Efficiency Optimization of Three Phase Induction Motor by Slip Compensation: A Review

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***Abstract*—Induction motor is a high efficiency electrical machine when working closed to its rated torque and speed. However, at light loads, there is no balance between copper and iron losses, which results in considerable reduction of efficiency for induction motor drive. The part load efficiency and power factor can be improved by making the motor excitation adjustment in accordance with load and speed. In this paper, an efficiency optimization controller of induction motor drive system, based on searching the value of stator voltage that maximizes the efficiency, will be developed. Then, the validity of the proposed controller and the performance of the drive system have been analyzed by simulation results. To reduce the slip at light loads and low frequencies, a slip compensator has been introduced.**

***Index Terms*—three phase Induction motor, Efficiency optimization, Slip Compensation, Stator Flux.**

I. INTRODUCTION

Induction motors are widely used in industry since they are rugged, inexpensive, and are maintenance free. It is estimated that more than 50% of the world electric energy generated is consumed by electric machines. Improving efficiency in electric drives is important, mainly for economic saving and reduction of environmental pollution [1], [2]. Induction motors have high efficiency at rated speed and torque. However, at light loads, motor efficiency decreases dramatically due to an imbalance between copper and core losses. Hence, energy saving can be achieved by proper selection of the flux level in the motor [3].

The optimization of induction motor design [4], with AI and NIA has received considerable attention recently. The design optimization of a three-phase induction motor can be formulated as a general non-linear programming and the standard non-linear programming (NLP) techniques can be used to solve it. But these techniques are computationally very expensive and inefficient whereas NIA is a competent tool to solve NLP.

To improve the motor efficiency [5], the flux must be reduced, obtaining a balance between copper and core losses. Many minimum-loss controls [6], schemes based on scalar control [7], or vector control [8], of induction motor drives have been reported in literature [9], [10]. Induction motor drive can be controlled according to a number of performance functions, such as input power, speed, torque, air gap flux, power factor, stator current, stator voltage, and overall efficiency [11]. Basically, there are three strategies, which are used in efficiency optimization of induction motor drive: Simple state control [12], [13], model based control, and search control. Search strategy methods have an important advantage compared to other strategies. It is completely insensitive to parameters changes, while effects of the parameters variations caused by temperature and saturation are expressed in two other strategies [14], [15].

II. PROBLEM FORMULATION

A. Different Strategies for Efficiency Optimization

Though induction motors have a high efficiency at rated speed and torque, however, at light loads, motor efficiency decreases due to an imbalance between the copper and the core losses. Hence, energy saving can be achieved by proper selection of the flux level in the motor. The main induction motor losses are usually split into: stator copper losses, rotor copper losses, and core (iron) losses, mechanical and stray losses.

Optimum control of IM is essential because it is not possible to optimize the motor efficiency for every operating point by optimizing machine design. In many applications of constant speed operation, induction motor operate under partial load for prolong periods, such as spinning drive in textile industry [16], mine hoist load, drill presses and wood saw. In these applications, induction motor should operate at reduced flux causing a balance in between iron losses and copper losses which results in improvement of efficiency.

The simplest method to improve efficiency of induction motor is to operate at light load and keep the motor in star connection which results in reduction of power consumption. When the motor runs in star mode, the voltage applied to stator phase winding is reduced by the factor of 3. Since the torque developed in the motor is directly proportional to the square of the voltage, the torque developed in star mode is also reduced by the factor of 3. Therefore, the motor can be operated in star mode up to 0.33 p.u loads. In this case the developed torque of the motor should be measured and find sufficient torque to drive the control system and also measure the temperature to be normal. Even though this method is not suitable for wide range of partial loads still it is working with many textile industries in India.

