

Fuzzy PID Control Compensation System for Speed of VVVF Induction Motor Drive

Opas Ruksaboon and Chaiyapon Thongchaisuratkrul

Abstract—The objective of research was to present the closed loop speed controller of variable-voltage variable-frequency (VVVF) induction motor drive. The main issues regarding a Fuzzy PID controller were designed for controlling an induction motor. The proposed controller is composed the rule base with analysis two degree of freedom to fuzzy rule. The little fluctuation slope of rise time can be minimize with compensation Fuzzy and PID controllers. The study used LabVIEW program and adjustment of controller parameters were set consistently with the mathematic equation of the motor. In this study, the 0.375 kW model of three phase induction motor was used in the simulation. The results showed that the Fuzzy PID controller can drive the induction motor system more effectively with good tracking and found robust is suitable for controlling the system.

Index Terms—Closed loop control, motor drive, fuzzy controller, PID controller.

I. INTRODUCTION

The induction motor is the electric motor type most used industry. The certain excellent features of the induction motor such as for the user this low cost and high reliability, good efficiency and low maintenance. The induction motors are asynchronous induction machines whose speed depends upon applied frequency, pole pair number, and load torque. This market need and growing at a healthy rate as users of operating motors at variable speeds [1].

The core of algorithm traditional control for induction motor drives were PI/PID control. That the simple structure and stable performance. But it is difficult to meet the high precision and fast response [2]. The Fuzzy Logic Control novel design applied for the speed of an induction motor [1], [3], [4]-[6].The fuzzy two-degree of freedom to obtain good tracking and regulating response [7]. An advantage of traditional controlled that can be easily modified into the conventional controller structure by adding a compensator [8], [9]. In addition, that the two-layered control structure is robust to variations, as well as the steady-state gain of the plant [10]. Unfortunately, in the real control application, a global model is very difficult to build, and even when a model is available, complex conditions are obtained.

The nonlinear system can be controlled if the dynamic

model was established [11].Induction motor is a complex system, the control techniques such as PI, PID or Fuzzy controllers with auto-tuning function can be applied for driving [12], [13]. The compensation control system minimized torque ripple, reaches the reference speed rapidly and without overshoot [11], [14].The remainder of this paper is the further verification concept of high application in system drive. To find the Fuzzy PID control compensation performance of this system, the three phase induction motor with variable voltage-variable frequency technique (VVVF) is implemented. The computer control experimental was setup two-degree of freedom are chosen for rule base to compensating signal is added to PID by using LabVIEW. The simulation and real time control results are illustrated and compared.

II. INDUCTION MOTOR DRIVE

A. Variable-Voltage Variable-Frequency (VVVF) Induction Motor Drive

Some problem in the operation of induction motor this open-loop control are the following: the speed cannot be controlled precisely, the slip speed cannot be maintained [12]. These problems are to an extent overcome by having outer speed loop in the induction motor drive. The actual rotor speed (V_{tg}) is compare with its command value(V^*)and the error is processed a controller usually a PI/PID. The slip-speed command is added to electrical rotor speed to obtain the stator frequency command. Thereafter, the stator frequency command is processed as in driven unit. The constant of proportionality between the dc load voltage and the stator frequency. The closed-loop variable-voltage variable-frequency (VVVF) shown in Fig 1. The induction motor drive system, limits on the slip speed, offset voltage and reference speed are adjustable variables. The speed controlled with the inverter-driven motor apart from variable frequency. Thus, the speed can be derived as follows [12]:

$$E_l = 4.4K_{wl}\phi_m f_s T_l \tag{1}$$

$$V_{ph} \cong E_l \tag{2}$$

$$\phi_m \cong \frac{V_{ph}}{K_b f_s} f_s T_l \tag{3}$$

$$K_{vf} \tag{4}$$

K_b is constant value

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$$\phi_m \propto \frac{V_{ph}}{f_s} \propto K_{vf} \quad (5)$$

