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A FUZZY LOGIC BASED SPEED CONTROL SYSTEM FOR THE WOUND-ROTOR THREE-PHASE INDUCTION MOTORS

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Abstract-- *In this paper, the effects of the voltage which has slip frequency and at the same phase of stator voltage applied on rotor windings of three-phase induction motor is examined. In order to prevent the decreasing of the speed resulted from the increasing load torque, the voltage injected in rotor windings is adjusted by using a fuzzy logic based controller. The results and the modelling related to simulation are given detailed.*

Key Words—*Wound-rotor Induction Motor, Injection of Voltage, Slip Frequency, Fuzzy Logic, Speed Control.*

1.INTRODUCTION

The different models for controlling the speed of drive systems have been developed. Some of them are based on the slip power recovery system. [1,4] It was seem that, the microprocessors based on DSP provides the speed to control algorithms. As a result the computerize control of the motors became easy.[4]

In the control systems based on PWM or PI, the inputs of controller are crisp values and the value closely to each other are shown in two control regions far off to each other. In Fuzzy Logic Controllers(FLC), although the inputs of the controller are crisp values, in order to controller unit fuzzify these values, the control values closely to each other are also explained with the membership functions which are also closely to each other. So that , the output of controller makes the response of the system soft.[2]

In addition , the fuzzy logic based controllers can consist of the self-learning algorithms and the control regions of optimal output can again be adjusted by using this algorithm. [6,8]

The speeds of induction motors used in technology change according to the load torque. The speeds of induction motors are controlled by different methods in the plants where the speed is important. One of these methods assumed that is a difficult method in the application is the injection of voltage in rotor windings. As the speed changes ,the frequency of the rotor induced voltage changes. For the injected voltage to balance the induced voltage, the frequency of the injected voltage must track the frequency of the induced voltage.[9] This, of course, requires a controller mechanism. In general, the frequency of injected voltage is adjusted by inverter circuits. Also, at the same time, the amplitude of injected voltage must be adjusted by rectifier because of its effects on the rotor speed.

In this study, the amplitude of injected voltage produced in rectifier unit is controlled by using the FLC and slip frequency is produced in inverter unit. In the computer program developed to examine the effects of injected voltage in the rotor circuit , the output of controller (*DU*) is used as a constant multiplier of the amplitude. In other words, the fuzzy logic unit controls the amplitude of rectifier output voltage.

The dynamic equations of wound-rotor three-phase induction motor reduced to stator is simulated by using Runge-Kutta algorithm and the results are presented. According to the reference speed determined before, error(*e*) and change in error(*de*) in the output speed are applied on fuzzy logic unit as two input parameters and the amplitude of injected voltage in rotor windings is adjusted by output of defuzzifier. The results of related to this simulation are given and concluded.

2. THE THREE-PHASE INDUCTION MOTOR FED BY STATOR AND ROTOR SIDE

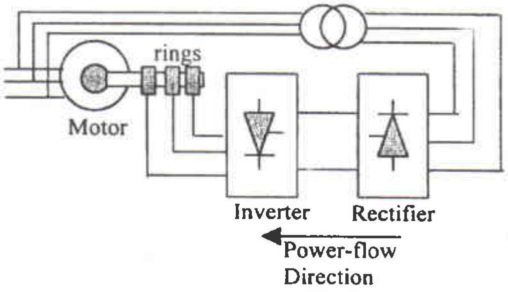

Fig.2.1 The principle schema of the doubly fed three-phase induction motor

The amplitude of the voltage injected in the rotor windings is adjusted by rectifier unit and its frequency is converted to the measured slip frequency in the inverter unit. In this case, the output voltage of the rectifier will have either positive or negative average values as the trigger control curve of rectifier changes in the interval of 0-π.

The effects of the injected voltage can be examined by using the equivalent circuit reduced to stator in rotor parameters.

