stator and the rotor; Lm denotes the mutual inductance; Te and TL represent the electromagnetic and external force load torques, respectively; J m and B_m are the rotor inertia and the coefficient of viscous damping, respectively; ω_r and ω_{rm} denote the rotor and motor mechanical speeds; ω_e stands for electrical angular velocity; N is the number of poles of the motor mechanical speed; p stands for the differential operator (d /dt) . The notational superscript "s" in Fig. 1 stands for stationary reference frame. For a DFOIM drive, the flux has to fall entirely on d-axis. To control the speed of the IM, the speed controller of the DFOIM drive transforms the speed error signal e into an appropriate electromagnetic torque commandT_e^*.

III. Dynamic Modeling of Induction Motor

The per phase equivalent circuit of the machine is only valid in steady-state condition. When studying steady state performance of the machine, the electrical transients are neglected during load changes and stator frequency variations. In an adducible-speed drive, the machine normally constitutes an element with in a feedback loop, and therefore its transient behavior has to be taken in to consideration. Besides, high-performance drive control, such as vector or field-oriented control is based on the dynamic d-q model of the machine. Therefore, to understand vector control principles, a good understanding of the d-q model is mandatory.

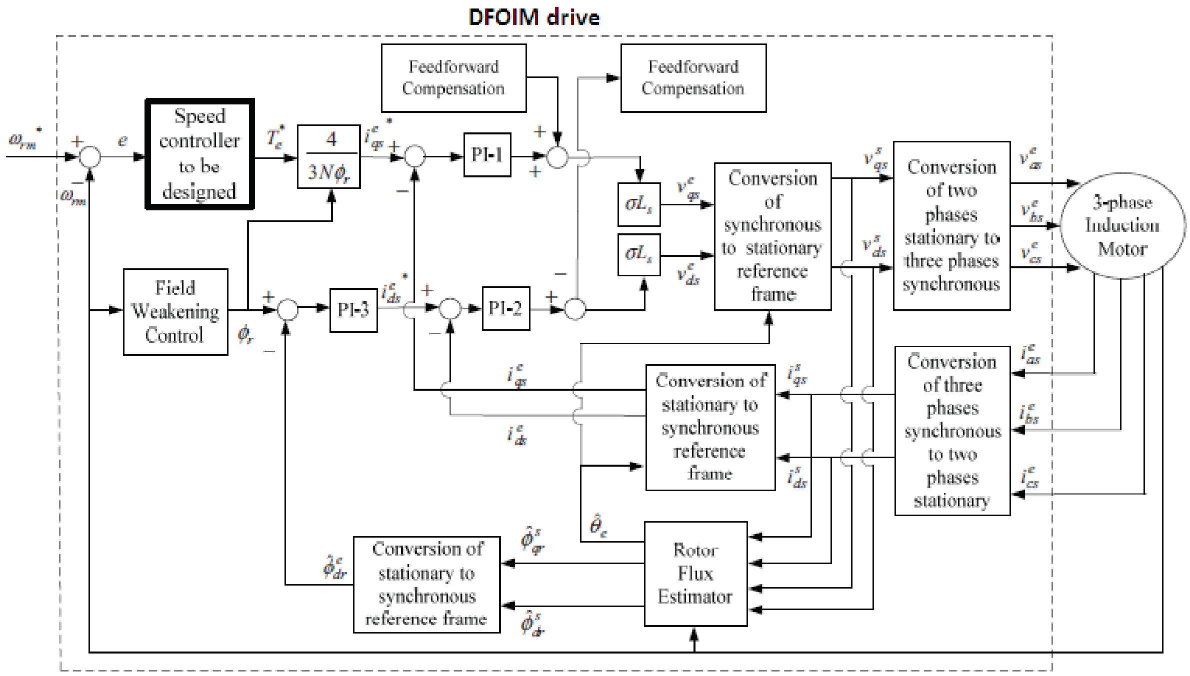

Fig.1.The block diagram of speed control of a DFOIM

3.1. Proposed Hybrid PID Plus Fuzzy Control for Test System

The structure of the proposed controller is shown in Fig. 2. The steps to acquire the Z-N PID [9] for speed control of the DFOIM in Fig. 1 are given as follows. First, we use a fixed step input ω_{rm} and a linear proportional speed controller. The proportional gain of the speed controller is increased until the