K_{vf} is the ratio between V_{ph} and f_s

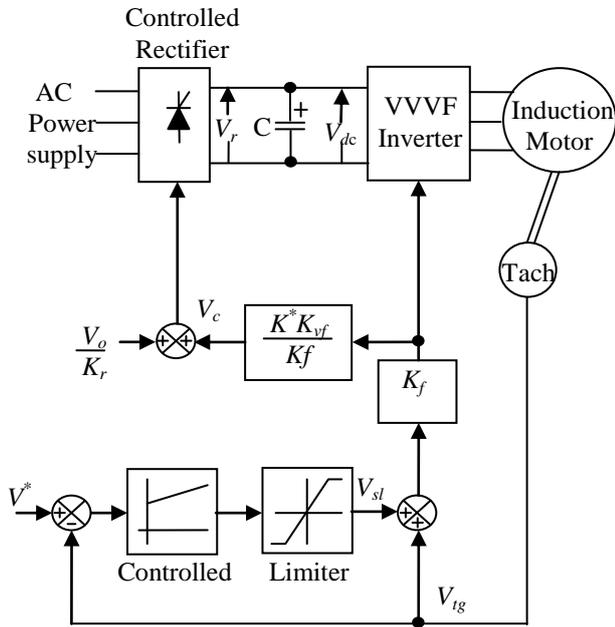


Fig 1. Overall block diagram of the VVVF controlled induction motor drive.

The external drive with input voltage V^* is used as follows [15]:

$$-V_{cm} < V^* < +V_{cm} \quad V \quad (6)$$

V_{cm} is the maximum control voltage (± 5 or $\pm 10V$)

V^* is the command speed of the motor

The proportionality constant is defined as

$$K^* = \frac{V^*}{\omega_r^*} = \frac{V_{cm}}{\max\{\omega_r^*\}} \text{ volt/(rad/sec)} \quad (7)$$

The gain of tachogenerator is defined as

$$K_{tg} = \frac{V_{cm}}{\omega_m} = \frac{V_{cm}}{\omega_r/(P/2)} = \frac{P}{2} \cdot K^* \quad (8)$$

$$K_f = \frac{1}{2\pi K^*} \quad \text{Hz/Volt} \quad (9)$$

K_f is the gain of the frequency transfer.

ω_r^* is the commanded electric rotor speed

ω_r is the electric rotor speed

Stator frequency are written

$$f_s = K_f \left(K^* \omega_{sl} + \frac{P}{2} \cdot K^* \omega_m \right) = K_f K^* (\omega_r + \omega_{sl}) \quad \text{Hz} \quad (10)$$

ω_{sl} is the electric rotor slip-speed

The output of rectifier is given in terms as

$$V_c = \frac{2.22}{K_r} (V_o + K_{vf} f_s) V_r = 2.22 K_f \{ V_o + K_f K^* K_{vf} (\omega_r + \omega_{sl}) \} \quad (11)$$

The slip speed and the offset voltage are generalized as follows:

$$V_o = I_{sr} R_s$$

$$\omega_{sl} = f_n \{ V^* - V_{tg} \}$$

$$= f_n \{ V^* - \omega_m K_{tg} \}$$

$$= f_n \{ K^* \omega_r^* - K^* \omega_r \} \quad (12)$$

I_{sr} is the rate stator current

f_n is the speed controller function

The synchronous speed is given in terms as

$$\omega_s = 2\pi f_s = 2\pi K_f K^* (\omega_r + \omega_{sl}) \quad (13)$$

B. Dynamic Modeling of Induction Motor

The model of three-phase induction motor can be described as D-Q equivalent circuit [5], [6], [11]. Thus, the vector can be derived as follows:

$$S = S_q - jS_d$$

In other words, $S_q = \text{Re}(S)$ and $S_d = -\text{Im}(s)$

The dynamic equation of an induction motors can be used as a standard form of difference equation. Thus, we have

