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# Comparative Study of Speed Control of Induction Motor Using PI and Fuzzy Logic Controller

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***Abstract:****This paper proposes the idea of using "Fuzzy Logic Technique" in estimating motor speed and controlling it for Induction motor. The Induction motor is modeled using dq axis theory. The main objective of this project is to develop a fuzzy logic based controller to control the speed of the induction motor, employing the scalar control model. The voltage and frequency input to the induction motor are to be controlled in order to obtain the desired speed response. The designed Fuzzy Logic Controllers performance is also weighed against with that of a PI controller. For V/f speed control of the induction motor, a reference speed has been set and the control architecture includes a rule base of 49 rules. These rules portray a nonchalant relationship between two inputs i.e. speed error (e), change in speed error (∆e) and an output i.e change ofcontrol ($\omega_{sl}$)*

***Keywords:****InductionMotor,V/f induction motor speed control, dq axis theory, Fuzzy Logic controller, MamdaniArchitecture, Membership functions and PI controller*

## I. Introduction

The induction motor is an important class of electric machines which finds wide applicability as a motor in industry and in its single phase form in several domestic applications. More than 85% of industrial motor used today are in fact induction motors. It is a singly fed motor (stator-fed). [1].

The speed of the induction motor is given by:

$$n = (1-s)\, n_s \qquad (1)$$

Where,
n=Rotor speed
s=Slip
$n_s$ =Synchronous speed

The synchronous speed in terms of frequency is expressed as:

$$n_s = (120*f)/p \qquad (2)$$

Where,
f=Supply frequency
n=Number of poles

From equation (2) it's evident that the synchronous speed and hence the rotor speed using equation (1) can be controlled by varying supply frequency. Voltage induced in stator is given by $E_1 = K\phi f$, where K is a constant,ϕ is the air-gap flux and f is the supply frequency. Neglecting the stator voltage drop (which is hardly 10% of the supply voltage), terminal voltage $V_1 = K\phi \mathbf{f}$ .It is evident that a reduction in the supply frequency without a change in the terminal voltage causes an increase in the air-gap flux (hence shifting the operating point of the motor towards saturation).Hence we keep V/f ratio constant so as to avoid any discrepancy in motor operation. This method is also known as Scalar Control.[8][9]

## II. Induction Motor-A General Overview

The stator of an induction motor is wound for three phases. Fig 1 shows the stator of an induction motor.[1]

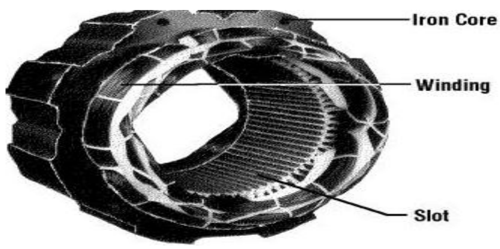
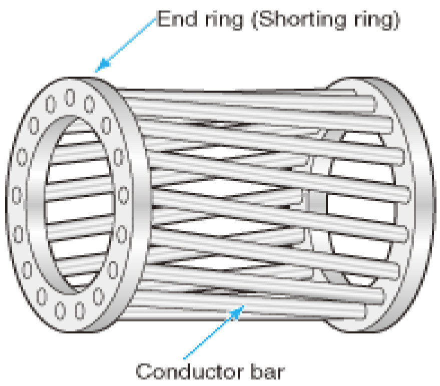



**Fig1:** Stator of an Induction Motor

Two types of constructions are employed for the rotor i.e. Squirrel - Cage Rotor andWoundRotor. The rotor core is of laminated construction with slots suitably punched in for accommodating the rotor winding /rotor bars. Fig 2 & Fig 3 shows squirrel cage and wound rotor respectively.[1]



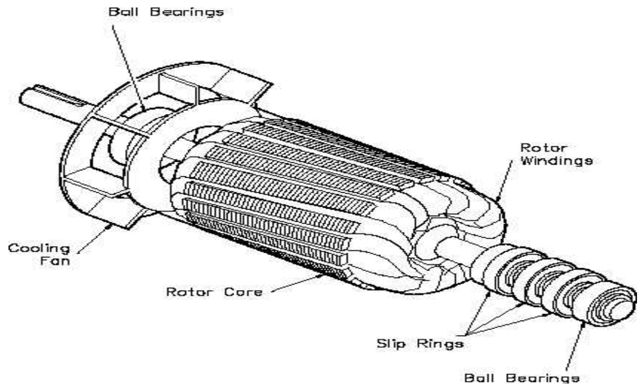




**Fig2:**Squirrel Cage rotor **Fig3:**Wound Rotor

**Speed Control Techniques in Induction Motor**

There are two basic ways of speed control, namely
(i) Slip-control for fixed synchronous speed.
(ii) Control of synchronous speed.
A stricter sorting reveals the following methods:
(i) Pole changing.
(ii) Stator voltage control.
(iii) Supply frequency control.
(iv)Eddy-current coupling.
(v) Rotor resistance control.
(vi )Slip power recovery [1][8]

## III. PI Controller

The PI controller computes the controlled output by calculating the proportional and integral errors and summing these two components to compute the output.