DFOIM reaches its stability limit. As a result, we obtain the period T_u of the critical oscillation at the stability limit of the DFOIM with the critical proportional gain Ku . Next, the values of the parameters Kp , T_I , T_D are given by

$$K_p = \frac{K_u}{1.7} \quad \text{--- (5)}$$

$$T_I = \frac{T_u}{2} \quad \text{--- (6)}$$

$$T_D = \frac{T_I}{4} \quad \text{--- (7)}$$

Where $K_p$the proportional is gain; T_I is the integral time and T_D is the derivative time. In the fuzzy process, we only employ three input membership functionsμ_{N_x}, μ_{Z_x} and μ_{P_x} shown in Fig. 3 to map a crisp input to a fuzzy set with a degree of certainty where x = g(t) or Δg(t) with g(t) = K1 f (t) and Δg(t) = K2Δf (t) . Those three membership functions are chosen because of their simplicity for computation since a large number of membership functions and rules can cause high computational burden for a fuzzy controller. For any x∈ N where N denotes the interval $(-\infty,0]$, its corresponding linguistic value is 'N'. Moreover, for any x∈ P where P denotes the interval $(0,\infty)$, its corresponding linguistic value is 'P'. For any x∈Z where Z denotes the interval $[-b, b]$, its corresponding linguistic value is 'Z'. The membership functionsμ_{N_x}, μ_{Z_x} and μ_{P_x} are given by

$$\mu_N(x) = \begin{cases} 1 & x \le -b \\ \frac{-x}{b} & -b < x \le 0 \\ 0 & otherwise \end{cases} \quad \text{---- (8)}$$

$$\mu_Z(x) = \begin{cases} \frac{x+b}{b} & -b < x \leq 0 \\ \frac{b-x}{b} & 0 < x \leq -b \\ 0 & otherwise \end{cases} \quad \text{--- (9)}$$

$$\mu_p(x) = \begin{cases} 1 & b \leq x \\ \frac{x}{b} & 0 < x \leq b \\ 0 & otherwise \end{cases} \quad \text{--- (10)}$$

The fuzzy inference engine, based on the input fuzzy sets in combination with the expert's experience, uses adequate IF-THEN rules in the knowledge base to make decisions and produces an implied output fuzzy set u . For this particular application, the proposed IF-THEN fuzzy rule base is shown in Table 1 and is described as follows:

i. **If** $\Delta g(t) \in N$, **then** $u(g(t), \Delta g(t)) = b$

ii. **If** $\Delta g(t) \in P$, **then** $u(g(t), \Delta g(t)) = -b$

iii. **If** $\Delta g(t) \in Z$, **and** $g(t) \in N$, **then** $u(g(t), \Delta g(t)) = -b$ ...

iv. **If** $\Delta g(t) \in Z$, **and** $g(t) \in P$, **then** $u(g(t), \Delta g(t)) = b$ ...

v. **If** $\Delta g(t) \in Z$, **and** $g(t) \in Z$, **then** $u(g(t), \Delta g(t)) = 0$ ...

--- (11)

Moreover, the Mamdani-type min operation for fuzzy inference is employed in this study.

