ISSN 2278 - 8875
International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering
Vol. 1, Issue 3, September 2012

Efficiency Improvement of 3 Phase Induction Motor

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ABSTRACT: Induction motor is the electrical drives which is widely used in major industrial applications. Generally efficiency of the induction motor is poor at lower load condition. It is necessary to improve the efficiency for the better performance that is possible with the modeling of an induction motor. In this work the mathematical model of an Induction Motor is developed. From the parameters obtained from the model, efficiency can be calculated from no load to full load condition considering all motor losses including Stray loss, Friction loss etc. Efficiency has been improved by using conventional and fuzzy optimization technique. The performance of developed induction motor model is analyzed with various parameters like torque, speed, current and various losses.

KEYWORDS: Induction Motor, Mathematical Model, Losses calculation, Efficiency model.

1. INTRODUCTION

The utility of induction motor is more than 50% in the electrical energy generation worldwide. A small improvement in efficiency would significantly save the total electrical energy. Hence, it is important to optimize the efficiency of motor drive systems if significant energy savings are to be obtained. The induction motor (IM), especially the squirrel-cage type, is widely used in electrical drives and is responsible for most of the energy consumed by electric motors. The main objective of the project is to develop the mathematical model of an Induction Motor for calculating the efficiency from no load to full load condition. The efficiency of the induction motor must be analyzed deeply over the various operating regions. From the analysis, efficiency of the induction motor is less accurate over some operating region. This work involves only in obtaining the efficiency model of induction motor including all the losses for various load conditions. Generally efficiency of the motor will be poor at low load conditions. Induction motor cannot be operated at full load condition in all applications, for example traction, electric vehicle etc. In many applications efficiency optimization of induction motor (IM) which is the most used electrical motor presents an important factor of control especially for autonomous electrical traction. Induction motor is well explained in Bimal k. Bose(2003), Efficiency calculation model can be studied in the paper presented by Cui shumei, Liang chen, Song liwei(2008).

In this work, Section 2 explains the development of mathematical model of Induction Motor using stator reference frame. Section 3 deals with calculation of losses. Section 4 deals with the determination of efficiency model. Section 5 explains about the results and analysis. Section 6 is the conclusion.

II. DEVELOPMENT OF MATHEMATICAL MODEL OF INDUCTION MOTOR USING STATOR REFERENCE FRAME

Induction motor model can be developed by using differential equations of the induction motor, there are six mathematical equations for developing the model of the induction motor which are as follows.

$$\frac{di_{ds}}{dt} = -\frac{\left(L^2{}_m R_r + L_r{}^2 R_s\right)}{aL_s L^2{}_r} i_{sr} + \frac{L_m R_r}{aL_s L^2{}_r}\psi_{qr} + \frac{PL_m}{2aL_s L_r}\psi_{dr}\omega_r + \frac{V_{ds}}{aL_s}$$

$$\frac{di_{qs}}{dt} = -\frac{\left(L_m{}^2 R_r + L_r{}^2 R_s\right)}{aL_s L_r{}^2} i_{ds} + \frac{L_m R_r}{aL_s L_r{}^2}\psi_{dr} - \frac{PL_m}{2aL_s L_r}\psi_{qr}\omega_r + \frac{V_{qs}}{aL_s}$$

$$\frac{d\psi_{dr}}{dt} = \frac{L_m R_r}{L_r} i_{ds} + \frac{R_r}{L_r}\psi_{dr} - \frac{P}{2}\psi_{qr}\omega_r$$

$$\frac{d\psi_{qr}}{dt} = \frac{L_m R_r}{L_r} i_{qs} - \frac{R_r}{L_r}\psi_{qr} + \frac{P}{2}\psi_{dr}\omega_r$$

$$\frac{d\omega_r}{dt} = \frac{3PL_m}{4L_r J}\left(\psi_{dr} i_{qs} - \psi_{qr} i_{ds}\right) - \frac{T_l}{J} - \frac{B\omega_r}{J}$$

