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Induction Motor Speed Control using Fuzzy Logic Controller

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***Abstract*—**Because of the low maintenance and robustness induction motors have many applications in the industries. The speed control of induction motor is more important to achieve maximum torque and efficiency. Various speed control techniques like, Direct Torque Control, Sensorless Vector Control and Field Oriented Control are discussed in this paper. Soft computing technique – Fuzzy logic is applied in this paper for the speed control of induction motor to achieve maximum torque with minimum loss. The fuzzy logic controller is implemented using the Field Oriented Control technique as it provides better control of motor torque with high dynamic performance. The motor model is designed and membership functions are chosen according to the parameters of the motor model. The simulated design is tested using various tool boxes in MATLAB. The result concludes that the efficiency and reliability of the proposed speed controller is good.

***Keywords*—**Induction motor, Field Oriented Control, Fuzzy logic controller, Maximum torque, Membership function.

I. INTRODUCTION

AC Induction motors are being applied today to a wider range of applications requiring variable speed. Generally, variable speed drives for Induction Motor (IM) require both wide operating range of speed and fast torque response, regardless of load variations. This leads to more advanced control methods to meet the real demand. The conventional control methods have the following difficulties

1. It depends on the accuracy of the mathematical model of the systems
2. The expected performance is not met due to the load disturbance, motor saturation and thermal variations
3. Classical linear control shows good performance only at one operating speed
4. The coefficients must be chosen properly for acceptable results, whereas choosing the proper coefficient with varying parameters like set point is very difficult

To implement conventional control, the model of the controlled system must be known. The usual method of computation of mathematical model of a system is difficult. When there are system parameter variations or environmental disturbance, the behavior of the system is not satisfactory. Usually classical control is used in electrical motor drives. The classical controller designed for high performance increases the complexity of the design and hence the cost.

Advanced control based on artificial intelligence technique is called intelligent control. Every system with artificial intelligence is called self-organizing system. On the 80th decade the production of electronic circuits and microprocessors with high computation ability and operating speed has grown very fast. The high power, high speed and low cost modern processors like DSP, FPGA and ASIC IC's along with power technique switches like IGBT made the intelligent control to be used widely in electrical drives. Intelligent control, act better than conventional adaptive controls. Artificial intelligent techniques divide two groups: hard computation and soft computation [14]. Expert system belongs to hard computation which has been the first artificial intelligent technique. In recent two decades, soft computation is used widely in electrical drives. They are,

1. Artificial Neural Network (ANN)
2. Fuzzy Logic Set (FLS)
3. Fuzzy-Neural Network (FNN)
4. Genetic Algorithm Based system (GAB)
5. Genetic Algorithm Assisted system (GAA)

Neural networks and fuzzy logic technique are quite different, and yet with unique capabilities useful in information processing by specifying mathematical relationships among numerous variables in a complex system, performing mappings with degree of imprecision, control of nonlinear system to a degree not possible with conventional linear systems.

Fuzzy logic is a technique to embody human-like thinking into a control system. A fuzzy controller can be designed to emulate human deductive thinking, that is, the process people use to infer conclusions from what they know. Fuzzy control has been primarily applied to the control of processes through fuzzy linguistic descriptions. Fuzzy control system consists of four blocks as shown in Fig. 1.

This paper deals about the sandwich of artificial intelligence technique particularly fuzzy logic in the speed control of Induction motor. Various control techniques are discussed in Section II. The Section III describes the block diagram of 3Φ IM drive along with fuzzy controller. Section IV describes the implementation of maximum torque generation under field oriented control using fuzzy logic controller. Simulation results are given to demonstrate the advantage of proposed scheme is described in Section V. Conclusion and reference studies are mentioned in the last section.

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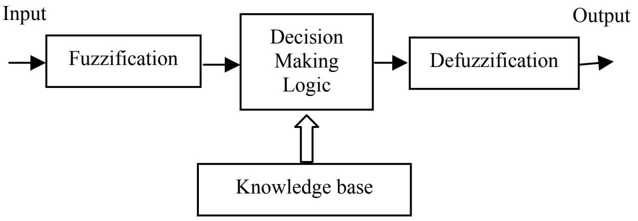


Fig. 1 Fuzzy Control System

II. VARIOUS CONTROL TECHNIQUES

Due to advances in power electronic switches and microprocessors, variable speed drive system using various control technique have been widely used in many applications, namely Field oriented control or vector control, Direct torque control, Sensorless vector control.