$$pX = AX + BU \quad (14)$$

The matrix quantities equation is given by

$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_s + L_s p & \omega_e L_s & L_m p & \omega_e L_m \\ -\omega_e L_s & R_s + L_s p & -\omega_e L_m & L_m p \\ L_m p & \omega_r L_s & R_r + L_r p & \omega_r L_r \\ -\omega_e L_m & L_m p & -\omega_r L_r & R_r + L_r p \end{bmatrix} \begin{bmatrix} I_{qs} \\ I_{ds} \\ I_{qr} \\ I_{dr} \end{bmatrix} \quad (15)$$

$$X = \begin{bmatrix} I_{qs} \\ I_{ds} \\ I_{qr} \\ I_{dr} \end{bmatrix}, U = \begin{bmatrix} V_{qs} \\ V_{ds} \\ 0 \\ 0 \end{bmatrix}, B = 1/\Delta \begin{bmatrix} L_r & 0 & -L_m & 0 \\ 0 & L_r & 0 & -L_m \\ -L_m & 0 & L_s & 0 \\ 0 & -L_m & 0 & L_s \end{bmatrix} \quad (16)$$

and $A = 1/\Delta$

$$\begin{bmatrix} R_s L_r & \omega_e L_s L_r - \omega_r L_m^2 & -R_r L_m & \omega_o L_m L_r \\ \omega_r L_m^2 - \omega_e L_s L_r & R_s L_r & -\omega_o L_r L_m & -R_r L_m \\ -R_s L_m & -\omega_o L_s L_m & R_r L_s & \omega_r L_s L_r - \omega_e L_m^2 \\ \omega_o L_s L_m & -R_s L_m & -\omega_e L_m^2 - \omega_r L_s L_r & R_r L_s \end{bmatrix} \quad (17)$$

Then, we have $\Delta = L_s L_r - L_m^2$, $\omega_o = p\theta_0$

The stator and the rotor voltage equations are given by

$$V_{qs} = R_s I_{qs} + p\lambda_{qs} + \omega_s \lambda_{ds} \quad (18)$$

$$V_{ds} = R_s I_{ds} + p\lambda_{ds} + \omega_s \lambda_{qs} \quad (19)$$

$$0 = R_r I_{qr} + p\lambda_{qr} + \omega_r \lambda_{dr} \quad (20)$$

$$0 = R_r I_{dr} + p\lambda_{dr} + \omega_r \lambda_{qr} \quad (21)$$

The flux linkage equations are as follows:

$$\lambda_{qs} = L_s I_{qs} + L_m I_{qr} \quad (22)$$

$$\lambda_{ds} = L_s I_{ds} + L_m I_{dr} \quad (23)$$

$$\lambda_{qr} = L_m I_{qs} + L_r I_{qr} \quad (24)$$

$$\lambda_{dr} = L_m I_{ds} + L_r I_{dr} \quad (25)$$

The torque equation is defined as

$$T_o = \frac{3}{4} P \left(\frac{L_m}{L_r} \right) (\lambda_{dr} I_{qs} - \lambda_{qr} I_{ds}) \quad (26)$$

The block diagram of induction motor dynamics is shown in Fig 2. [5], [6].

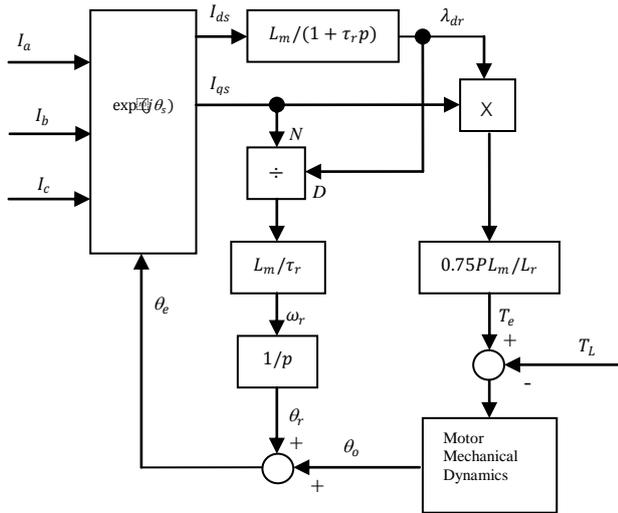


Fig. 2. Block diagram of induction motor dynamics.