When $I_r=0$,

$$s = \frac{a.Vr}{E} \tag{1}$$

by taking ***a***, as the turn ratio from stator to rotor can be written. In unloaded condition , the angular speed of rotor is;

$$\omega_{mo} = (1-s)\omega_{ms} \tag{2}$$

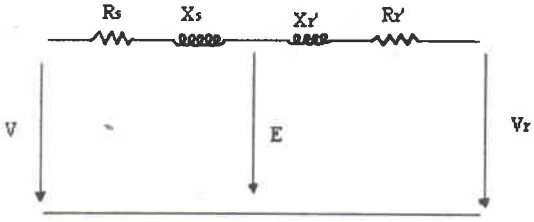

Fig.2.2 The equivalent circuit reduced to stator

For air-gap power P_g, induced torque

$$T = \frac{P_g}{\omega_{ms}} \qquad (3)$$

$$P_m = T.\omega_m = \frac{P_g}{\omega_{ms}}(1-s)\omega_{ms} = (1-s)P_g \qquad (4)$$

Where P_m is mechanical power and ω_{ms} is synchronous angular speed. Hence, the rotor circuit electrical power

$$P_e = P_g - P_m = P_g - (1-s)P_g = sP_g \qquad (5)$$

The rotor electrical power is sum of the power absorbed by V_r $(=P_r)$ and the rotor copper loss P_{cr}.
Thus,

$$sP_g = P_e = P_r + P_{cr} \qquad (6)$$

$$P_m = P_g - P_r - P_{cr} \qquad (7)$$

$$\omega_m = \omega_{ms} - \frac{P_r + P_{cr}}{T} \qquad (8)$$

A portion of the air-gap power equal to ***(1-s)P_g*** is converted into mechanical power. The remaining portion ***sP_g*** ,known as slip power, is used to supply rotor copper loss.

From the equivalent circuit,

$$I'_r = \frac{V/0 - (V'_r/s)\angle\varphi_r}{(R_s + +R'_r/s) + j(X_s + X'_r)} \qquad (9)$$

Where, I'_r is the rotor current reduced to stator. [9]

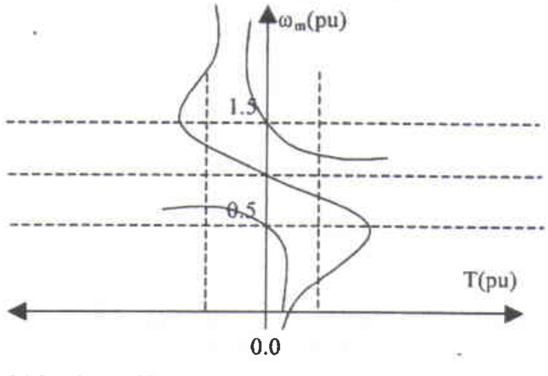

Fig 2.3 Speed control by injection of voltage in rotor (Torque-Speed Characteristic)

3. THE DYNAMIC EQUATIONS

When the symmetrical and balanced voltages are injected in rotor windings ,these voltages place in the dynamic equations of wound-rotor three-phase induction motor. Voltage and current equations are written in **the arbitrary reference frame system** related to the flux linkages.

$$\begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{0s} \\ i'_{qr} \\ i'_{dr} \\ i'_{0r} \end{bmatrix} = \frac{1}{D} \begin{bmatrix} X'_{rr} & 0 & 0 & -X_M & 0 & 0 \\ 0 & X'_{rr} & 0 & 0 & -X_M & 0 \\ 0 & 0 & \frac{D}{X_{ls}} & 0 & 0 & 0 \\ -X_M & 0 & 0 & X_{ss} & 0 & 0 \\ 0 & -X_M & 0 & 0 & X_{ss} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{D}{X'_{lr}} \end{bmatrix} \begin{bmatrix} \varphi_{qs} \\ \varphi_{ds} \\ \varphi_{0s} \\ \varphi'_{dq} \\ \varphi'_{ds} \\ \varphi'_{0s} \end{bmatrix} \qquad (10)$$