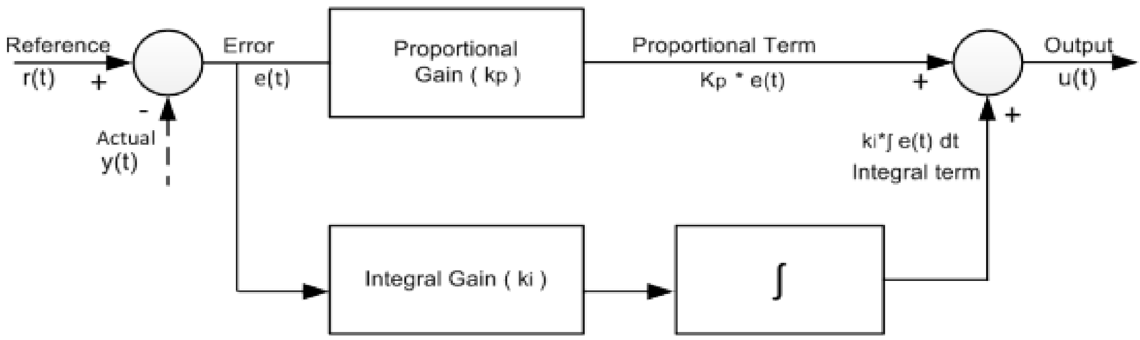



**Fig 4:** PI Controller block diagram.

In PI controller due to presence of the integral term, steady state error of speed is zero, making the system quite accurate. It does not require high gain as required in proportional gain controller. However it has certain drawbacks like if very fast response is desired, the penalty paid is a higher overshoot which is undesirable. The PID controller offers a very efficient solution to numerous control problems in the real world. [2][4][5].In our MATLAB model (Fig 14) we have used the inbuilt PI controller present in Simulink library of MATLAB.

## IV. Fuzzy Logic Controller

Fuzzy logic control is a control algorithm based on a linguistic control strategy, which is derived from expert knowledge into an automatic control strategy. While the other control systems use difficult mathematical calculation to provide a model of the controlled plant, it only uses simple mathematical calculation to simulate the expert knowledge. Although it doesn't need any difficult mathematical calculation however it gives good performance in a control system. Thus, it can be one of the best available answers today for a broad class of challenging control problems. [2][3][4]

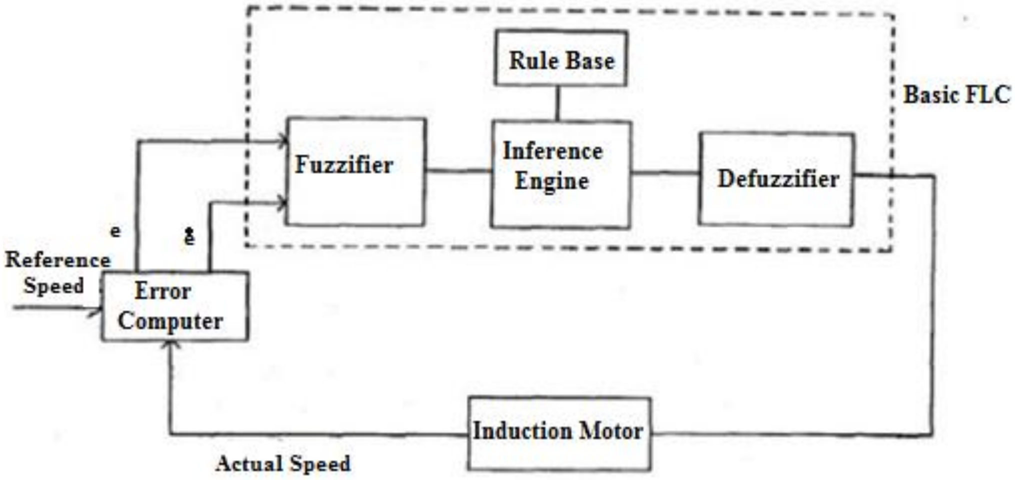



**Fig 5:**Block diagram of a Fuzzy Logic Controller

The fuzzifier scales and maps input variables to fuzzy sets.Inference engine with the help of rule base does the approximate reasoning and deduce the control action.Defuzzifier converts fuzzy output values to control actions.[7]

**Advantage Of Using Fuzzy Technique**

Fuzzy technique have gained in wide acceptance in expert systems, control units and in wide range of applications because of fast adaptation, high degree of tolerance, smooth operation, reduction in the effect of non-linearity, easy if-else logics and inherent approximation adaptability. [6]

A fuzzy logic controller (FLC) has already been proved analytically to be equivalent to a non-linear PI controller when a non-linear defuzzification method is used. Also, the result from the comparisons of conventional and fuzzy logic control techniques in the form of a FLC and fuzzy compensator showed fuzzy logic can reduce the effects of non-linearity in a DC motor and improve the performance of a controller. [2][3][4]