The three phase induction motor's parameters are shown in Table I.

TABLE I: THE THREE PHASE INDUCTION MOTOR'S PARAMETERS MODEL

Parameter	Value
Phase	3
V_{ll} : Line Voltage	380 V
P : Number of pole	4
Power	0.375 KW
f : Frequency	50 Hz
R_s : Stator resistance	0.005 p.u.
R_r : Rotor resistance	0.005 p.u.
X_{ls} : Stator magnetizing leakage	0.028 p.u.
X_{lr} : Rotor magnetizing leakage	0.025 p.u.
X_m : Magnetizing resistance	1.11 p.u.
J : Inertia	0.01 p.u.

III. CONTROLLER

A. PID Controller

The classical PID control system (proportional-integral-Derivative control) is the methodology to relate system performance - error attenuation as a function of time [10]. The error (e) was compared V^* command and V_{tg} actual. Tuning the three parameters K_p, K_i, K_d in the controller were provide control design. The output terms are summed defining $u(k)$ the final form of the PID algorithm is given by:

$$u(k) = k_p e(k) + k_p k_i \int_0^t e(t) dt + k_p k_d \frac{de(t)}{dt} \quad (27)$$

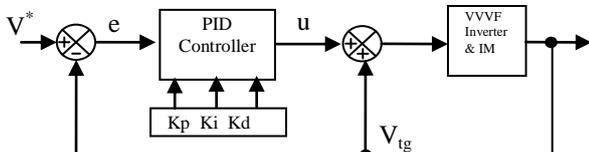


Fig. 3. Block diagram of a PID controller.

There are two ways of tuning:

Ziegler Nichols method is the type of controller turning base on the trial-and-error. In the process that calculated from start oscillating ultimate gain K_u , ultimate time period of oscillation P_u are use to find the tuning constants for the Table II.

TABLE II: CONTROLLER PARAMETERS FOR ZIEGLER NICHOLS METHOD

Controller	K_p	T_i	T_d
P	$0.5K_u$	∞	0
PI	$0.45K_u$	$P_u/1.2$	0
PID	$0.6K_u$	$P_u/2$	$P_u/8$

Process reaction curve is the variables being measured of a system (open loop), in the process that calculated from the dead time (τ_{dead}), the time response to change (τ), the ultimate value at steady state (M_u) and the step change disturbance x_o .

$$K_o = \frac{x_o \tau}{M_u \tau_{dead}} \quad (28)$$

K_o and τ_{dead} were used to find the tuning constants for the Table III

TABLE III: CONTROLLER PARAMETERS FOR PROCESS REACTION CURVE

Controller	K_o	T_i	T_d
P	K_o	∞	0
PI	$0.9 K_o$	$3.3\tau_{dead}$	0
PID	$1.2 K_o$	$2\tau_{dead}$	$0.5\tau_{dead}$

The both turning methods, Hence in this paper decided to use *Ziegler Nichols method*. However, PID method is not robust, cannot accurately control. Among the successful application of this theory has been devoted to develop PID controller [10], [15].

B. Fuzzy Logic Controller

D. D. Neema, R. N. Patel, A. S. Thoke, represented the fuzzy set theory and application of FLC in IM [3]. Fuzzy logic controller (FLC) has found robust is suitable for controlling the system. The fuzzy theory is better performance than that a PID controller [2], [5], [6], [15]. Fig 4. shows the structure of a Fuzzy logic controller.

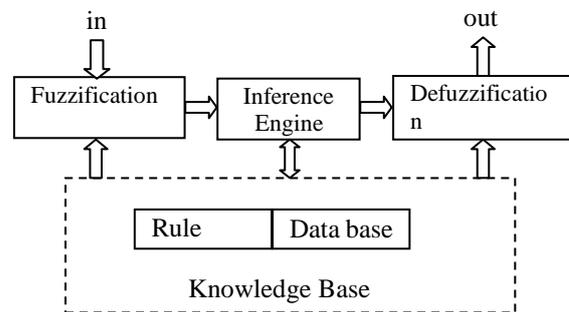


Fig. 4. Structure of a fuzzy logic controller.