$$\frac{dT_e}{dt} = \frac{3PL_m}{4L_r}(\psi_{dr} i_{qs} - \psi_{qr} i_{ds})$$

Where i_{ds} - stator d-axis current, i_{qs} -stator q-axis current, ψ_{dr} - Rotor d-axis flux Linkage, ψ_{qr} - Rotor q-axis flux Linkage, ω_r - Rotor speed, T_e - Developed Torque, L_m - Magnetizing inductance, L_s - Stator Inductance, a - constant, R_r - Rotor resistance, B - Friction coefficient, P - No of poles, J - Moment of Inertia

For developing induction motor model, vector model is the best way, because vector model decouples the interaction between the flux and torque. Normally, in dc separately excited motor flux and torque can be controlled independently because there is natural decoupling between the flux control quantity and torque controlling quantity. Construction wise armature and field windings are placed orthogonal to each other but in ac motor this is not there, so always there is a interaction between the stator current and rotor torque. In the graph, 850 sampling instants are taken for motor starting condition, motor reaches its rated speed after 850 sampling instants. V/F control has been applied for motor starting in order to reduce the starting current which can be reduced further by reducing the step increase in V/F ratio. When V/F ratio is reduced, starting time of motor will also increase. For calculating motor parameters at different load conditions, load torque which varies at different time instants is taken as load variable. Variation in the load current, flux linkage, speed, and developed torque has been plotted in the figures below. Variation in the q-axis and d-axis current at various load conditions are shown in Fig1 and 2

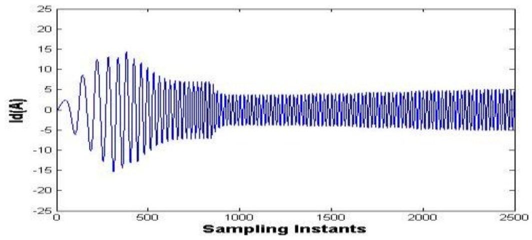

Fig1: Stator d-axis current

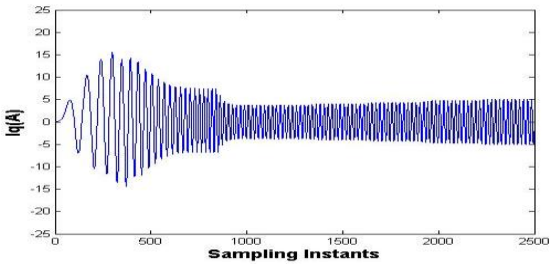

Fig2: Stator q-axis current

The flux linkage of the motor is constant for load variation. For the starting of motor, V/F control is applied so starting flux linkage value will be lower. When the load is increasing motor speed will start to reduce. The reduction in the motor speed is plotted in Fig3. Here low loads are applied so reduction in the speed will be less.

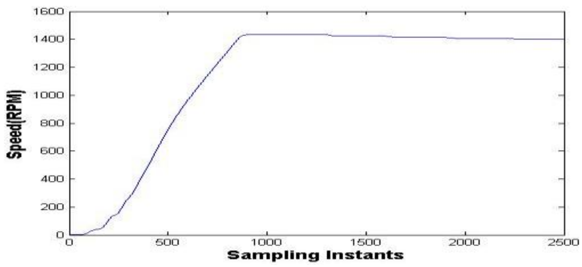

Fig3: Motor speed

Developed torque of the motor is plotted in the Fig4, whereas the Output power of the motor which is calculated from the speed and torque of the motor is shown in the Fig.5

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Vol. 1, Issue 3, September 2012