## V. Rule Base For Speed Control Of Induction Motor

The design of a Fuzzy Logic Controller requires the choice of Membership Functions. The membership functions should be chosen such that they cover the whole universe of discourse. It should be taken care that the membership functions overlap each other. This is done in order to avoid any kind of discontinuity with respect to the minor changes in the inputs. To achieve finer control, the membership functions near the zero region should be made narrow. Wider membership functions away from the zero region provides faster response to the system. Hence, the membership functions should be adjusted accordingly. After the appropriate membership functions are chosen, a rule base should be created. It consists of a number of Fuzzy If-Then rules that completely define the behaviour of the system. These rules very much resemble the human thought process, thereby providing artificial intelligence to the system.[10]In this paper, the speed controller make use of 49 rules mentioned in the matrix below, based on which Fuzzy Logic controller operates to give the desired result.

| Δe \ e | NL | NM | NS | ZE | PS | PM | PL |
|---|---|---|---|---|---|---|---|
| **NL** | NL | NL | NLM | NM | NMS | NS | ZE |
| **NM** | NL | NLM | NM | NMS | NS | ZE | PS |
| **NS** | NLM | NM | NMS | NS | ZE | PS | PMS |
| **ZE** | NM | NMS | NS | ZE | PS | PMS | PM |
| **PS** | NMS | NS | ZE | PS | PMS | PM | PLM |
| **PM** | NS | ZE | PS | PMS | PM | PLM | PL |
| **PL** | ZE | PS | PMS | PM | PLM | PL | PL |

**Fig 6:**Rule Matrix for control output, change of control($\omega_{sl}$)

Where,

| | | | |
|---|---|---|---|
| e | Speed error | NS | Negative small |
| Δe | Change in speed error | Z | Zero |
| $\omega_{sl}$ | Change of control | PL | Positive large |
| NL | Negative large | PM | Positive medium |
| NM | Negative medium | PS | Positive small |
| NLM | Negative large medium | PLM | Positive large medium |
| NMS | Negative medium small | PMS | Positive medium small |

The general considerations in the design of the controller are:

1. If both error and change in speed error are zero maintain the present control setting i.e. output=0.
2. If the error is not zero but is approaching this value at a satisfactory rate, then maintain the present controlsetting.
3. If the error is growing then change the control signal output depending on the magnitude and sign of error and change in speed error to force the error towards zero.

The typical rules of the table are read as(*shaded portion in matrix*):
IF **e=Z** AND Δe = **NS** THEN $\boldsymbol{\omega_{sl}}$ = **NS**
IF **e=PS** AND Δe = **NS** THEN $\boldsymbol{\omega_{sl}}$ = **ZE**
IF **e=ZE**AND Δe= **ZE**THEN $\boldsymbol{\omega_{sl}}$ = **ZE**
IF **e=PS** AND Δe= **ZE**THEN $\boldsymbol{\omega_{sl}}$= **PS**