The structure of fuzzy logic controller in general contains four main parts which are:

- 1) Fuzzification
- 2) Knowledge Base
- 3) Inference Engine
- 4) Defuzzification

The input variables go through the fuzzification interface that inform to linguistic variables. The rule base holding the

decision-making logic used to infer the fuzzy output, a defuzzification converts the fuzzy output into a signal output.

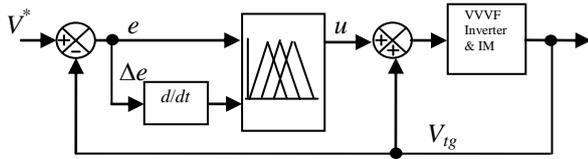


Fig. 5. Block diagram of a Fuzzy logic controller.

Fig. 5 shows the block diagram of a Fuzzy logic controller. The two variable input are the error of speed (e) and the change in error of speed (Δe). The output (u) is voltage signal to control the amplifier and VVVF Inverter.

C. Dynamic Signal

Tracking and regulating that importance proposes to methodology design of system [7]. The speed error tuning to fasted by using the fuzzy controlled [5], [6], [9]. The two degrees of freedom that was to check the error and assisted e , Δe input of Fuzzy Logic Controller (FCL). Fig. 6. shows the compared of the command, reference and dynamics signal.

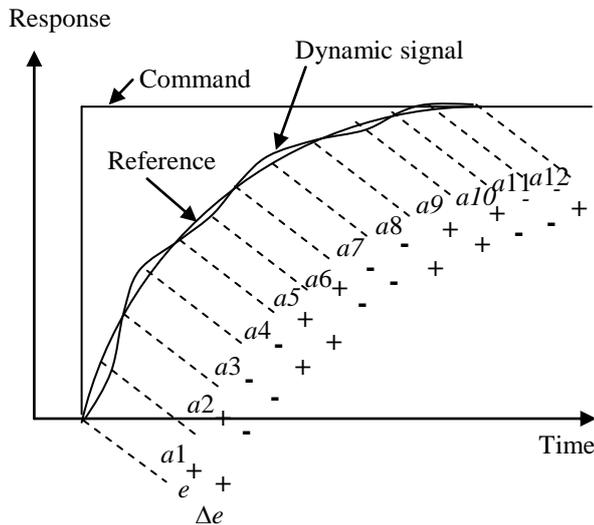


Fig. 6. Dynamics signal analysis: step command.

Our aim is to eliminate the steady state error and improve the performance of the output response for control system. The purposed controller we define the error $e(k)$ and change error $\Delta e(k)$ as follows [9], [15]:

$$e(k) = V^*(k) - V_{tg}(k) \tag{29}$$

$$\Delta e(k) = e(k) - e(k - 1) \tag{30}$$

$a1, a5, a9$: $e = +$ and $\Delta e = +$, the error is positive and error increased

$a2, a6, a10$: $e = +$ and $\Delta e = -$, the error is positive and error decreased

$a3, a7, a11$: $e = -$ and $\Delta e = -$, the error is negative and error increased

$a4, a8, a12$: $e = -$ and $\Delta e = +$, the error is negative and error decreased, the error is positive and error increased

D. Design of Fuzzy Tuning Speed Controller

The error (e), change in error (Δe) and output variable (u)

are represented as linguistic values as follows:

1) Fuzzy number

- Positive Big: PB Positive Medium: PM
- Positive Small: MS Zero: ZE
- Negative Small: NS Negative Medium: NM
- Negative Big: NB

2) Membership function

In this paper, the triangular-shaped functions were selected. The fuzzy number and membership function is shown in Fig. 7.