Where,

$$D = X_{ss}X'_{rr} + X^2_M \qquad (11)$$

$$\begin{bmatrix} v_{qs} \\ v_{ds} \\ v_{0s} \\ v'_{qr} \\ v'_{dr} \\ v'_{0s} \end{bmatrix} = \begin{bmatrix} \frac{r_s X'_{rr}}{D} + \frac{p}{\omega_b} & \frac{\omega}{\omega_b} & 0 & \frac{r_s X_M}{D} & 0 & 0 \\ -\frac{\omega}{\omega_b} & \frac{r_s X'_{rr}}{D} + \frac{p}{\omega_b} & 0 & 0 & \frac{r_s X_M}{D} & 0 \\ 0 & 0 & \frac{r_s}{X_{ls}} + \frac{p}{\omega_b} & 0 & 0 & 0 \\ \frac{r'_r X_M}{D} & 0 & 0 & \frac{r'_r X_{ss}}{D} + \frac{p}{\omega_b} & (\frac{\omega - \omega_r}{\omega_b}) & 0 \\ 0 & \frac{r'_r X_M}{D} & 0 & -(\frac{\omega - \omega_r}{\omega_b}) & \frac{r'_r X_{ss}}{D} + \frac{p}{\omega_b} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{r'_r}{X'_{lr}} + \frac{p}{\omega_b} \end{bmatrix} \begin{bmatrix} \varphi_{qs} \\ \varphi_{ds} \\ \varphi_{0s} \\ \varphi'_{dq} \\ \varphi'_{ds} \\ \varphi'_{0s} \end{bmatrix} \qquad (12)$$

Since the flux linkages are selected as independent variables each q- and d- voltage equation contains only one derivative of flux linkage, in the computer simulation of the induction motor , flux linkages are selected as state variables.

The induced torque in the arbitrary reference frame system is obtained related to flux linkages.[3,1]

$$T_e = (\frac{3}{2})(\frac{p}{2})\frac{X_M}{D\omega_b}(\varphi_{qs}\varphi'_{dr} - \varphi'_{qr}\varphi_{ds}) \qquad (13)$$

4. THE FUZZY LOGIC BASED SPEED CONTROL

Initially, since the speed is equal to zero, per unit value of error is 1 and change in error is equal to zero per unit. The change in error which is resulted by taking the difference between the previous error value and relative discrimination of error between the reference speed and the measured rotor speed, are used as the inputs of the fuzzifier.

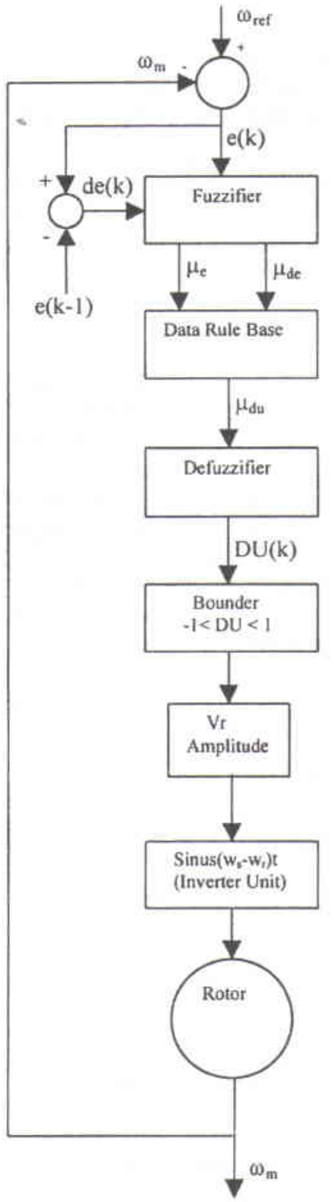

Fig 4.1 The adjustment of the voltage injected in rotor by using fuzzy logic based controller

The intervals of the error and the change in error are determined according to the dynamic behaviours of the induction motor during the rotor windings are in short-circuit, and the sinusoidal membership functions are selected for error and change in error. The fuzzy logic rule assignment table is formed after the consideration of the control will be done. The result of the rule base is the output of defuzzifier and then bounded in the interval of [-1,1] according to the output function of rectifier unit. This value is used as a cosines function of fire angle of thyristors in the output function of rectifier in the control system. The average value of the voltage that will be applied on rotor circuit is determined as the controller output. The inverter is considered in the system just only as a unit produces the sinus in slip frequency. The dynamic behaviours of induction motor are examined by using numerical analysis methods when the rotor windings are in short-circuit and the results of the simulation are shown in Fig 4.2 and Fig.4.3.