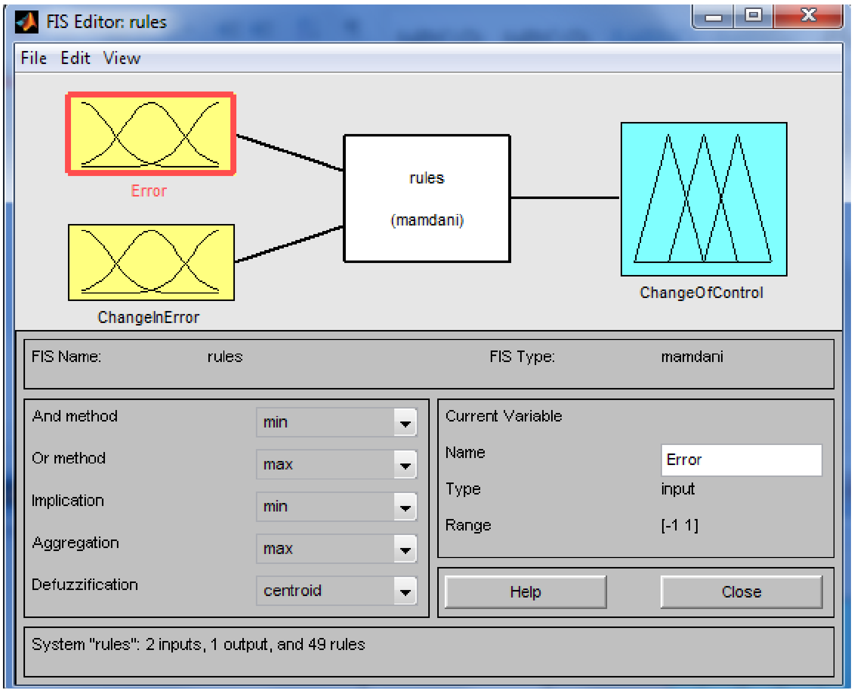



**Fig 7:**FIS Editor

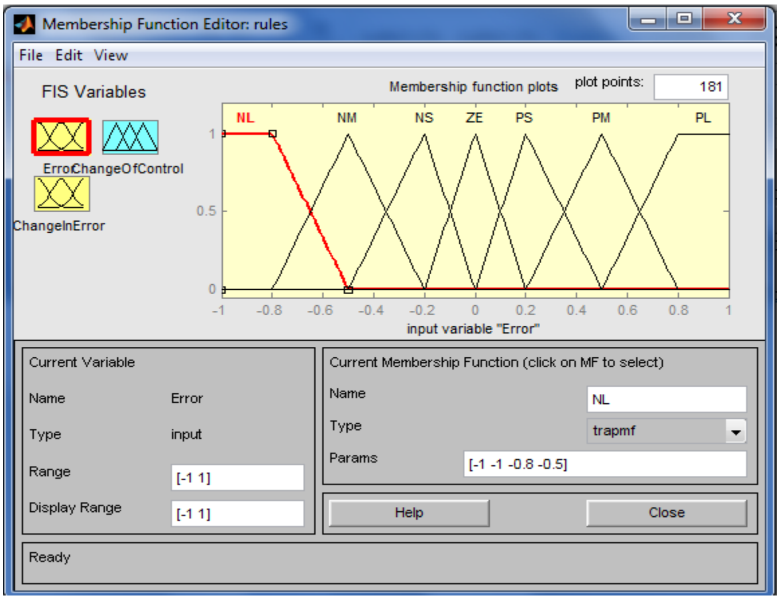



**Fig 8:**Membership Function for change in speed

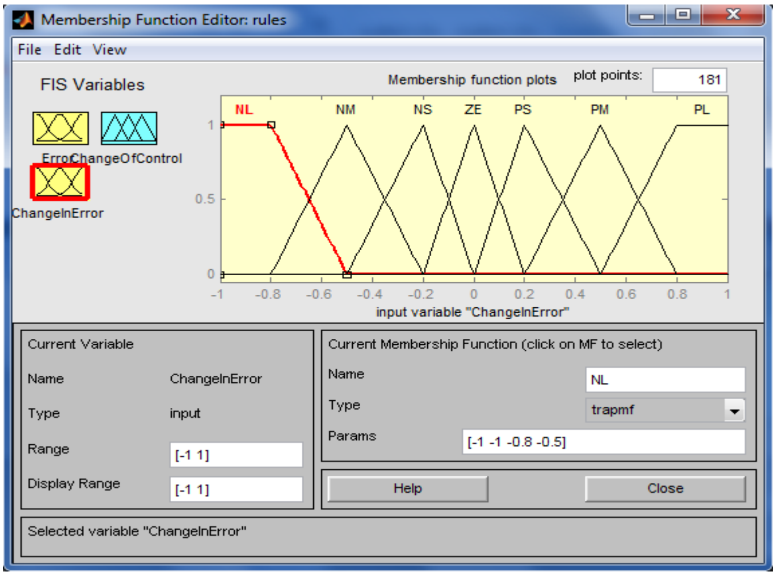



**Fig 9:**Membership Function for change in speed error

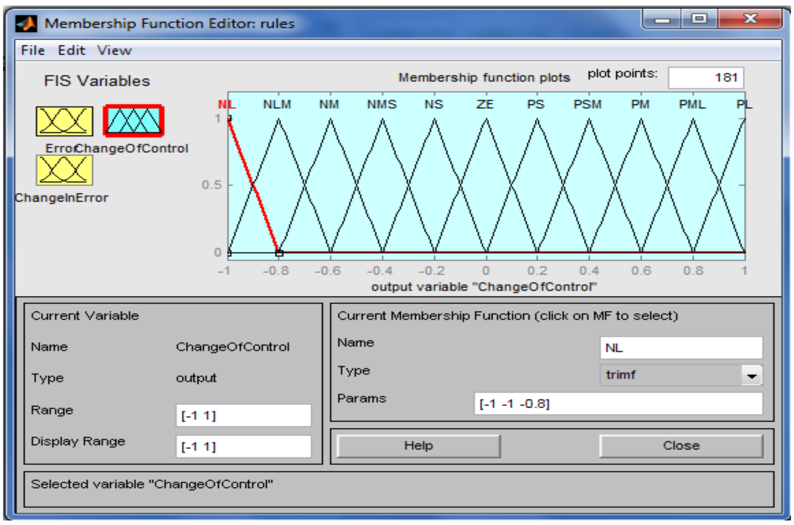



**Fig 10:**Membership function for output

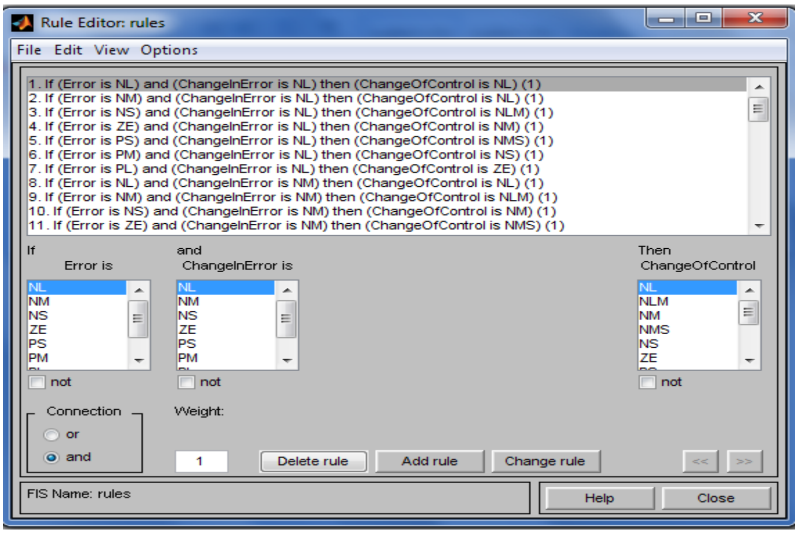



**Fig 11:**Rules

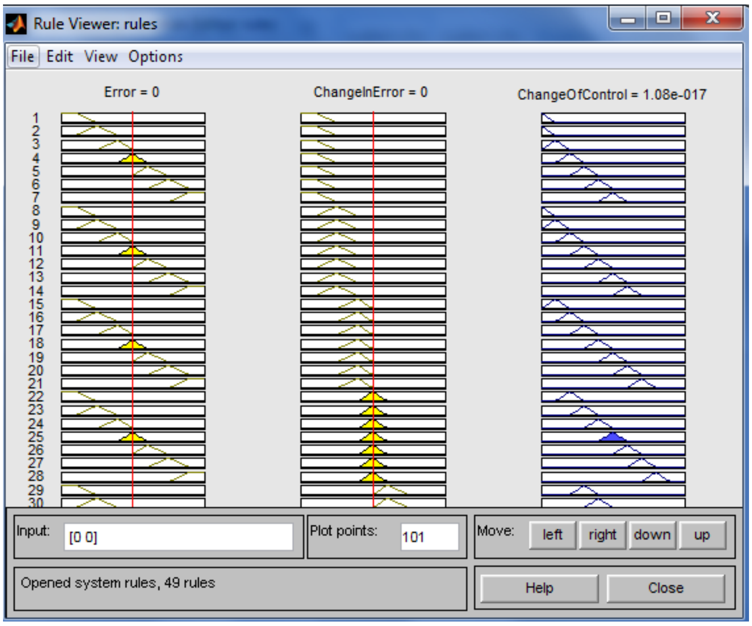



**Fig 12:**Rule Viewer

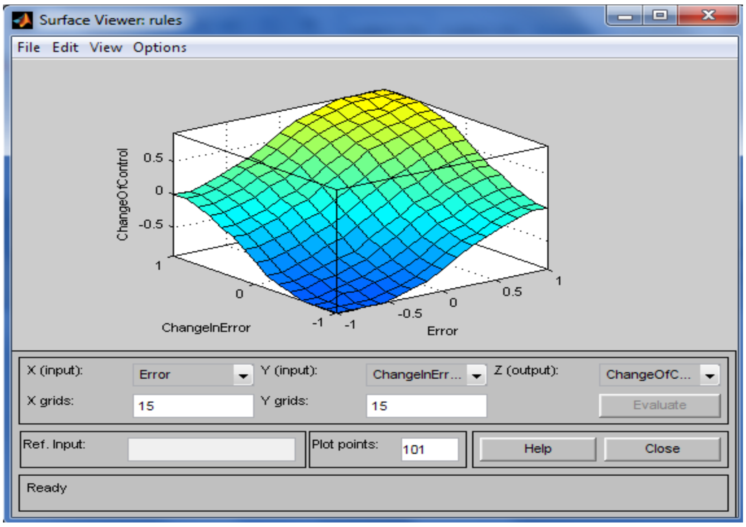



**Fig13:**Surface Viewer

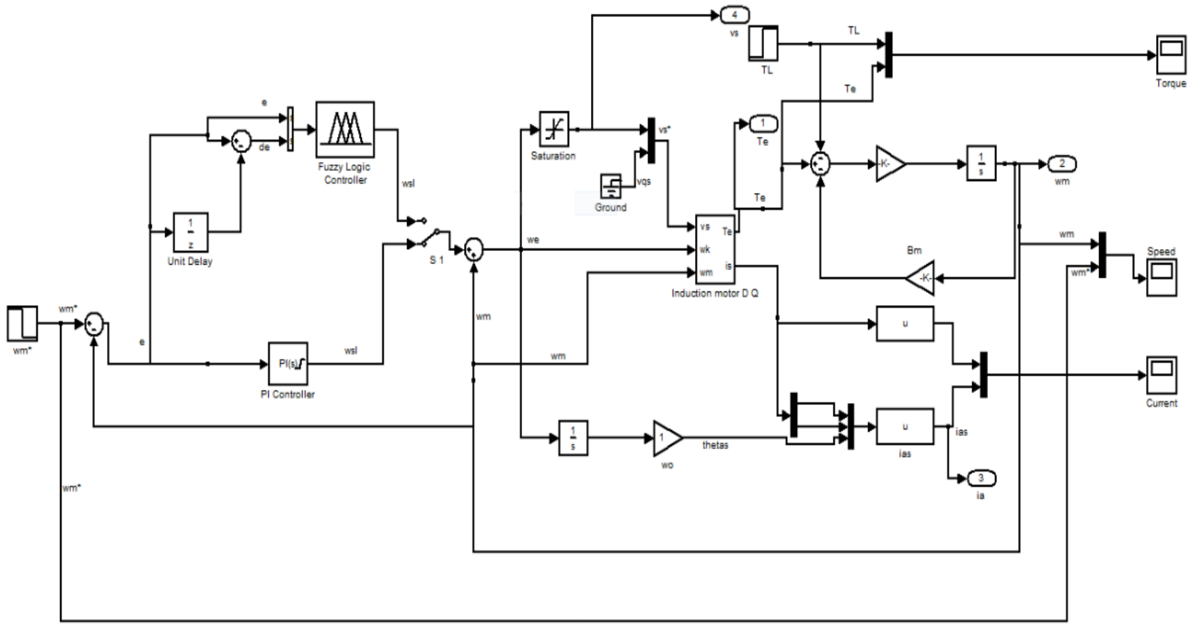



**Fig14:**Matlab/Simulink Model of PI Controller

As shown in the simulink diagram, "wm*" is chosen as the reference speed. The use of speed as reference signal is justified as the output of the system is speed and our aim is to control the speed of the induction motor. A tacho-generator, attached to the shaft of the induction motor, provides the current speed of the motor, "wm" which is compared with the reference speed "wm*", thus providing us with