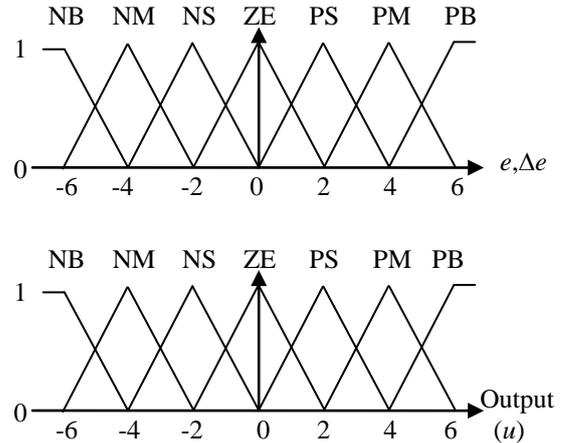


Fig. 7. The membership functions.

3) Quantization levels

Fuzzy sets of a FLC shows the corresponding rule table for the speed control. There are $7 \times 7 = 49$ possible rules in the matrix, for example as follows:

If e negative small (NS) and Δe is positive small (PS) then output (u) is zero (ZE).

Δe	NB	NM	NS	ZE	PS	PM	PB
e	NB	NB	NS	ZE	PS	PM	PB
NB	NB	NB	NS	ZE	PS	PM	PB
NM	NB	NB	NS	ZE	PS	PM	PB
NS	NB	NM	NS	ZE	PS	PM	PB
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

The fuzzy inference process to calculated fuzzy output. The Mamdani's method that found suitable for DC machine or Induction machine [7]. The Mamdani's method was convert fuzzy output into the crisp value of the output variable. This method, the centre of area (COA) de-fuzzification method is generally used. The crisp value of the output variable torque is applied to the VVVF inverter. The VVVF inverter controlled the magnitude and frequency of the V/f to desired speed of the motor.

E. Fuzzy PID Compensation System

The PID controllers are widely, exhibit poor performance when applied to nonlinearities [9]. However, the PID controllers are minimized the steady state error system. The closed loop PID controller can be used controls the speed of DC motor [10]. A variable gain PI controller that designed to replace the classical PI the motor reaches the reference speed

rapidly and without overshoot [16]. The constant flux of three phase induction motor drives using fuzzy logic controller that has been achieved in rise time and steady state of speed controlled [3], [5], [6]. The robust, tracking and regulating of induction motor drive that analysis by compensated method [9], [17]. Hence, Fuzzy PID compensation control can improve of the performance single loop control. The Fuzzy PID compensation structures system is shown in the Fig. 8.

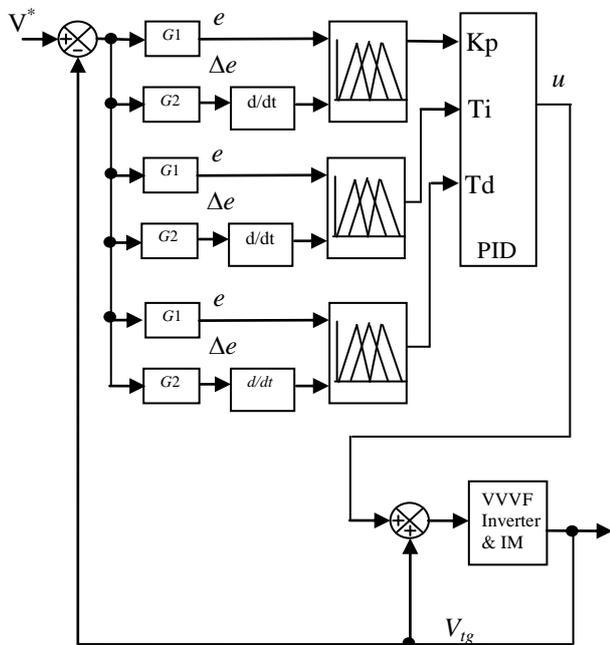


Fig. 8. Block diagram of the Fuzzy PID control system.

F. Simulation the Speed Control System

The system is modeled and implemented via LabVIEW program is shown in Fig 9. For the turning in this paper, we set PID gains with Ziegler Nichols and trial-error method. The variable quantities of K_p , T_i , T_d are derived by fuzzy logic controller.