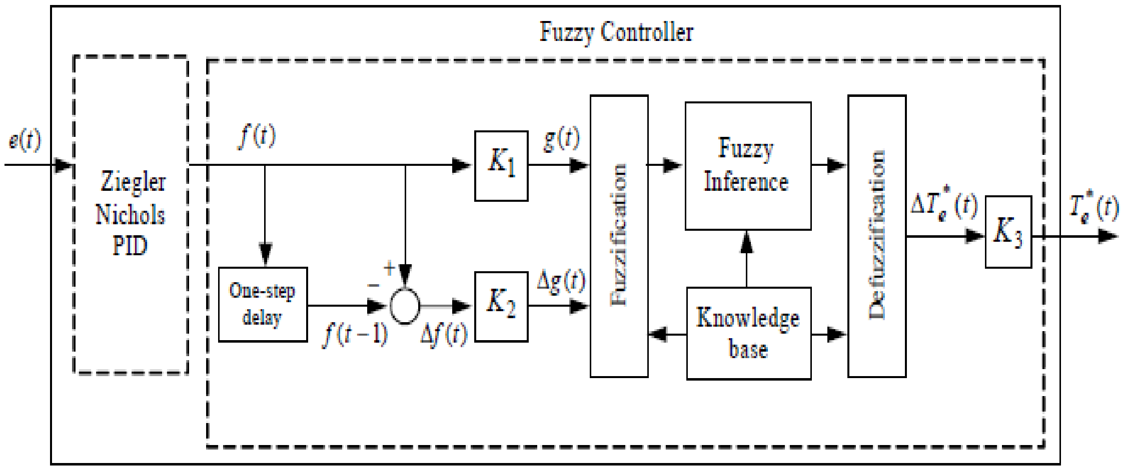

Fig.2.The block diagram of the proposed controller

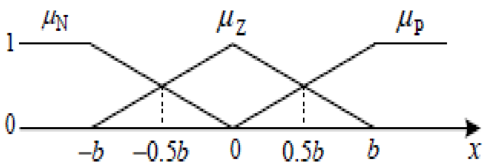

Fig.3. Membership functions with x=g(t)

Table 1.Fuzzy rule base

Table 1. Fuzzy rule base

$\Delta g(t)$ \ $g(t)$ / u	N	Z	P
N	b	b	b
Z	-b	0	b
P	-b	-b	-b

In the de fuzzification process, we employ the'center of mass' defuzzification method for transforming the implied output fuzzy set into a crisp output, and obtain

$$\Delta T_e^*(t) = \frac{\sum_{i \in FL(g(t))} \sum_{j \in FL(\Delta g(t))} \min\{u_i(g(t)), u_j(\Delta g(t))\} X u(i,j)}{\sum_{i \in FL(g(t))} \sum_{j \in FL(\Delta g(t))} \min\{u_i(g(t)), u_j(\Delta g(t))\}} \quad \text{--- (12)}$$

$$FL(a) = \begin{cases} \{N, Z\} & \text{if } a \in N \text{ and } a \in Z \\ \{P, Z\} & \text{if } a \in P \text{ and } a \in Z \\ \{N\} & \text{if } a \in N \text{ and } a \notin Z \\ \{P\} & \text{if } a \in P \text{ and } a \notin Z \end{cases} \quad \text{---- (13)}$$

The output of the fuzzy controller is given by

$$T_e^*(t) = K_3 . \Delta T_e^*(t) \quad \text{---- (14)}$$

3.2. Proposed Control Strategy: d-q Model Transformation

The dynamic performance of an ac machine is somewhat complex because the three-phase rotor windings move with respect to the three-phase stator windings as shown in figure 3.1(a).

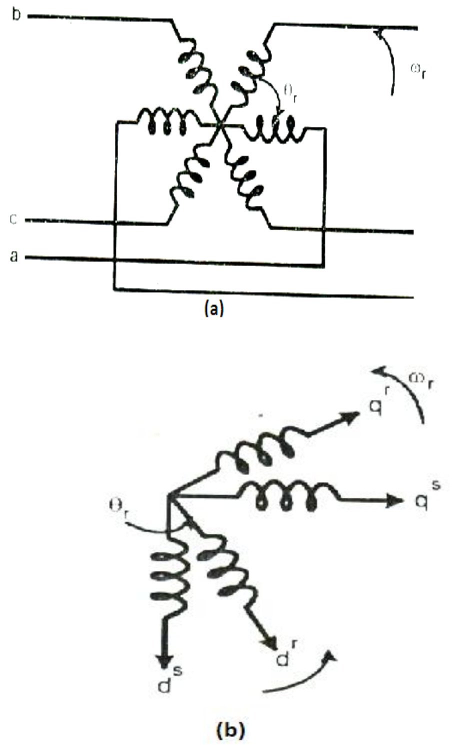

Fig.4. (a) Coupling effect in three-phase (b) Equivalent two-phase machine Stator and rotor windings

Basically, it can be looked on a s a transformer with a moving secondary, where the coupling coefficients between the stator and rotor phases change continuously with the change of rotor position θ_r. The machine can be described by differential equations with time-varying mutual inductances, but such a model tends to be very complex. Note that a three-phase machine can be represented by an two-phase machine as shown in 3.1(b), where $d_s - q_s$ correspond to stator direct and quadrature axes, and $d_r - q_r$ correspond to rotor direct and quadrature axes.