the speed error (e). This mechanism is called the feedback mechanism. The information about the instantaneous state of the output is fed back to the input which in turn is used to revise the same in order to achieve a desired output. [1]Speed error (e) is fed to the PI controller, to give an output variable. This output variable is then added to the motor speed "wm" which in turn forms the input to the V/f controller.

**Electrical System Equations**

$v_s=R_s i_s+ d\lambda_s/dt+\omega_k M\lambda_s$ (3)

$v_r=R_r i_r+ d\lambda_r/dt+(\omega k-\omega_m)M\lambda_r$ (4)

Where the space vector f= $[f_d f_q]^T$ and the π/2 rotational operator M= $\begin{vmatrix} -1 & 0 \\ 0 & 1 \end{vmatrix}$

**Flux Linkage-Current Relations**

$\lambda_s = L_s i_s+L_m i_r$ (5)

$i_s= \Gamma_s\lambda_s-\Gamma_m\lambda_r$ (6)

$\lambda_r = L_m i_s+L_r i_r$ (7)

$i_r = -\Gamma_m\lambda_s+\Gamma_r\lambda_r$ (8)

Ls = Lm +Lsl (9)

Lr = Lm + Lrl (10)

$\Gamma_s = Lr/\Delta$ (11)

$\Gamma_r = Ls/\Delta$ (12)

$\Gamma_{rm} = Lm/\Delta$ (13)