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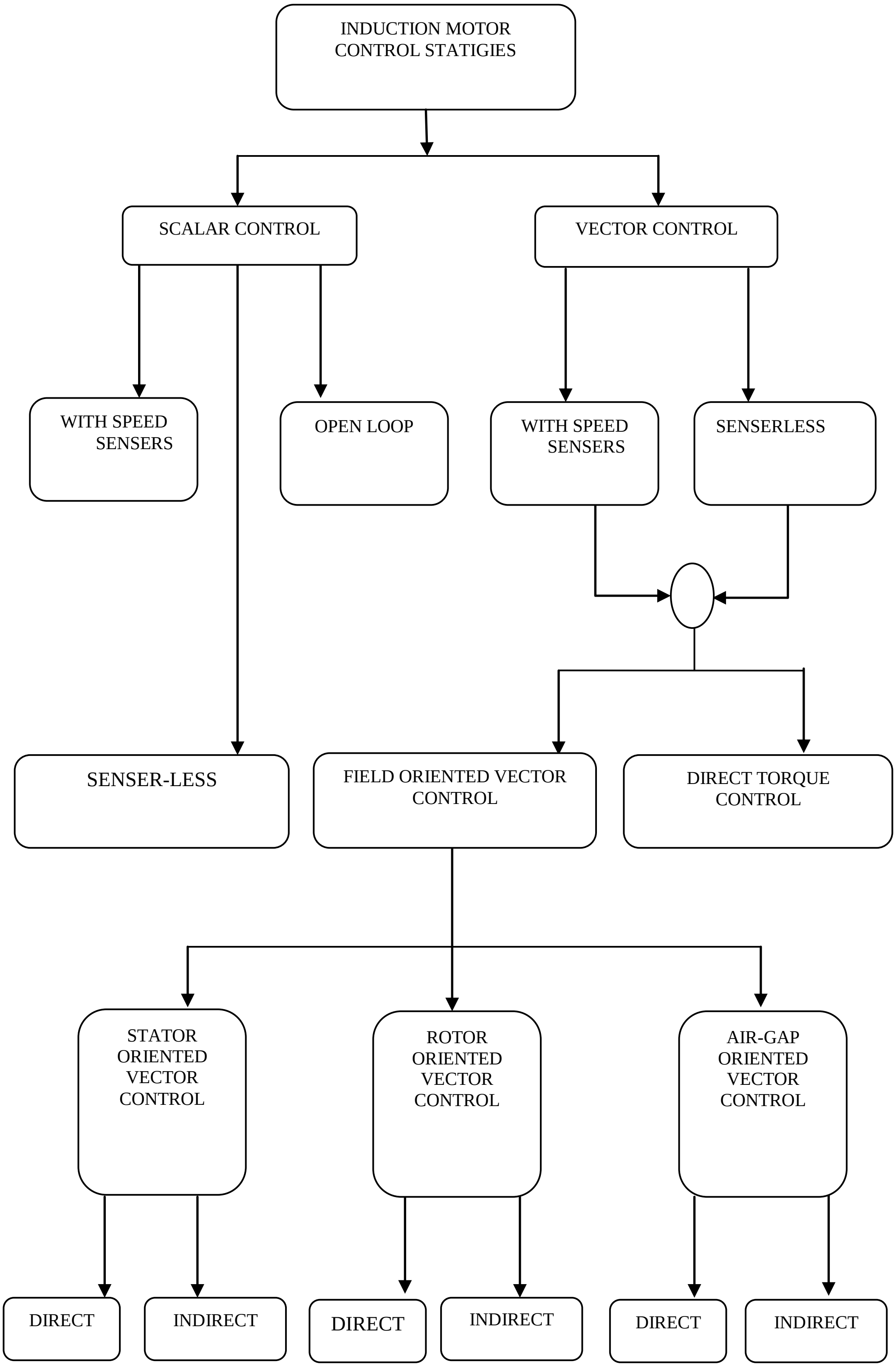

Figure. 1. Different strategies for efficiency optimization.

Different strategies for efficiency optimization [17], [18] are shown in Fig.1. In scalar control technique variables are controlled in magnitude only, whereas in vector control, variables are controlled in magnitude and phase both. The complex induction motor can be modeled as DC motor by performing simple transformation in the vector control scheme [19], [20], One advantage of loss model controller is that there is no delay in calculation of optimal flux and drive performances but time delay occurs in case of search control due to the searching.

There are three strategies, which are used in efficiency optimization of induction motor drive:

- Simple state control
- Model based control
- Search control.

B. *Search Control Method*

Search strategy methods have an important advantage compared to other strategies. It is completely insensitive to parameters variations in the motor due to thermal and

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core saturation effects. If the power input is measured on the source side of the rectifier, the minimization is not restricted to the motors but affects the entire system and thus reduces the total amount of energy consumed. Since the source voltage and current waveforms have much smaller harmonic content than the corresponding motor waveforms, the power measurement is more accurate and easier to obtain. An efficiency optimization [21], controller of induction motor drive system, based on searching the value of stator voltage that maximizes the efficiency [22], has been developed.