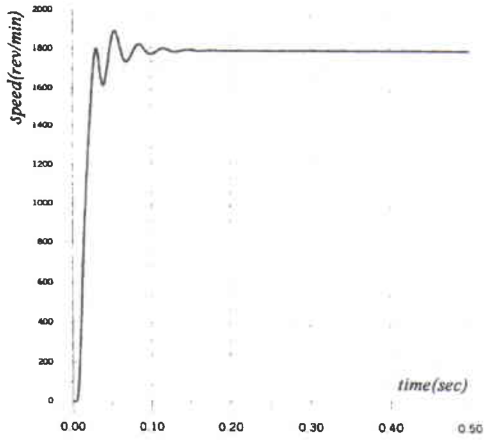

Fig. 4.2 The speed characteristic of induction motor with short-circuited rings under the load

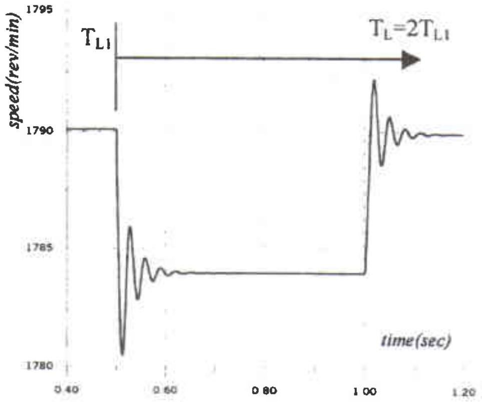

Fig. 4.3 The speed characteristic of induction motor with the injected voltage at t=1sec.

When the load torque is increased twice the present value, the speed suddenly fell down with an oscillation as seen in Fig.4.3. The voltage injected in rotor windings for regulating of the speed to the reference.

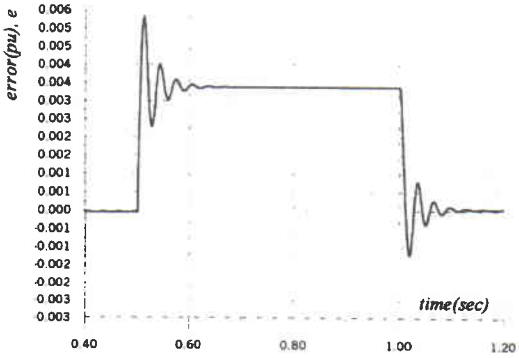

Fig.4.4 The error, during the injection of the uncontrolled voltage.

Since a specific value of the voltage applied suddenly, the increase in speed will be seen which has an oscillation form. The expected results from the fuzzy logic based controller shown in Fig.4.1 are; to reduce these oscillations , to regulate the reduction in the speed and to hold the speed in the reference as the changes in load.

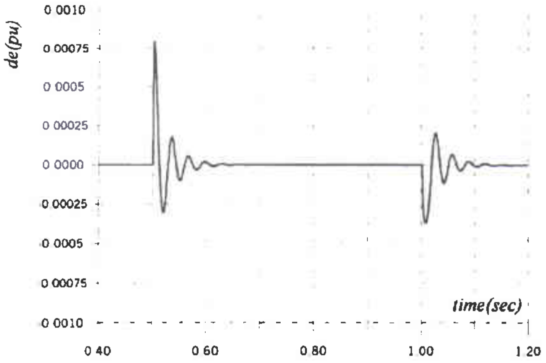

Fig 4.5 The change in error, during the injection of the uncontrolled voltage in loaded condition.