Although, it is somewhat simple, the problem of time-varying parameters still remains. R.H. Park, in1920s, proposed a new theory of electric machine analysis to solve this problem. He formulated a change of variables, which, in effect, replaced the variables (voltages, currents and flux linkages) associated with the stator windings of synchronous machine with variables associated with fictitious windings rotating with the rotor with synchronous speed. Essentially, he transformed, or referred, the stator variables to a synchronously rotating reference frame fixed in the rotor. With such transformation (called park's transformation), he showed that all the time-varying inductances that occur due to an electric circuit in relative motion and electric circuits with varying magnetic reluctances can be eliminated. Later, in. The 1930s, H.C.Stanley showed that time-varying inductances in the voltage equations of the induction machine due to electric circuits in relative motion can be eliminated by transforming the rotor variables to variables associated with fictitious stationary windings. In this case, the rotor variables are transformed to a stationary reference frame fixed on the stator. Later, G.Kron proposed a transformation of both rotor and stator variables to a synchronously rotating reference frame that moves with the rotating magnetic field. D.S.Brereton proposed a transformation of stator to a rotating reference frame that is fixed on the rotor. In fact, it was shown later by Krause and Thomas that time-varying inductances can be eliminated by referring the stator and rotor variables to a common reference frame which may rotate at any speed (arbitrary reference frame). Without going deep in to rigor of machine analysis, we will try to develop a dynamic machine model in a synchronously rotating and stationary reference frames.

Consider a symmetrical three-phase induction machine with stationary as-bs-cs axes at 2Π/3 angle apart, as shown in figure 3.2. Our goal is to transform the three-phase stationary reference frame (as-bs-cs) variables into two – phase stationary reference frame (d^s-q^s) variables and then these to synchronously rotating reference frame (d^e-q^e), and vice versa. Assume that the d^s-q^s axes are oriented at θ angle, as shown in figure 3.2. The voltages $v_{ds}^{\ s}$ and $v_{qs}^{\ s}$ can be resolved into as-bs-cs components and ca n be represented in matrix form as

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta - 120^o) & \sin(\theta - 120^o) & 1 \\ \cos(\theta + 120^o) & \sin(\theta + 120^o) & 1 \end{bmatrix} \begin{bmatrix} v_{qs}^{\ s} \\ v_{ds}^{\ s} \\ v_{os}^{\ s} \end{bmatrix}$$

--- (15)

The corresponding inverse relation is

$$\begin{bmatrix} v_{qs}^{\ s} \\ v_{ds}^{\ s} \\ v_{os}^{\ s} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos(\theta - 120^o) & \cos(\theta + 120^o) \\ \sin\theta & \sin(\theta - 120^o) & \sin(\theta + 120^o) \\ 0.5 & 0.5 & 0.5 \end{bmatrix} \begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix}$$

---- (16)

Where V_{os}^{s} is added as the zero sequence component, which may or may not be present. We have considered voltage as the variable. The current and flux linkages can be transformed by similar equations. It is convenient to set θ = 0, so that the q^s-axis is aligned with the as-axis. Ignoring the zero sequence components, the transformation relations can be simplified as

$$\mathbf{V_{as} = V_{qs}^{s}} \quad \text{--- (17)}$$
$$\mathbf{V_{bs} = -(1/2)V_{qs}^{s} - (\sqrt{3}/2)\, V_{ds}^{s}} \quad \text{--- (18)}$$
$$\mathbf{V_{cs} = -(1/2)\, V_{qs}^{s} + (\sqrt{3}/2)\, V_{ds}^{s}} \quad \text{--- (19)}$$
$$\mathbf{V_{qs}^{s} = (2/3)\, V_{as} - (1/3)\, V_{bs} - (1/3)\, V_{cs}} \quad \text{--- (20)}$$

The synchronously rotating d^e-q^e axes, which rotate at synchronous speed ω_e with respect to the d^s-q^s axes and the angle $\theta e = \omega_e t$. Two-phase d^s-q^s windings are transformed into the hypothetical windings mounted on the d^e-q^e axes. The voltages on the d^s-q^s axes can be converted (or resoled) into the d^e-q^e frame.