$\Delta = L_m L_{sl} + L_m L_{rl} + L_{sl} L_{rl}$ (14)

**Mechanical System Equations**

$T_e = J(d\omega_{mech}/dt)+B_m\omega_{mech}+T_l$ (15)

Where,

$Te = k(\lambda_s\times i_s) = k(M\lambda_s.i_s) = k(\lambda_{ds}i_{qs} - \lambda_{qs}i_{ds})$ or, (16)

$Te = k(i_r\times \lambda_r) = kL_m(i_r\times i_s) = k(L_m/L_r)(\lambda_r\times i_s) = k\Gamma_m(\lambda_r\times\lambda_s)$ and, (17)

$\omega_{mech} = (2/p)\,\omega_m$, $k=(3/2)(p/2)$

Where,

| | | | | | |
|---|---|---|---|---|---|
| v | Voltage space vector (V) | Γ | Inverse inductance ($H^{-1}$) | × | Cross product |
| i | Current space vector (A) | $f_0$ | Base frequency (Hz) | . | Dot product |
| λ | Flux linkage space vector (Wb) | $\omega_0$ | Base frequency (rad/s) | M | Rotation |
| R | Resistance (Ω) | $\omega_k$ | Speed of dq frame (rad/s) | s | Stator |
| L | Inductance (H) | $\omega_m$ | Rotor speed (rad/s) | r | Rotor |
| Te | Electromagnetic torque (Nm) | J | Moment of inertia ($kg.m^2$) | d | Direct axis |
| $T_L$ | Load torque (Nm) | P | Number of poles | q | Quadrature axis |