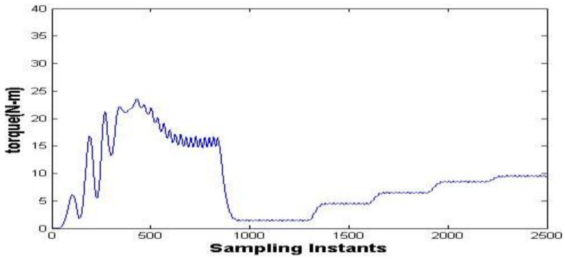

Fig4: Developed torque

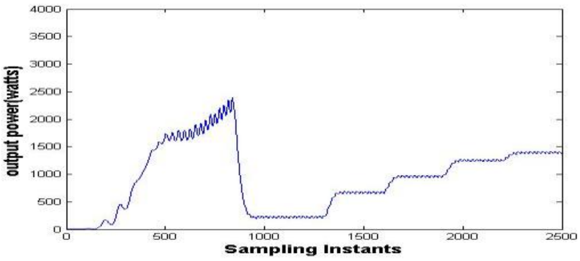

Fig5: Output power of the motor

III. CALCULATION OF LOSSES

Different types of losses present in Induction motor are

1. Core Loss (constant loss)
2. Copper Loss (I^2R loss, Variable loss)
3. Friction and Windage Losses (Mechanical losses)
4. Stray loss

Total Loss = $P_c + P_{cus} + P_{cur} + P_{fw} + P_s$

3.1 Core loss

Core loss is a constant loss, i.e. it will not change when the load is changing. The core loss of motor is directly proportional to supply voltage. The core loss of a induction motor depends upon the frequency and the maximum flux density when the volume and thickness of the core lamination are given. The core loss can be reduced by reducing the supply voltage. Core Loss contains two components which are as follows,

3.2 Eddy current loss

Eddy current loss is occurring due to flow of circulating current in the motor core, this circulating current can limited by laminating the motor core, the eddy current loss is occurring in the form of heat.

$$P_e \, \alpha f^2 B^2$$

f =operating frequency, B =Max.flux density.

3.3 Hysteresis loss

Hysteresis loss is occurring due to the magnetic property of the core material, due to the saturation of the material hysteresis loss occurs in the form of heat.

$$P_h \alpha \, fB^{1.6}$$

For reducing the core loss we can adjust supply frequency, flux density and supply voltage, core loss occur due to flow of I_w(core loss current) through the R_0(core loss resistance),the no load current of the motor is combination of the I_w+I_μ. When we reduce the magnetizing current by adjusting the voltage core loss can be reduced.

Nominal values, for 1 to 10 HP motors,

1. Thickness of the lamination can be varying in between 0.3mm to 0.5 mm based on the motor ratings.
2. Flux density can be vary in between 0.3 wb/m^2 to 0.45wb/m^2

Core loss is the combination of eddy current and hysteresis loss. In this work V/F control is applied at starting of motor so both the flux density and frequency will be increased gradually upto rated speed after reaching rated speed it will become constant irrespective of load conditions. Eddy current is shown in the Fig6, Hysteresis loss is shown in the Fig7

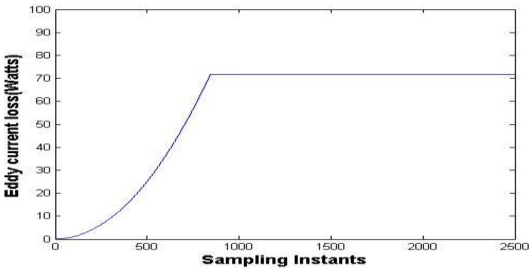

Fig6: Eddy current loss

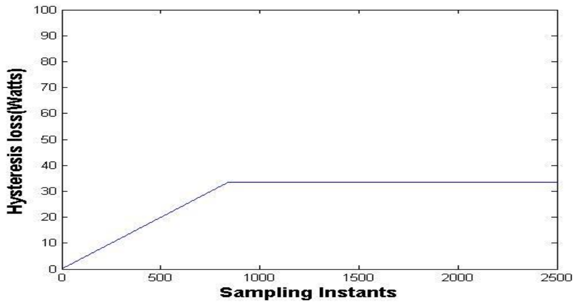

Fig7: Hysteresis loss

3.4 Copper Loss

Copper loss varies as a function of load current. Whenever load is applied to the motor copper loss also will change. In squirrel cage induction motor normally turns ratio is taken as 1, because due to short circuit on the rotor side rotor no of turns will replicate stator no of turns, so in squirrel cage induction motor stator and rotor currents are considered as equal in magnitude. Due to this stator and rotor copper loss will be same in magnitude. Copper Loss contain two components they are,