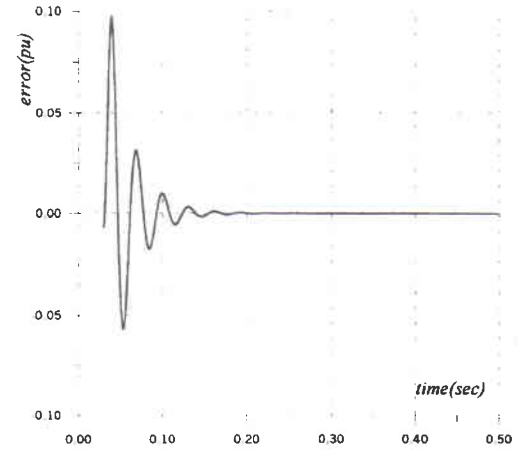

Fig.4.6 The error , during the start of induction motor with short-circuited rings in loaded condition.

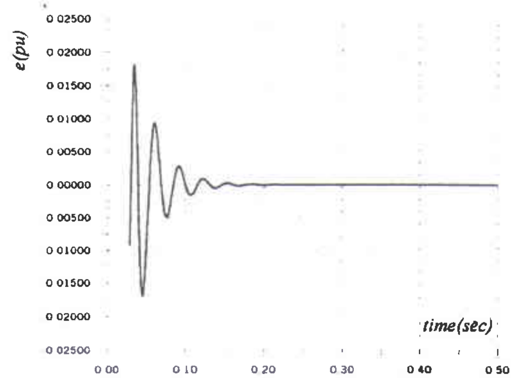

Fig. 4.7 The change in error, during the start of induction motor with short-circuited rings in loaded condition.

Considering the variation intervals of the error and the change in error in Fig.4.6 and Fig.4.7, the sinusoidal membership functions selected, as shown in Fig.4.8.

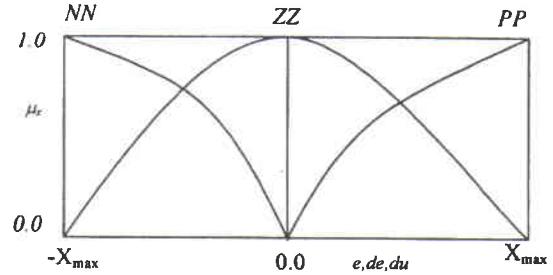

Fig.4.8 The sinusoidal membership functions for inputs and output of fuzzy logic based controller

Where the locations of the fuzzy numbers NN,ZZ and PP on the universe of discourse X are in the order of NN< ZZ < PP from negative x to positive x, as shown in Fig.4.8. The letter *w* in the definition equation is the cycling frequency of the sinusoid function, and is defined as $w=\pi/(2.X_{max})$ for 3 fuzzy numbers on one cycle.[2] As taking for error $X_{max}=0.05$ and for change in error $X_{max}=0.0002$ and for output of controller (du) $X_{max}=1.0$, sinusoid membership functions are defined as below related to these values.

For the positive fuzzy numbers PP,

$$\mu_P(x)=\begin{cases} 1 & X>=Xmax \\ \sin(wX) & 0<X<Xmax \\ 0 & X<=0 \end{cases} \qquad (14)$$

For the zero fuzzy numbers ZZ,

$$\mu_z(x)=\begin{cases} \cos(wX) & -Xmax<X<Xmax \\ 0 & \text{in other values} \end{cases} \qquad (15)$$

For the negative fuzzy numbers NN,

$$\mu_N(x)=\begin{cases} 0 & X>=0 \\ 1 & X<=-Xmax \\ -\sin(wX) & -Xmax<X<0 \end{cases} \qquad (16)$$

Taking Fig.4.3 into consideration , let us analysis the effects of the injection of the voltage in rotor windings. For example, if the error is positive and the change in error is positive then the speed is under the reference, but the speed approaches to the reference. In this situation , if the negative voltage applies on rotor windings , the speed of the motor gains acceleration and reaches the reference. In other words,