IV. MATLAB/SIMULINK for Proposed Test System

Usually, when an electrical machine is simulated in circuit simulators like PSPICE, its steady state model is used, but for electrical drive studies, the transient behavior is also important. One advantage of SIMULINK over circuit simulators is the ease in modeling the transients of electrical machines and drives and to include drive controls in the simulation. As long as the equations are known, any drive or control algorithm can be modeled in SIMULINK. However, the equations by themselves are not always enough; some experience with differential equation solving is required. SIMULINK induction machine models are available in the literature [I-3], but they appear to be black boxes with no internal details. Some of them [1-3] recommend using *S*- functions, which are software source codes for SIMULINK blocks. This technique does not fully utilize the power and ease of SIMULINK because S-function programming knowledge is required to access the model variables. *S*- Functions run faster than discrete SIMULINK blocks, but SIMULINK models can be made to run faster using "accelerator" functions or producing stand-alone SIMULINK models. Both of these require additional expense and can be avoided if the simulation speed is not that critical. Another approach is using the SIMULINK Power System Block set [4] that *can* be-purchased with SIMULINK. This block set also makes use of S-functions and is not as easy to work with as the rest of the SIMULINK blocks Reference [5] refers to an implementation approach similar to the one in this paper but fails to give any details. In this paper, a modular, easy to understand SIMULINK induction motor model *is* described. With the modular system, each block solves one of the model equations; therefore, unlike black box models, all of the machine parameters are accessible for control and verification purposes. SIMULINK induction machine model discussed in this paper has been featured in a recent graduate level text book [6].

The inputs of a squirrel cage induction machine are the three-phase voltages, their fundamental frequency, and the load torque. The outputs, *on* the other hand, are the three phase currents, the electrical torque, and the rotor speed. The d-q model requires that all the three-phase variables have to be transformed to the two-phase synchronously rotating frame. Consequently, the induction machine model will have blocks transforming the three-phase voltages to the d-q frame and the d-q currents back to three-phase. The induction machine model implemented in this paper is shown in Fig. 2. It consists of five major blocks. The o-n conversion, abc-syn conversion, syn-abc conversion, unit vector calculation, and the induction machine d-q model blocks. The following subsections will explain each block.

4.1. Induction machine d-q model

The inside of this block where each equation from the induction machine model is implemented in a different block. First consider the flux linkage state equations because flux linkages are required to calculate all the other variables. These equations could be implemented using SIMULINK "State-space" block, but to have access to each point of the model, implementation using discrete blocks is preferred.