3.4.1 Stator copper loss

Stator copper loss is directly proportional to the supply or stator current of motor, this stator current can be measured directly at stator side so calculation of this loss is easier. When load is increasing load current also will increase so this copper loss also will increase.

$$P_{cus}=I_s^2 * R_s$$

3.4.2 Rotor copper loss

Rotor copper loss is directly proportional to the rotor current. Measurement of rotor current is not so easy as stator current measurement. The easiest way to measure rotor current is turns ratio. Rotor copper loss can be calculated by measuring the slip value, since rotor loss is proportional to slip speed. When slip value is low, rotor copper loss will be less. One way to reduce rotor copper loss is by controlling the speed of induction motor.

$$P_{cur} = I_r^2 * R_r$$

Total copper loss

$$P_{cu}= I_s^2 Rs+I_r^2 R_r$$

I_s− stator current.

R_s− stator resistance.

I_r − rotor current.

R_s – rotor resistance.

Here stator and rotor copper losses are calculated for per phase value of current. For total copper loss, it is necessary to multiply with no of phases. Stator copper loss is shown in the Fig8 and rotor copper loss is shown in the Fig9 for variations in the load. Total copper loss is the addition of stator and rotor copper loss.

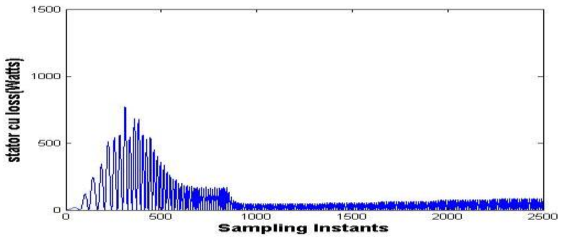

Fig8: Stator copper loss

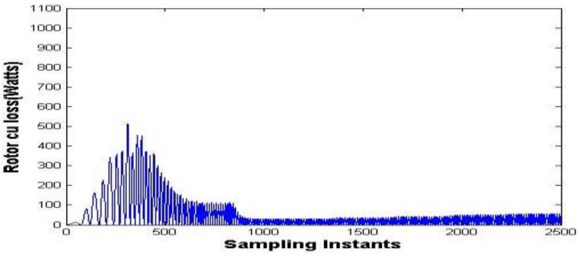

Fig9: Rotor copper loss

3.5 Friction and Windage Losses

Friction and Windage losses are mechanical losses present in the motor, friction loss occurs due to the friction in motor parts like bearings. Windage loss occurs due to the wind opposition for motor rotation. According to IEEE standard friction loss will be 1% of output power for 5HP motor. This standard value varies based on the motor power rating. Friction and windage loss is shown in the Fig10.

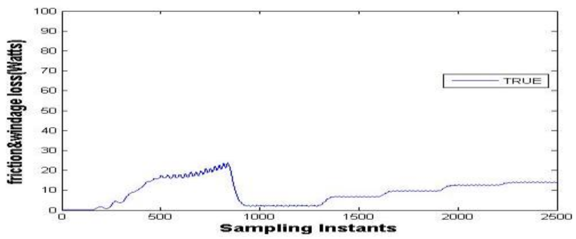

Fig10: Friction and windage loss

3.6 Stray Loss

The stray loss could be calculated by the following way. Both the pulsation loss P_t and the harmonic loss P_B are in proportion to the stator current I_1. The surface loss is proportional to the square of stator current. The sum of the pulsation loss and the harmonic loss equals the surface loss approximately, and hence it is deduced that the sum of pulsation loss, harmonic loss and surface loss are occupied 50% of the total stray loss. Stray loss is the combination of five losses such as Surface loss, Pulsation loss, Harmonic current loss of rotor part, Cross–path loss, and Flux leakage loss.

$$P_{st}=P_{stf}*(I_{st}^2/I_{stf}^2)$$

P_{st} =stray loss at operating load.
P_{stf}=stray loss at full load.
I_{st}=load current at operating load.
I_{stf}=load current at full load.