If e is PP and de is PP then du is NN *(17)*

Table 4.1 Rule assignment table, the rule base

de / e	NN_{de}	ZZ_{de}	PP_{de}
NN_e	PP_{du}	PP_{du}	ZZ_{du}
ZZ_e	PP_{du}	ZZ_{du}	NN_{du}
PP_e	ZZ_{du}	NN_{du}	NN_{du}

The rule assignment table with 9 rules is obtained and used for all membership functions without altering its structure. The same applies for all of the 9 rules of the rule base. These rules are included in algorithm of the solution as given in Eq. (18),(19). [2]

*If **Rule e** is Negatif And **Rule de** is Pozitif then*

$$du(n)=0$$

$$\mu_{du}(n)=min(\mu_{eN},\mu_{deP}) \qquad (18)$$

The output of defuzzifier for all of the computed fuzzy outputs ,

$$DU = \frac{\sum_{i=1}^{n} du(i) * \mu_{du}(i)}{\mu_{du}(i)} \qquad (19)$$

5. RESULTS AND CONCLUSIONS

For the results obtained from simulation can be analyzed considering Fig.4.2 and Fig.4.3.

When the load torque increased twice the present value, the speed of the motor falls to 10 rev/min and oscillations are seen in the dynamic behaviour of the machine as coming steady state , as shown in Fig.4.3. But, when The speed is controlled by using fuzzy logic based controller the speed decreases to 1-2 rev/min . This decreasing in the speed is not upright and the output of the controller tries to lock the system to the reference speed , as shown Fig.5.2 and Fig.5.3.

In motor drives ,it may be required to change the motor speed easily without giving any harm to the drive system by a torque and current with a high amplitude. As shown in Fig.5.3 and Fig.5.6, a fuzzy logic based controller performs it easily. The output of controller, which is stable when the system in the reference , tries to balance the system for the new reference speed when the reference speed is changed in the algorithm any time.

In order to supply the controller system to obtain the optimal results , the self-learning algorithms can be included in simulation. In this case , the control intervals determined for the inputs of the controller are continuously changed by the self-learning algorithm for desired results.[6]

It is known that, the positive and the negative pulses in the induced torque are formed, if the voltage injected in rotor windings is not controlled .[1] These destructive and torsional pulses in the induced torque can be minimized easily by using the fuzzy logic based controllers, since the system reflexes are become soft and the rotor voltage is applied according to the output speed carefully.

This paper can be taken as a reference for the experimental studies which will be accomplished this subject. If the inverter-rectifier circuits are modelled as bi-directional power-flow converter , The induction motors can be controlled for the slip power recovery.

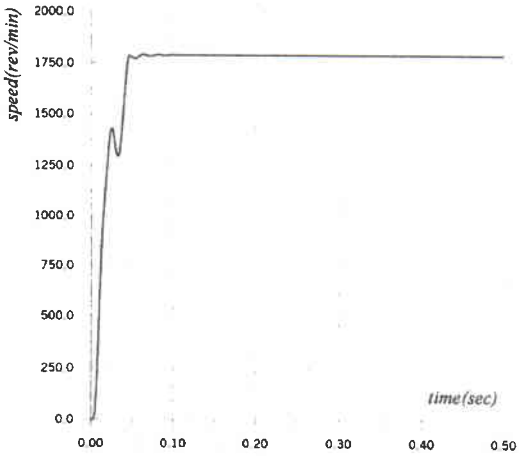

Fig.5.1 The speed controlled by FLC in starting under the load

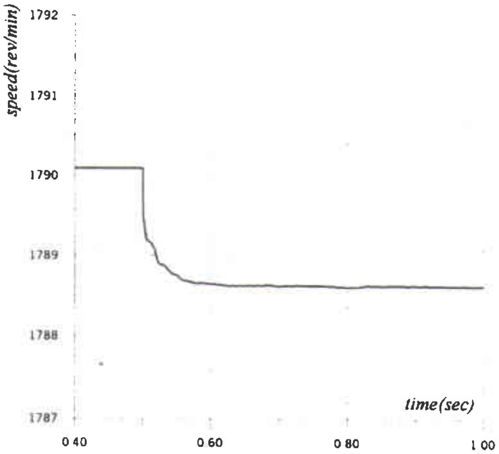

Fig.5.2 The controlled speed when the load torque increased twice the present value (Figures are detailed)