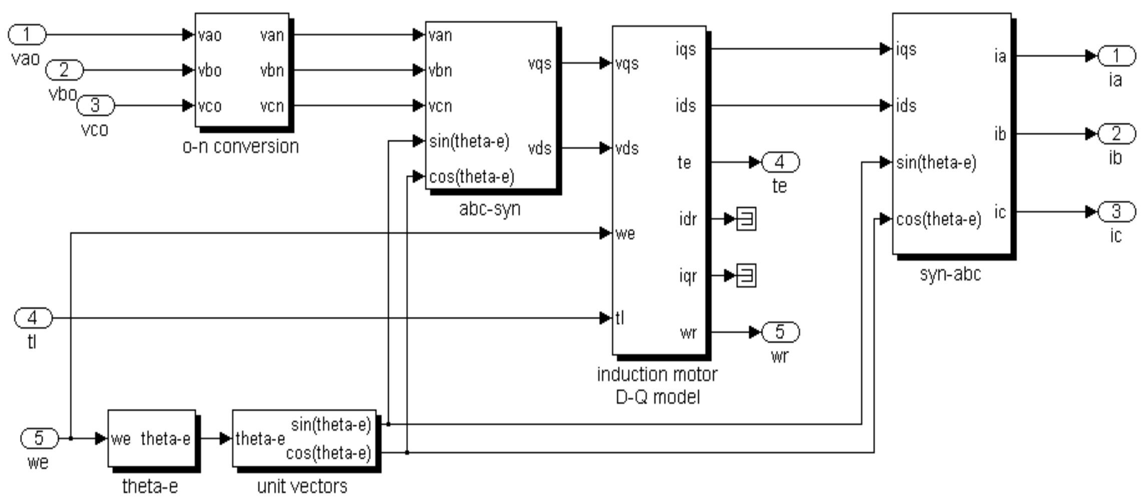

Figure.5.Complete Induction Motor SIMULINK model

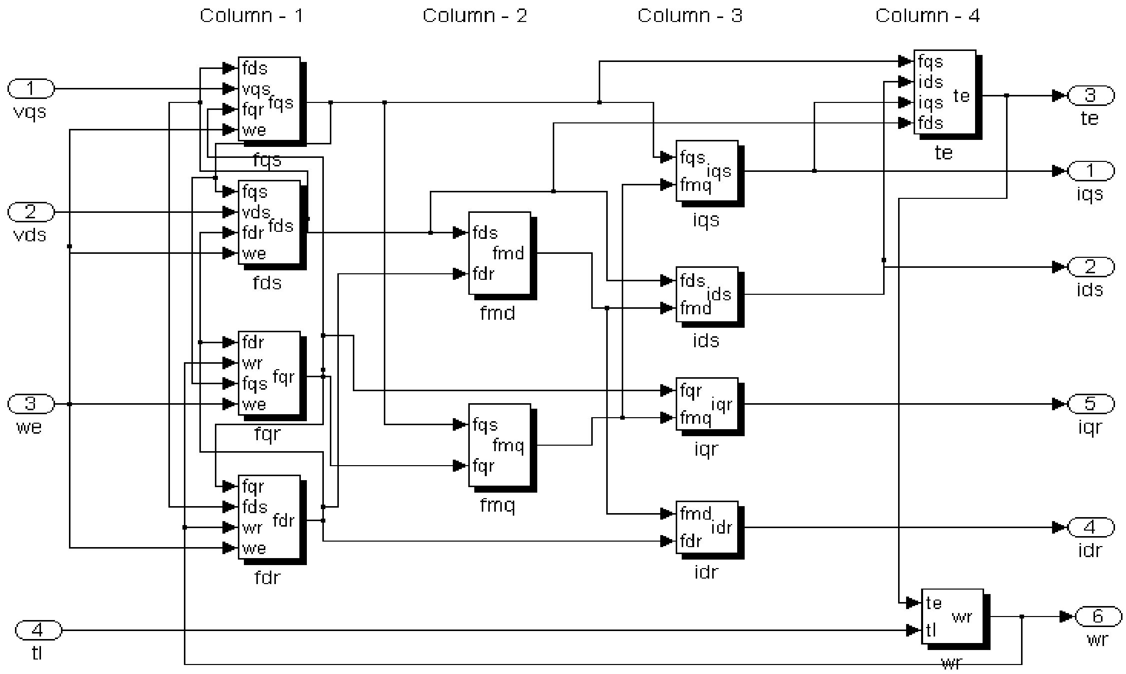

Figure.6. SIMULINK Implementation of Induction motor d-q model

V. Results and Discursions

A model of test system is developed using the MATLAB /SIMULINK software. The parameter values of the 0.14-hp squirrel-cage induction motor are given as follows:

$$R_s(\Omega) = 17 \,, R_r(\Omega) = 11 \,. L_s(H) = 0.196 \,, L_r(H) = 0.196$$

$$L_m(H) = 1.88\, X10^{-3} \,, N = 4 \,, j_m\,((Kg - cm - s^2) = 2.4\, X10^{-4}$$