Stray loss of the motor is varying when the load is varying. Stray loss is the function of load current. Variation in the stray loss is shown in the Fig11 and Total loss of the motor is shown in the Fig12

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Vol. 1, Issue 3, September 2012

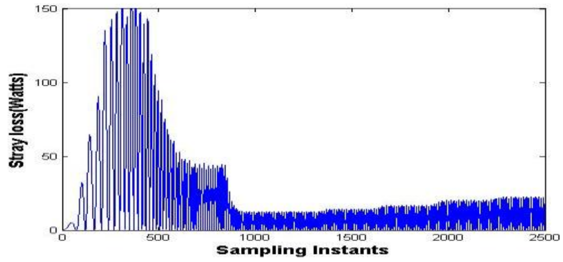


Fig11: stray loss

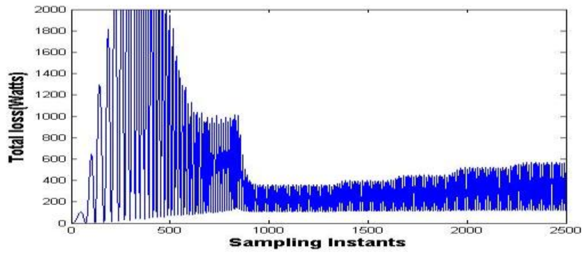


Fig12: Total loss.

Input power is nothing but output power plus losses. Following graph Fig13 shows the Input power to the motor.

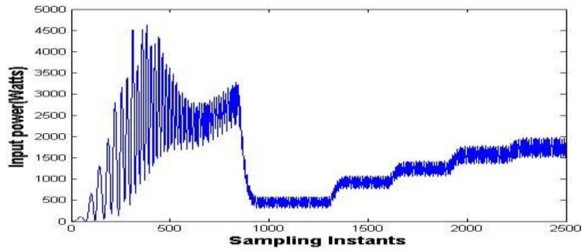


Fig13: Input power

IV. DEVELOPMENT OF EFFICIENCY MODEL

Performance of induction motor can be analyzed by calculating the efficiency of the motor knowing the input and output of the motor. But when one of these parameters is unknown, by calculating losses unknown can be inferred. In this work input power to the motor is unknown since Power factor of the motor is not known, so by calculating output power and losses, input power is calculated. Efficiency can be calculated by using the formula.

$$EFFICIENCY = \frac{OUTPUTPOWER}{OUTPUTPOWER + LOSSES}$$

Efficiency of the motor varies as load varies, when the applied load is low, efficiency of the motor becomes less. As load increases, efficiency also will start to increase.

Efficiency of the motor is calculated for variations in the load which is less than half of the rated load. It is possible to find efficiency upto full load condition. Fig14 shows the efficiency at low load condition.

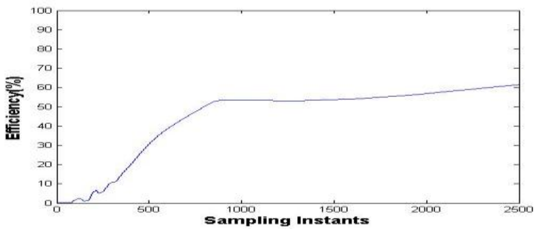


Fig14: Efficiency of motor in open loop

ISSN 2278 - 8875
International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering
Vol. 1, Issue 3, September 2012

METHODS FOR EFFICIENCY IMPROVEMENT

Efficiency has been improvement in two methods
1. Conventional method using PID.
2. Fuzzy optimization technique.