A. Direct Toque Control

The Direct Torque Control (DTC) scheme is very simple. In its basic configuration it consists of DTC controller, torque and flux calculator and VSI. In principle, the DTC method selects one of the inverter's six voltage vectors and two zero vectors in order to keep the stator flux and torque within a hysteresis band around the demand flux and torque magnitudes. The torque produced by the induction motor can be expressed as shown below

$$T_{em} = \frac{3}{2}\frac{P}{L_s}\frac{L_m}{L_r}\left|\overline{\lambda_r}\right|\left|\overline{\lambda_s}\right|\sin\alpha$$

This shows the torque produced is dependent on the stator flux magnitude, rotor flux magnitude and the phase angle between the stator and rotor flux vectors. The induction motor stator equation is given by

$$\overline{V_s} = \frac{d\overline{\lambda_s}}{dt} - \overline{I_s}r_s$$

Can be approximated as shown below over a short time period if the stator resistance is ignored, then

$$\Delta\overline{\lambda_s} = \overline{V_s}.\Delta t$$

This means that the applied voltage vector as shown in the Fig. 2 determines the change in the stator flux vector as shown in Fig. 3. If a voltage vector is applied that changes the stator flux to increase the phase angle between the stator flux and rotor flux vectors, then the torque produced will increase. Two problems are usually associated with DTC drives which are based on hysteresis comparators are:

i. Variable switching frequency due to hysteresis comparators used for the torque and flux estimators
ii. Inaccurate stator flux estimations which can degrade the drive performance

Some schemes have managed to maintain an average constant switching frequency by utilizing apace vector modulation, predictive control, and dead beat control. All of these techniques increase the complexity of the drive systems.

B. Sensorless Vector Control

The sensorless control method is valid for both high and low speed range. Using the traditional method, the stator terminal voltages and currents estimate the rotor angular speed, slip angular speed and the rotor flux. In this case, around zero speed, the slip angular velocity estimation becomes impossible since division by zero takes place. Another strategy is, as short sampling time is assumed, we could solve the linearized differential equations, then get an algebraic equation for the estimation of rotor parameters. The problem of achieving high dynamic performance in AC motor drives without the need for a shaft position/speed sensor has been under study widely.

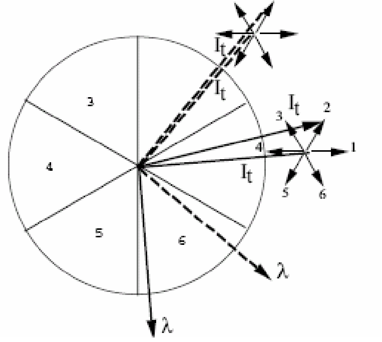


Fig. 2 Applied Voltage Vector

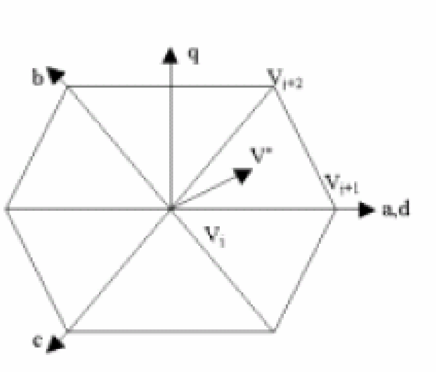


Fig. 3 Stator Flux Vector

The advantages of speed sensorless operation of the drives are lower cost, reduced size of the drive machines, elimination of the sensor cable and increased capability. The zero rotor speed problem persisting in the sensorless speed control scheme was resolved sacrificing the dynamic and steady state performance.

C. Field Oriented Control

Field oriented control (FOC) technique is intended to control the motor flux, and thereby be able to decompose the AC motor current into "flux producing" and "torque producing" components. These current components can be treated separately, and then recombined to create the actual motor phase currents. This gives a solution to the boost adjustment problem, and also provides much better control of the motor torque, which allows higher dynamic performance.

Some approaches which yield the maximum torque have been published. Xu and Novotny [3] insisted that a method which set the stator flux reference inversely proportional to the rotor speed should produce more output torque than a conventional method, which set the rotor flux reference inversely proportional to the rotor speed. However, in their method, there exist some speed ranges where the maximum torque cannot be obtained.