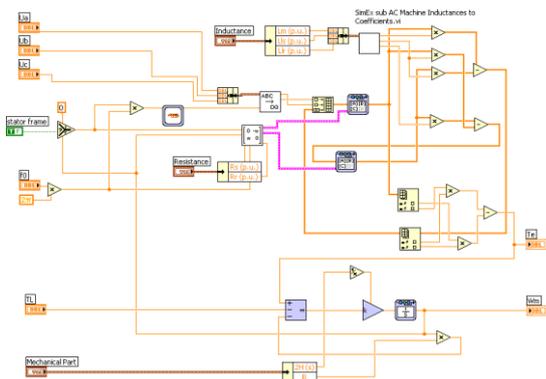


Fig. 9. The three phase induction motor model.

Experiment 1. The PI VVVF controller set references speed = 0.6 pu, $K_p = 0.045$, $K_i = 0.009$ for the no load 0.375 kW, 3-phase induction motor started. And take load 0.5 pu. at 3 second of time.

Experiment 2. The Fuzzy PID compensation VVVF drive set values are references speed = 0.6 pu., $G_1 = 3.8$, $G_2 = 0.345$, $K_p = 20$, $T_i = 0.008$ and $T_d = 0.001$, for the no load 0.375 kW, 3-phase induction motor started. And take load 0.5 pu. at 3 second of time.

Experiment 3. The Fuzzy PID compensation VVVF drive set values are references speed = 0.5 pu. , $G_1 = 3.8$, $G_2 = 0.345$, $K_p = 20$, $T_i = 0.008$ and $T_d = 0.001$, for the no load 0.375 kW, 3-phase induction motor started. And take load 0.5 pu. at 3 second of time.

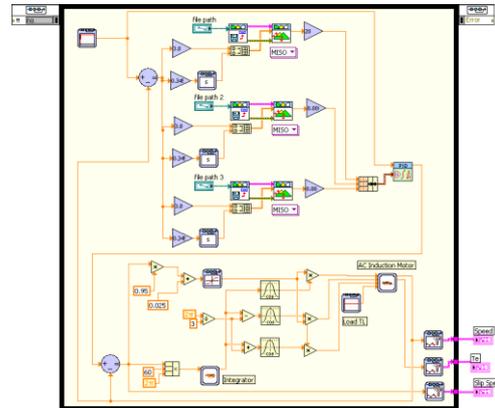


Fig. 10. The Volt/Hz controlled induction motor drive usually is a Fuzzy PID compensation controller.

IV. RESULTS AND DISCUSSION

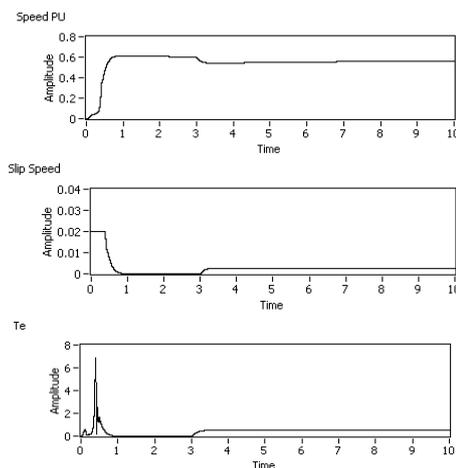


Fig. 11. Result of induction motor PI VVVF controller drive. The simulation of speed, slip speed and T_e with references speed = 0.6 pu., $K_p = 0.045$, $K_i = 0.009$, load 0.5 pu. at 3 sec.