CONVENTIONAL METHOD:

Normally efficiency can be improved in two methods,
1. Power factor improvement method (for low load condition)
2. Constant speed control method (for higher load condition)

At the low load condition the major part of the loss is core loss, the core loss of the motor can be reduced by reducing the magnetizing current of the motor. Cause for core loss is magnetic saturation of the motor windings. If the supply voltage to the motor is reduced at low load condition, the reactive current taken by the motor will be reduced and real current will be increased in order to make apparent current remains same and the power factor also increases. But voltage should not be reduced below certain limit.

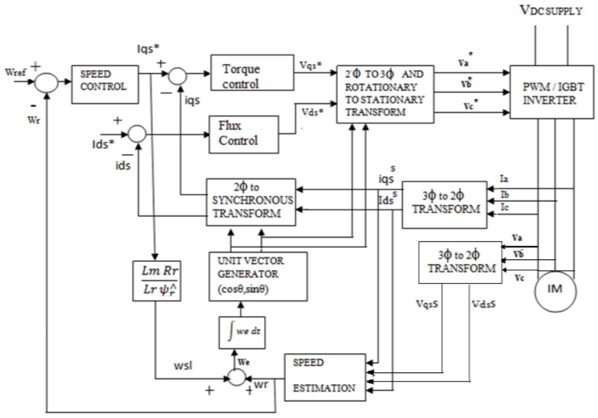


Fig15: conventional PID control scheme

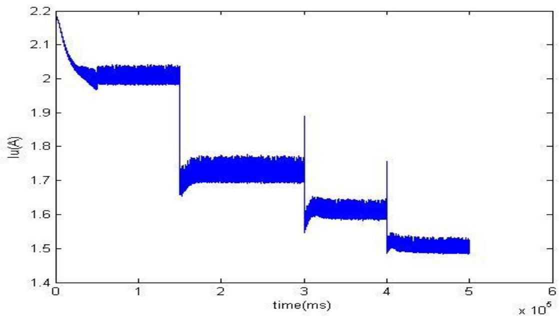


Fig16: Magnetizing current component

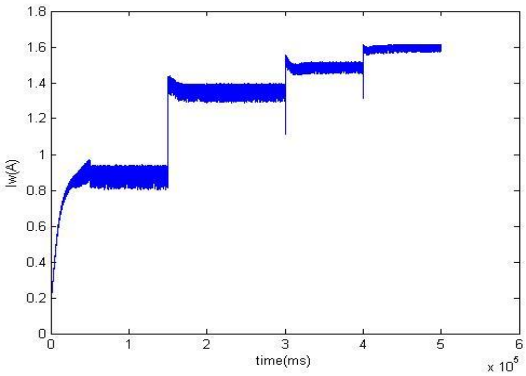


Fig17: core loss current component.

ISSN 2278 - 8875
International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering
Vol. 1, Issue 3, September 2012