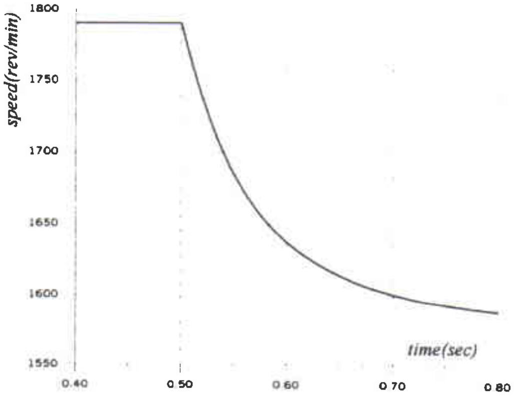

Fig.5.3 The speed controlled when the reference is taken as 1570 rev/min

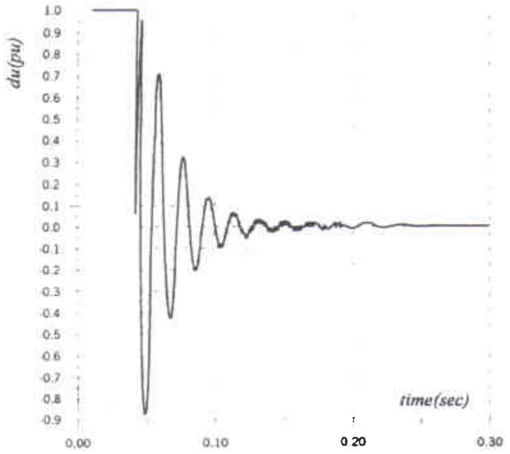

Fig 5.4 The output of the controller in starting under the load.

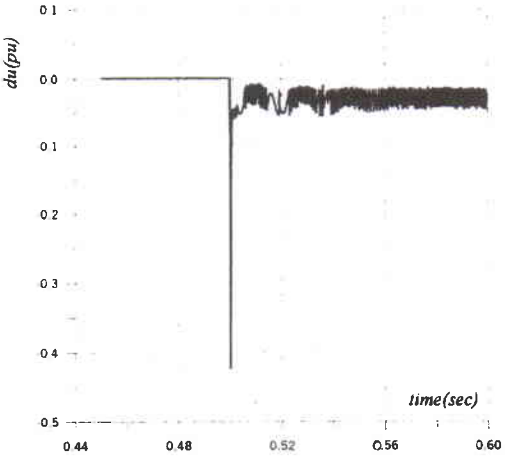

Fig 5.5 The output of the controller when the load is increased twice the present value.

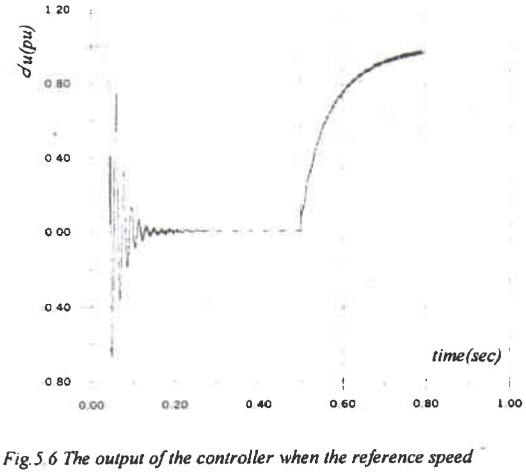

Fig.5.6 The output of the controller when the reference speed is taken as 1570 rev/min.

The system is locked the reference speed without oscillation during the motor starts in loaded condition. In the steady state , the output of the controller is stable . If the system is not in the reference speed , the controller is also not stable, as shown in Fig.5.4 ,Fig.5.5 and Fig.5.6.

6. REFERENCES

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