$$B_m(kg - cm) = 9.2\, X10^{-3}$$

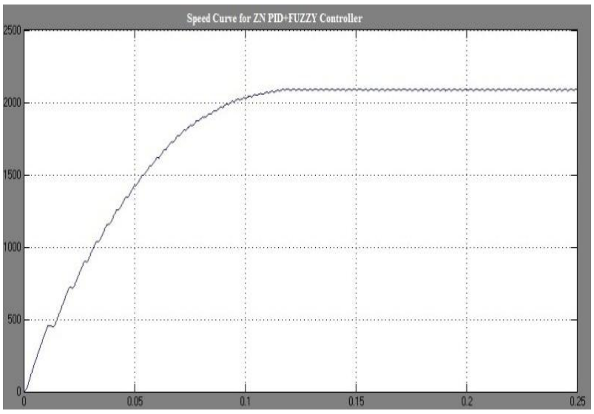

Figure.7. Speed of Induction motor with Z-N PID Controller

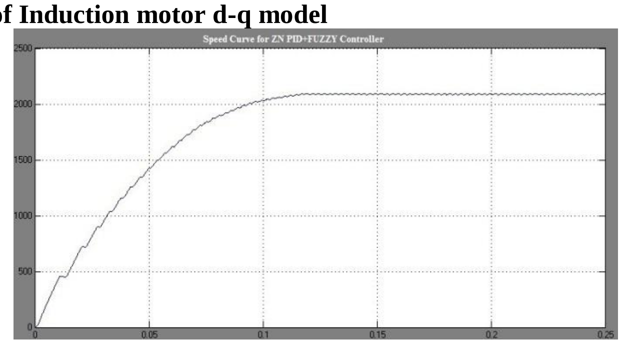

Figure.8. Speed of Induction with Z-N PID+Fuzzy Controller

From figure 7&8 shows the variation between speed characteristics of Induction motor with ZN PID Controller and ZN PID Combined with Fuzzy Controller. Meanwhile, the speed curve which shown figure.7 contains speed of 2000 rpm at 4.8 sec with ZN PID Controller and by using ZN PID+Fuzzy Controller, the same speed achieved in 4.2 sec. So, the ZN PID+ Fuzzy Controller will show the better performance speed characteristic in less settling time.

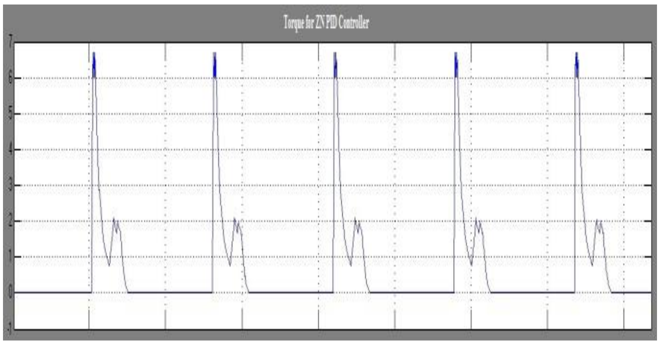

Figure.9. Torque per phase of IM with Z-N PID

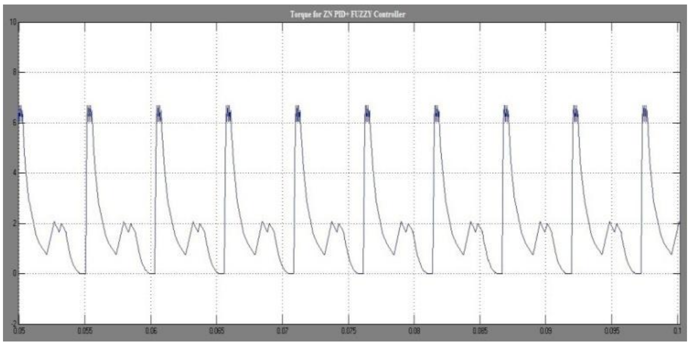

Figure.10. Torque per phase of IM with Z-N PID+Fuzzy Controller

From figure 9&10 shows the variations for torque responses of DFIM operating with PID and PID+Fuzzy Controller. Here from the very first figure torque response is 0.81N-m for 15sec duration with PID Controller. And this load torque per phase was modified and improved, compensated to 0.69N-m in 12sec. Hence simultaneously, the PID combined with FLC will improve the DFIM pay load torque responses.

VI. Conclusion

In this paper, a novel hybrid modified Z-N PID+FLC-based speed control of a DFOIM has been presented. The proposed controller has exhibited the combined advantages of a PID controller and a FLC. Specifically, it can improve the stability, the transient response and load disturbance rejection of speed control of a DFOIM. The complete DFOIM drive incorporating the proposed controller has been implemented in real time using a MRC-6810 AD/DA servo control card for the Nikki Denso NA21-3F 0.14Hp induction motor. The fuzzy logic and only with three membership functions are used for each input and output for low computational burden, which can achieve satisfactory results. Simulation and experiment results have illustrated that the proposed controller scheme has a good and robust tracking performance. As suggested topology says that a modified Z-N PID can perform better than a Z-N PID, our future effort will focus on how to further improve the performance of the proposed controller herein by incorporating a modified Z-N PID.

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