Kim and Sul [1] suggested a voltage control strategy for the maximum torque operation of induction motors in the field-weakening region, considering the voltage and current constraints. However this approach neglects the stator resistor for the analysis.

Wallace and Novotny [4] suggested an instantaneous maximum-torque generation method for induction motors. In this approach, the entire current input is used for generating the rotor flux before the torque is developed. Then, at the moment that the rotor flux reaches the steady state value, the entire input current is switched to produce torque current component.

III. BLOCK DIAGRAM OF INDUCTION MOTOR

In order to accomplish field oriented control, the controller needs to have an accurate "model" of the motor. Over the last several years a large number of different schemes have been proposed to accomplish the "flux and torque control" desired. Many of the today's technique involve some sort of self-tuning at startup in order to obtain information which helps to design accurate model of the motor to produce more optimal control. In addition, there are also techniques by which the models can adaptively adjust to changing conditions such as the motor temperature going from cold to warm which will have an impact of slip. The state equations of the induction motors can be expressed in the synchronously rotating *d-q* reference frame as follows [19].

$$\frac{dX}{dt} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} X + \begin{bmatrix} B_1 \\ 0 \end{bmatrix} U$$

where,

$$X = \begin{bmatrix} i_{ds} & i_{qs} & \phi_{dr} & \phi_{qr} \end{bmatrix}^T$$

$$U = \begin{bmatrix} V_{ds} & V_{qs} \end{bmatrix}^T$$

$$A_{11} = \begin{bmatrix} -\frac{R_s}{\sigma L_s} - \frac{(1-\sigma)R_r}{\sigma L_r} & \omega_e \\ -\omega_e & -\frac{R_s}{\sigma L_s} - \frac{(1-\sigma)R_r}{\sigma L_r} \end{bmatrix}$$

$$A_{12} = \begin{bmatrix} \frac{L_m R_r}{\sigma L_s L_r^2} & \frac{L_m}{\sigma L_s L_r}\omega_r \\ -\frac{L_m}{\sigma L_s L_r}\omega_r & \frac{L_m R_r}{\sigma L_s L_r^2} \end{bmatrix}$$

$$A_{21} = \begin{bmatrix} \frac{L_m R_r}{L_r} & 0 \\ 0 & \frac{L_m R_r}{L_r} \end{bmatrix}$$

$$A_{22} = \begin{bmatrix} -\frac{R_r}{L_r} & \omega_e - \omega_r \\ -\omega_e - \omega_r & -\frac{R_r}{L_r} \end{bmatrix}$$

$$B_1 = \begin{bmatrix} \frac{1}{\sigma L_s} & 0 \\ 0 & \frac{1}{\sigma L_s} \end{bmatrix}$$

and

V_{qs}, V_{ds} ,*q*- and *d*- axes stator voltages;

i_{qs}, i_{ds}, *q*- and *d*- axes stator currents;

R_s, R_r stator and rotor resistances;

ϕ_{qr}, ϕ_{dr}, *q*- and *d*- axes rotor fluxes;

ω_r rotor speed;

ω_e synchronous speed.

The generating torque of the induction motor is

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\frac{L_m}{L_r}\left(i_{qs}\phi_{dr} - i_{ds}\phi_{qr}\right)$$

where,

P pole number;

L_m mutual inductance;

L_r rotor inductance;

From the above the continuous- time model of the induction motors, a discrete-time model can be derived with the following assumptions

1) The sampling time is sufficiently small enough to achieve a good approximation of a continuous-time model.
2) Since the mechanical time constant is much larger than the electrical one, rotor speed of an induction motor is assumed to be constant during the sampling period.
3) Stator currents, rotor flux, and input voltages are also considered constant during the sampling period.

Using the above assumptions, a discrete-time model of induction motors can be expressed as

$$X(k+1) = A_d X(k) + B_d U(k)$$

where,

$$A_d = e^{AT}$$

$$B_d = \left(\int_0^T e^{A\alpha} d\alpha\right) B$$

T sampling time

The discrete model is used in the simulation.