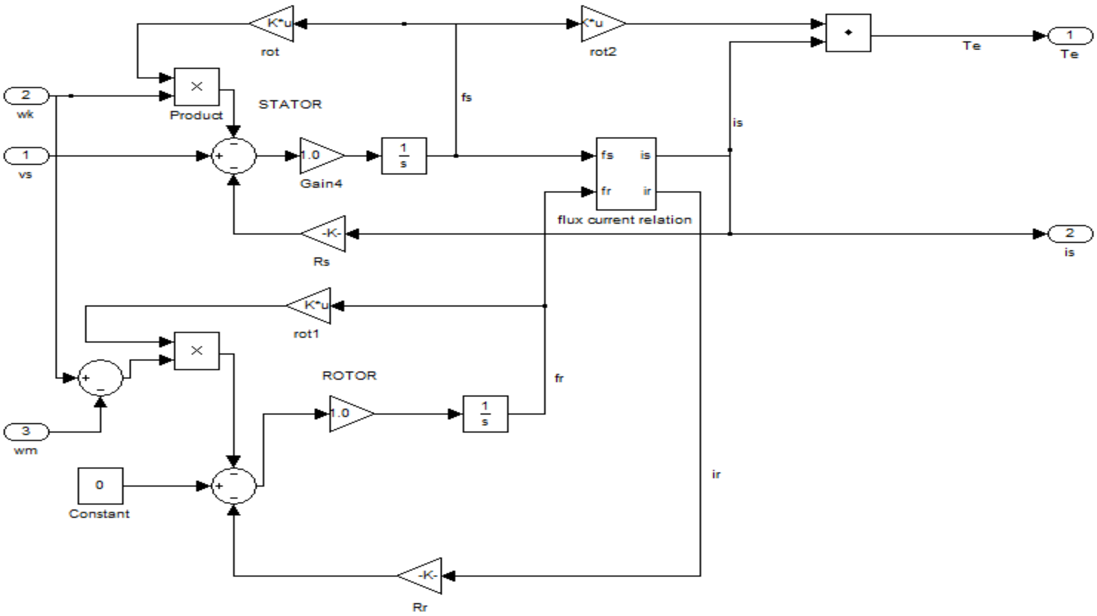



**Fig15:** Space vector model of Induction Motor

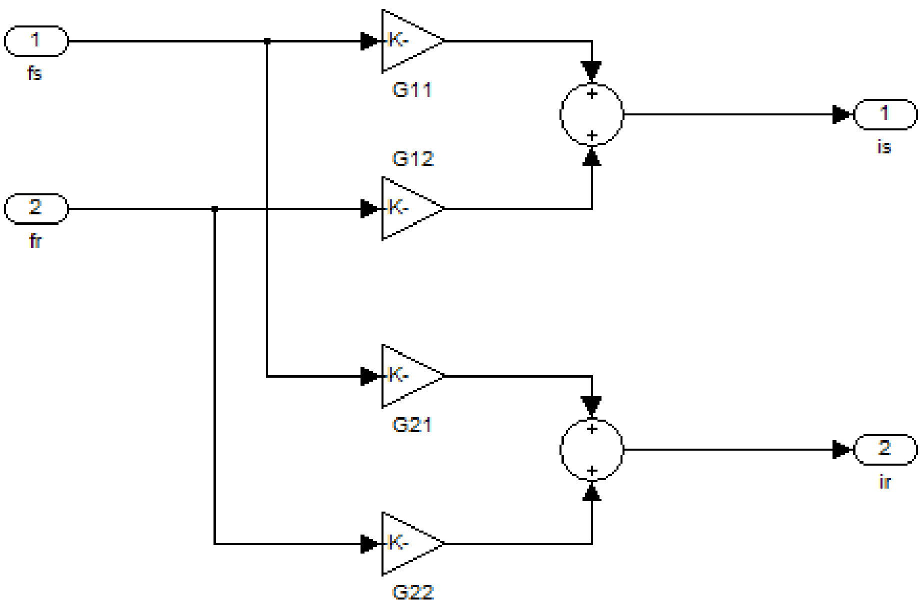
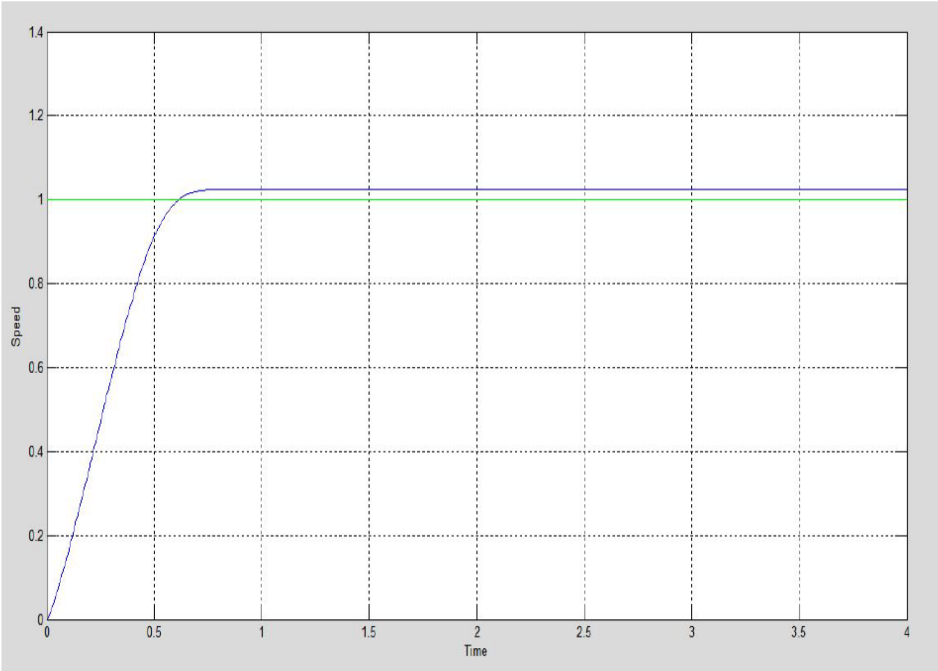



**Fig16:** Model for flux current relations

The space vector model of induction motor and the model for flux current relations has been modelled using equations (5) to (17).