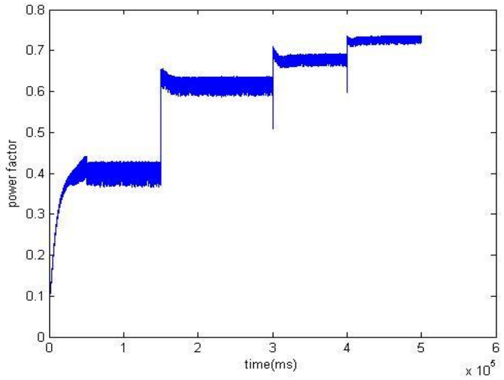


Fig18: Power factor

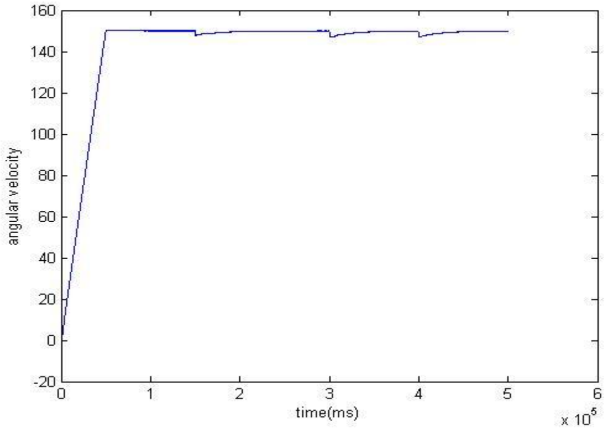


Fig19: Speed of the motor

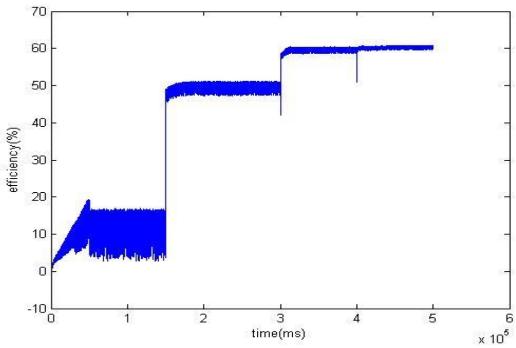


Fig20: Efficiency in conventional control

FUZZY LOGIC CONTROL SCHEME:

Fuzzy controller is acting in supervisory mode for providing set point to control the direct axis current.

The fuzzy logic is an aggregation of rules, based on the input state variables condition with a corresponding desired output. According to the optimization principle, two input variables are considered torque current component I_{ds} and its integral square variation. The output of the fuzzy controller is the no load I_0, which is calculated to minimize iron losses. A simplified block diagram of the optimization procedure is depicted in Fig21

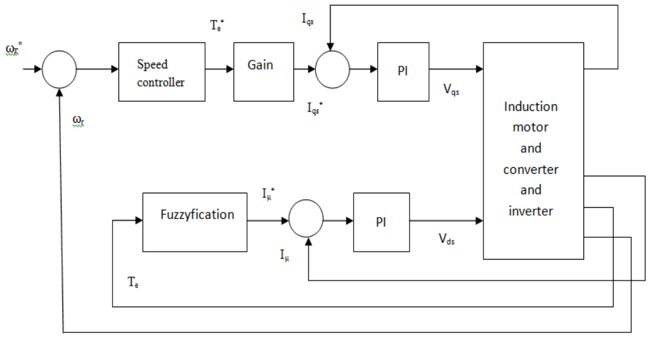


Fig21: Block diagram of the optimization control system

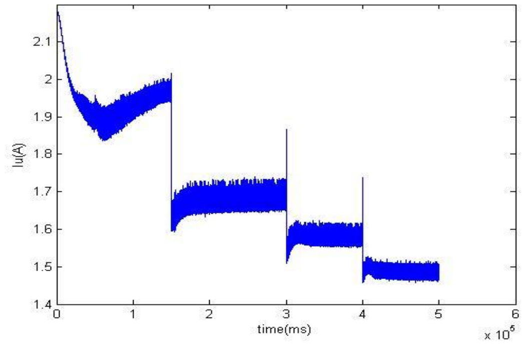


Fig22: magnetizing current component

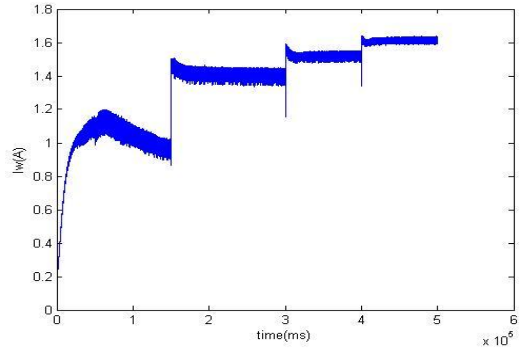
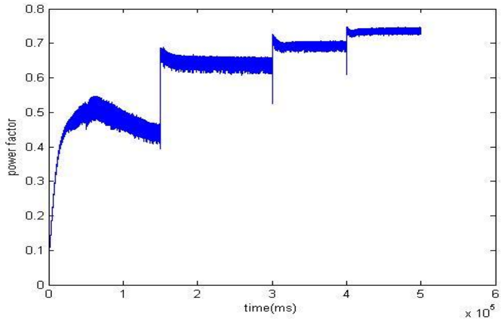