Maximum torque generation

Maximize $T_e = K i_{ds} i_{qs}$

Under constraints $V_{qs}^2 + V_{ds}^2 \le V_{\max}^2$

$$i_{qs}^2 + i_{ds}^2 \le I_{\max} 2$$

where,

$$K = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\frac{L_m^2}{L_r}$$

the steady state voltage equations of an induction motor in the synchronously rotating reference frame are given as [1]

$$V_{ds} = R_s i_{ds} - \omega_e \sigma L_s i_{qs}$$

$$V_{qs} = R_s i_{qs} - \omega_e L_s i_{ds}$$

where,

$\sigma = \left[1 - \left(\frac{L_m^2}{L_s L_r}\right)\right]$ is the leakage inductance. So another current limit condition can be derived as follows

$$\left(R_s^2 + \omega_e^2 L_s^2\right) i_{ds}^2 + \left(R_s^2 + \omega_e^2 \sigma^2 L_s^2\right) i_{qs}^2 + 2\omega_e \frac{L_m^2}{L_r} R_s i_{qs} i_{ds} \le V_{\max}^2$$

If $\omega_e = 0$, then the above equation is a circle with radius V_{max}/R_s. As ω_e increases, the circle is turned into an eclipse. The following α_0 and α_∞ are the limiting values of the angle α as ω_e goes to zero or infinity:

$$\alpha_0 = \frac{1}{2}\lim_{\omega_e \to 0} \arctan\left[\frac{2R_s}{\omega_e L_s (1+\sigma)}\right] = 45^\circ$$

$$\alpha_\infty = \frac{1}{2}\lim_{\omega_e \to \infty} \arctan\left[\frac{2R_s}{\omega_e L_s (1+\sigma)}\right] = 0^\circ$$

The diagram of field oriented control block is shown in Fig. 4. A proportional–integral controller regulates the stator voltage to achieve the calculated stator current. The proportional-integral controller is shown in Fig. 5.

IV. IMPLEMENTATION OF FUZZY LOGIC CONTROLLER

To obtain fuzzy based model of the motor, the training system derives information from two main sources,

a. The static flux linkage curves of the motor, which provides important information about the electro-magnetic characteristics of the motor
b. The dynamic real time operating waveforms of the motor, which can include real-time operating effects, such as mutual coupling between phases, temperature variations, eddy currents and skin effects.

During the training phase, each input-output data pair, which consists of a crisp numerical value of measured flux linkage, current, angle and voltage is used to generate the fuzzy rules.

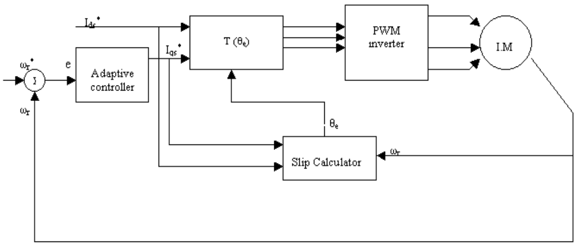


Fig. 4 Block diagram of Field Oriented Control System

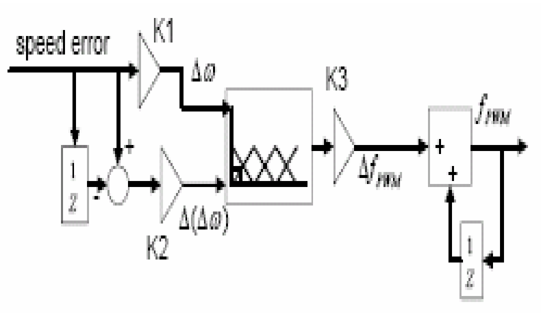


Fig. 5 Fuzzy PI controller

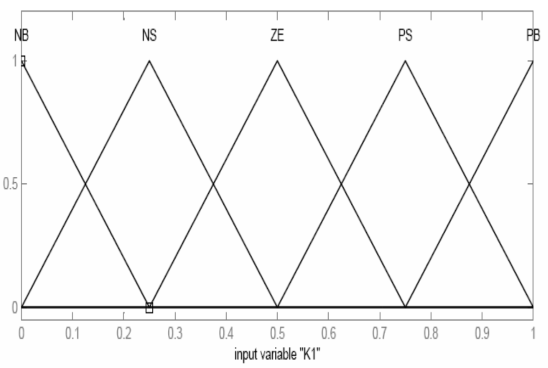
To determine a fuzzy rule from each input-output data pair, the first step is to find the degree of each data value in every membership region of its corresponding fuzzy domain. The variable is then assigned to the region with the maximum degree.