The speed responses with the step speed references input are implemented by LabVIEW program. The parameters from table I. are used and the references speed is referred to 0.6 pu. and 0.5 pu. The first simulation is setup for the no load 0.375 kW 3- phase induction motor and take load 0.5 pu. at 3 second of time. The simulation model in LabVIEW is shown in Fig. 9 and Fig 10. The results of PI VVVF controller drive obtained by $K_p = 0.045$, $K_i = 0.009$ is shown in Fig. 11. Membership function of error and change in error are the same. The inputs of fuzzy logic controller are the error and change in error. The variable quantities of PID parameters are derived by fuzzy reasoning, and corresponding values for PID control parameter are tuned (use of the Ziegler-Nichols and trial-error method) until the output follows the set point adequately. The proportional parameter K_p obtained between 20 and 25. The integration parameter K_i obtained between 0.008 and 0.006. The differential parameter K_d obtained between 0.001 and 0.0015. The results of PI VVVF control and Fuzzy PID compensation VVVF control are compared

and showed in Fig. 11-Fig. 13.

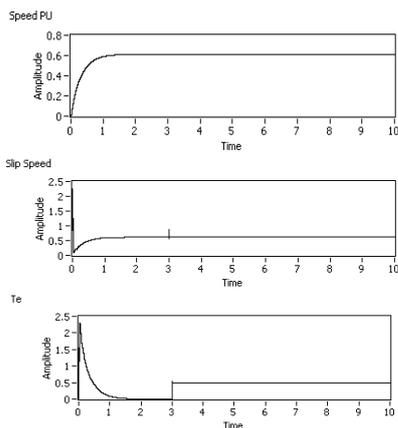


Fig. 12. Result of induction motor Fuzzy PID compensation VVVF drive. The simulation of speed, Te and Slip speed with references speed = 0.6 pu. $K_p = 20$, $T_i = 0.008$, $T_d = 0.001$, load 0.5 pu. at 3 sec.

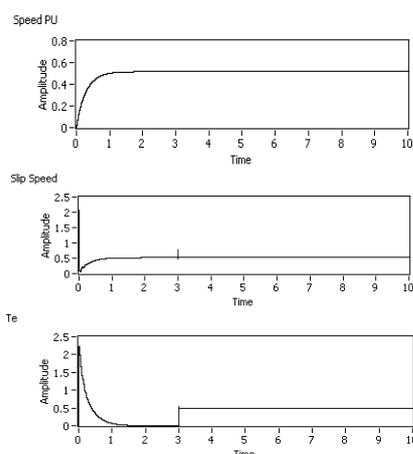


Fig. 13. Result of induction motor Fuzzy PID compensation VVVF drive. The simulation of speed, Te and Slip speed with references speed = 0.5 pu. $K_p = 20$, $T_i = 0.008$, $T_d = 0.001$, load 0.5 pu. at 3 sec.

The speed response of PI VVVF controller have the little fluctuation slope of rise time. an approximately 0.9 second for rise time. The slip speed 0.02 at 0 to 0.6 second and fall to 0 at 0.9 second. The maximum value of Te an approximately 7 Nm, and fluctuation during 0 to 0.9 second. When take load 0.5 pu. at 3 second of time the speed response have fall, and little of fluctuation.

The speed response of Fuzzy PID compensation VVVF controller have smooth slope of rise time, an approximately 0.9 second for rise time. The slip speed has little spike when start and take load at 3 second. The maximum value of Te an approximately 2 Nm, and smooth curve during 0 to 1.2 second. The Te has rapidly response and were set when take load. The numerical results are presented when take load 0.5 pu. at 3 second of time the speed response is robust to variations in load.

V. CONCLUSION

The Fuzzy PID compensation system has been developed for speed control of induction motor for simulation 0.375 kW 3- phase induction motor. The performance of Fuzzy PID compensation VVVF controller and PI VVVF controller in terms of setting time, speed and torque are shown for variation in reference speed and load torque, which simulation results the improved regulation with smaller value

of setting time. In all simulation test results of speed and torque response are achieved with the Fuzzy PID compensation system. The Fuzzy PID compensation VVVF strategy can drive an induction motor system more effectively. The heuristic knowledge is improved into the design of rule base and heave compensation system, that the resulting in a nonlinear control performance over linear conventional PI controller. The new and improved control technique for driven has good tracking and found robust is suitable for controlling the system.

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