Motor speed (pu)




Time in seconds

**Fig 17:** Speed V/S Time Response of PI controlled Induction Motor

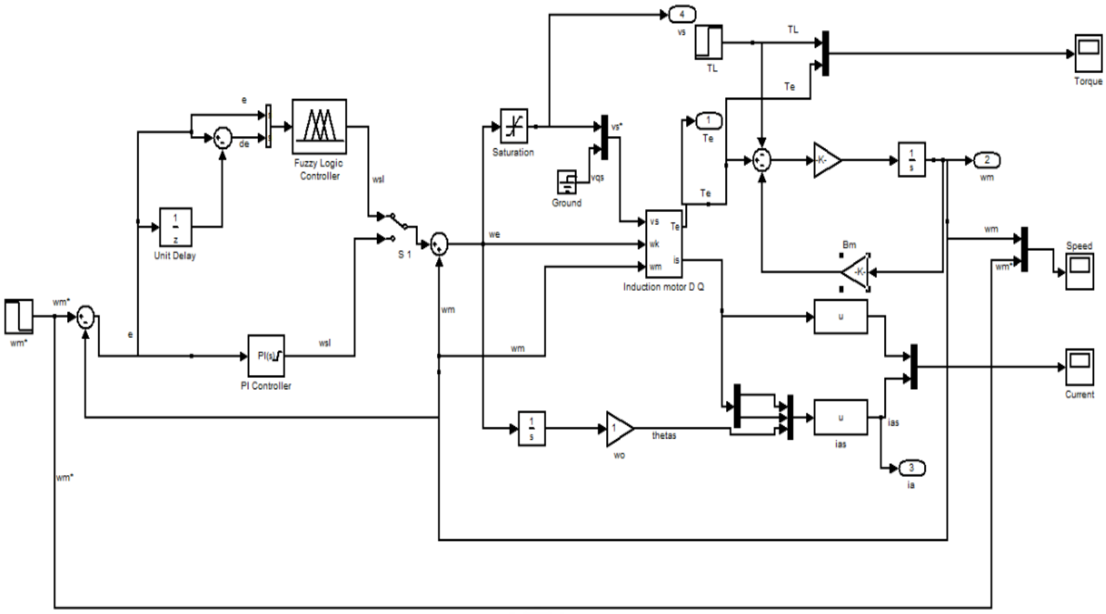
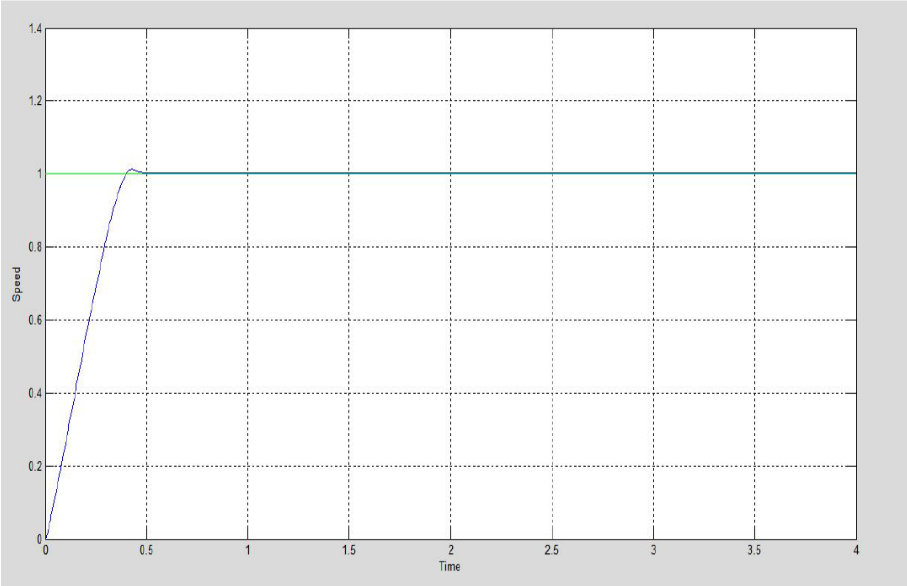



**Fig18:**Matlab/Simulink Model of Fuzzy Controller

The model for Fuzzy Controller works on the same principle as PI controller explained above except that the change-both e and de (Fig 18) are fed to the fuzzifier for fuzzification. The inference system then processes these two fuzzy inputs using the fuzzy control rules and the database, which are defined by the programmer based on the chosen membership function and fuzzy rule table, to give an output fuzzy variable. The fuzzy output thus obtained is defuzzified by the defuzzifier to give a crisp value.[1]

Motor speed (pu)




Time in seconds

**Fig 19:**Speed V/S Time Response using Fuzzy logic controller

## VI. Conclusion

The background of Induction Motor is studied and a study of the characteristics of induction motor is done. Graph for the speed response of induction motor using fuzzy logic controller (FLC) is successfully simulated in MATLAB and compared with graph for the speed response of Induction Motor with PI controller.It is established that fuzzy logic controller has finer performance in comparison to PI controller as steady state error (SSE) is zero in FLC whereas in PI controller the SSE is about 2%. Even the rise time in FLC is less as compared with PI controller which shows FLC have faster dynamic response as compared to designed PI controller.

## Appendix-A

**Specifications Of The Induction Motor**

Stator Resistance = 0.050pu
Rotor Resistance = 0.030pu
Stator Leakage Inductance = 0.20 pu
Rotor Leakage Inductance = 0.02pu
Magnetizing Inductance = 6.0 pu
Base Frequency = 2*π*50 rad/s
Number of Poles = 2
Moment of Inertia = 1.2pu
Viscous Friction Coefficient = $2*10^{-5}$pu

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