When each new rule is generated from the input-output data pairs, a rule degree or truth is assigned to that rule, where this rule degree is defined as the degree of confidence that the rule does in fact correlate to the function relating voltage and current to angle. In the developed method a degree is assigned which is the product of the membership function degree of each variable in its respective region.

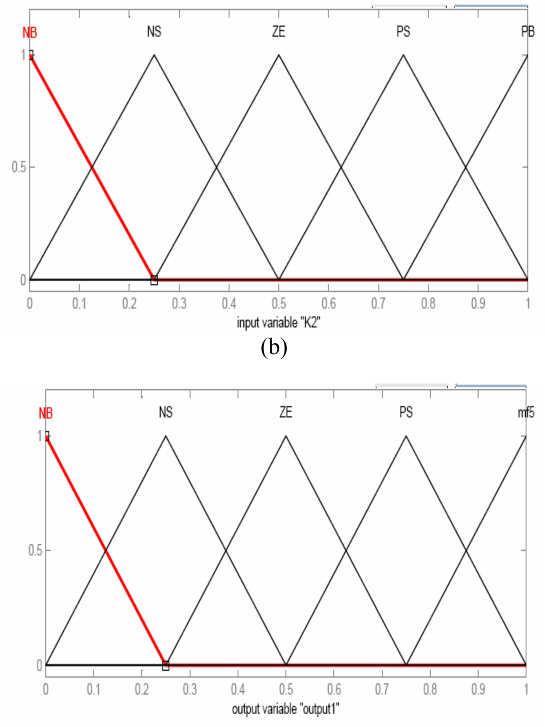
Every training data set produces a corresponding fuzzy rule that is stored in the fuzzy rule base. Therefore, as each input-output data pair is processed, rules are generated. A fuzzy rule or knowledge base is in the form of two dimensional table, which can be looked up by the fuzzy reasoning mechanism.

Speed error is calculated with comparison between reference speed and speed signal feedback. Speed error and speed error changing are fuzzy controller inputs. Input variables are normalized with a range of membership functions specified and the normalization factors are named as K1 and K2. Suitable normalization has direct influence in algorithm optimality and faster response. Refer Fig. 5.

Fig. 6 shows normalized membership functions for input and output variables. A fuzzy logic controller operation is based on the rules formed.



(a)



(b)

(c)

Fig 6 (a) Membership function for input variable K1 (b) Membership function for input variable K2
(c) Membership function for output variable

Fuzzy steps for generating torque

Step 1: Calculate X, Y, Z, X', Z' and α.

$$x = i_{ds}, y = i_{qs}$$

$$X = R_s^2 + \omega_e^2 L_s^2$$

$$Y = 2\omega_e \frac{L_m^2}{L_r} R_s$$

$$Z = R_s^2 + \omega_e^3 \sigma^2 L_s^2$$

$$X' = \frac{X + Z + \sqrt{(X - Z)^2 + Y^2}}{2}$$

$$Z' = \frac{X + Z - \sqrt{(X - Z)^2 + Y^2}}{2}$$

$$i_{qs}^* = i_{ds}^* = \frac{I_{\max}}{\sqrt{2}}$$

$$\begin{bmatrix} i_{ds}^* \\ i_{qs}^* \end{bmatrix} = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} x' \\ y' \end{bmatrix}$$

Where

$$x' = \left[\frac{V_{\max}^2 - Z' I_{\max}^2}{X' - Z'}\right]^{\frac{1}{2}}$$

$$y' = \left[\frac{X' I_{\max}^2 - V_{\max}^2}{X' - Z'}\right]^{\frac{1}{2}}$$

Step-2: Calculate the reference currents i_{ds}^* and i_{qs}^* in order to generate the maximum torque

$$i_{ds}^* = \left[\frac{\sqrt{Z}}{\sqrt{X}\left(Y + \sqrt{4XZ}\right)}\right]^{\frac{1}{2}} V_{\max}$$

$$i_{qs}^* = \left[\frac{\sqrt{X}}{\sqrt{Z}\,(Y + \sqrt{4XZ})}\right]^{\frac{1}{2}} V_{\max}$$