Fig23: core loss current component



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Vol. 1, Issue 3, September 2012

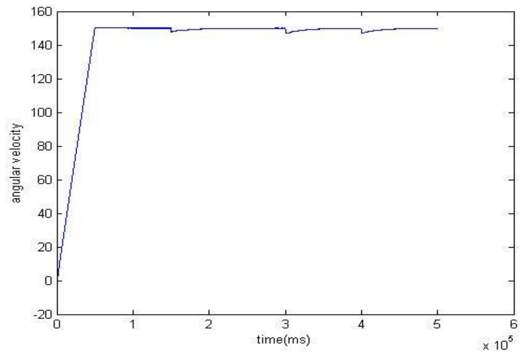

Fig24: power factor in fuzzy control Speed of the motor

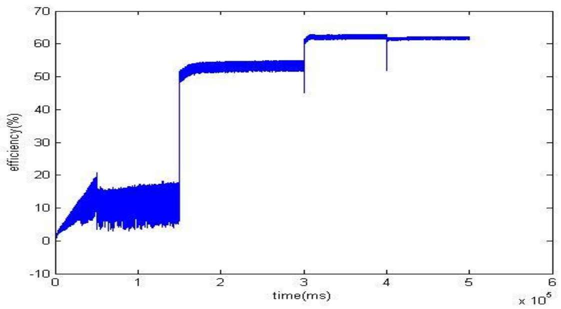

Fig25: Efficiency in fuzzy control

4.3 PERFORMANCE ANALYSIS OF CONVENTIONAL AND FUZZY CONTROLLER

The following table 4.1 shows the performance of conventional controller as well as performance of fuzzy optimization where fuzzy controller acting in supervisory mode and PID in regulatory mode.

Parameter	Conventional Controller	Fuzzy Optimization
Supply Voltage	**430 V**	**408 V**
Stator D-Axis Current	**3a**	**2.7a**
Power Factor	**0.7**	**0.74**
Magnetizing Current	**2.2 To 1.54**	**2.2 To 1.54**
Core Loss Component	**0 To 1.6**	**0 To 1.64**

From the table above it is clear that efficiency of the induction motor is improved by using fuzzy controller in supervisory mode, thus proves that fuzzy optimization has better control performance when compared to conventional controller.

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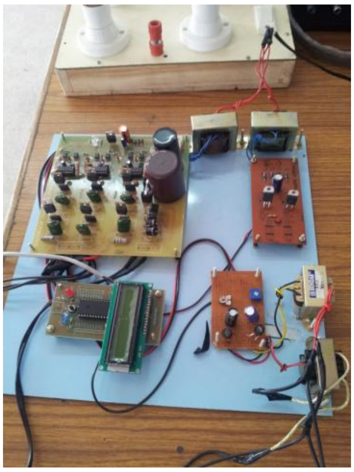
Vol. 1, Issue 3, September 2012

V. CONCLUSION

The efficiency model of the induction motor is developed by modeling the induction motor using vector model. From the developed induction motor model, output parameters(current,flux linkage,speed and torque) are obtained. By using those output parameters various losses of induction motor are calculated. In that Core loss is calculated using maximum flux density from flux linkage and copper loss from output current. The output power and calculated losses of the motor gives the Input power thereby efficiency of the induction motor is calculated at lower load conditions. Using conventional and Fuzzy optimization techniques efficiency is improved by minimizing losses. From the simulation results it is proved that in the efficiency maximization, fuzzy controller has better performance than conventional controller.

Induction Motor With Sensor Unit



PWM Circuit

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