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\frac{L_m^2}{L_r} i_{qs}^* i_{ds}^*$$

Step-3: Calculate the reference torque from torque and speed relation of an induction motor

$$T_{ref} = \frac{2J}{P}\frac{\omega_{ref} - \omega_r}{T} + B\omega_r$$

Where
'J' motor inertia
'B' biscous coefficient
'P' pole number
'T' sampling period

Step-4: When $T_{ref} \geq T_{\max}$, maximum torque operation is required. When $T_{ref} < T_{\max}$, maximum torque operation is not required. In order to obtain good dynamic response, i_{ds}^* should be determined according to the operating point and i_{qs}^* is given as follows:

$$i_{qs}^* = \frac{T_{ref}}{\frac{3P}{4}\frac{L_m^2}{L_r} i_{ds}^*}$$

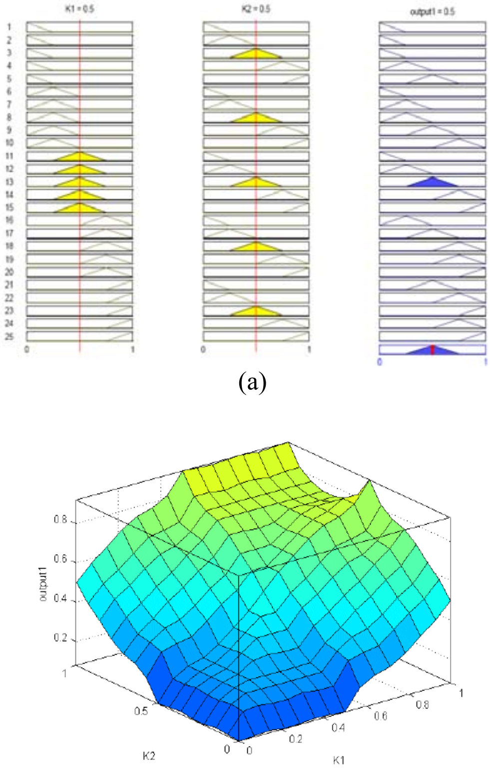
Step-5: Input voltages V_{ds}^* and V_{qs}^* can be obtained from the motor model.

V. SIMULATION RESULTS

Fuzzy Controller results: Input variables are required to be normalized with ranges of membership functions specified. Suitable normalization has direct influence in algorithm and results in optimality and faster response. Fig. 7 shows the membership functions and the output of the fuzzy logic controller. The fuzzy logic controller operation is based on the control operation shown in Table I.

TABLE I
FUZZY CONTROLLER OPERATIONS

	Δe	NB	NS	ZE	PS	PB
e	o/p					
NB		NB	NB	NS	NS	ZE
NS		NB	NS	NS	ZE	PS
ZE		NS	NS	ZE	PS	PS
PS		NS	ZE	PS	PS	PB
PB		ZE	PS	PS	PB	PB

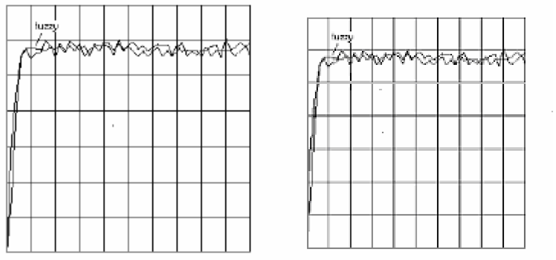


(a)

(b)

Fig. 7 (a) Rules view of fuzzy controller output
(b) Surface view of fuzzy controller output

Motor test results: Any induction motor can be used to show the performance of the proposed speed controller. Fig. 8 shows the simulation results of the torque, rotor speed and flux and energy loss obtained using MATLAB optimization toolbox. Since the rotor flux is maintained at a high level in the steady state, it can be seen that total energy loss maintains the constant level after the reference speed is achieved.



No load Full load

Fig. 8 Steady state response

VI. CONCLUSION

The proposed speed controller gives maximum torque over the entire speed range. In the steady state, the efficiency of the induction motor is increased. The validity of the proposed controller is confirmed through the simulation results. To implement it in the laboratory various parameters like rotor flux, rotor current and operating points, rotor parameter tuning are to be estimated. The proposed speed control system can be useful for the variable speed drive system.

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