III. Proposed Methodolgy

A. Modeling and Simulation of Induction Motor Drive System

The original drive system studied in this thesis consists of IGBT-inverter-based AC to AC converter [23], [24], three-phase squirrel cage induction motor and V/f controller. In order to analyze the system performance, all of these components should be modeled (mathematically described). The inverter-based AC-to-AC converter is considered to be an ideal system, where the DC voltage at the input of the inverter has no AC component, and the output voltage of the filter at the output of the inverter has no harmonics. For sinusoidal pulse width modulation SPWM, the ratio of the amplitude of the sinusoidal waveform to the amplitude of the triangular waveform is called the modulation index m, which can be in the range of 0 to 1. The stator voltage Vs can be de-fined as:

$$V_s = \mathrm{mV_n} \tag{1}$$

where Vn= nominal value of stator voltage.

The frequency of the stator voltage f equals the frequency of the sinusoidal input waveform fin

$$f = \mathrm{f_{in}} \tag{2}$$

Varying the modulation index and the sinusoidal waveform frequency will change the RMS value of the stator voltage and frequency, respectively. Equations (1) and (2) constitute the steady-state model of inverter.

The controller with constant V/f must apply the following function:

$$m = \begin{cases} \mathrm{kf}, & 0 < \mathrm{f} < \mathrm{f_n} \\ 1, & f > f_n \end{cases}$$

where K=1/ fn, and fn = nominal frequency. Based on the flux linkages and voltages equations, the electrical and mechanical models of the squirrel cage three-phase induction motor with respect to a synchronously rotating d-q coordinates were adopted for simulation [25]. The parameters of modeled and simulated induction motor are given in Table I.

TABLE I. Induction Motor Parameter

Parameter	**Value**
Stator resistance R_1	1.4050Ω
Stator InductanceL_1	0.0058 H
Mutual Inductance L_m	1.172 H
Rotor resistance referred to the stator R'_2	1.395Ω
Rotor Inductance referred to the stator L'_2	0.0058 H
Nominal voltage V_n	230/400 V
Nominal output power P_n	4 kW
Nominal power factor cosΦ	0.850
Nominal frequency f_n	50 Hz
Number of poles P	4
Nominal rotational speed n_n	1430 rpm
Moment of inertia J	0.0132 $kg.m^2$

B. Design of Efficiency Optimization Controller

The efficiency of the drive system at any steady state operating point can be calculated as: $\eta = \frac{\mathrm{P_m}}{\mathrm{P_s}}$

where Pm = Lω, mechanical output power and Ps total input power supplied to the stator.

$$P_s = \frac{3}{2}\left(v_{sd}i_{sd} + v_{sq}i_{sq}\right)$$

To design the efficiency optimization controller based on search method, a matrix, as shown in Table II, consisting of loads, frequencies and stator voltage values (optimal voltage), which maximize the efficiency, was constructed using MATLAB SIMULINK model of the studied drive system. The relationship between load torque, frequency and optimal voltage in matrix shown in Table II was used to form a 2D lookup module (table) in

TABLE II. Optimal Stator Voltage as a Function of Load Torque and Frequency.

		Load Torque, Nm				
		5	10	15	20	25
Frequency, Hz	5	32.8	46.4	57.6	65.6	73.6
	10	58.4	86.4	100	116	130.4
	15	83.2	116	143.2	176	190.4
	20	109.6	151.	185.6	220	246.4
	25	137.6	196.	236.8	267.	308.8
	30	160.8	222.	272.8	324	349.6
	35	189.6	276.	326.4	369.	400
	40	220.8	295.	353.6	400	400
	45	243.2	340	391.2	400	400
	50	272.8	372.	400	400	400

MATLAB, which serves as the main part of the proposed efficiency optimization controller, The output of the controller is the modulation index m, which correspondences the optimal value of voltage maximizing the efficiency under certain operation condition.

Simulation results showed that the main disadvantage of the proposed efficiency optimization technique was the increase in slip, especially at light loads and low frequencies So, there is a need to compensate (reduce) the slip according to some reference (acceptable) value refs.

Optimal stator voltage can be achieved by increasing the electromagnetic torque. Optimal stator voltage as a function of load torque and frequency. Voltage, V of the motor by increasing the stator voltage in the optimized

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system. In this case, the error in slip will be gained and integrated to get the value of compensation voltage that should be added to the voltage in the optimized system. The value of compensation voltage can be calculated by the following equation:

$$V_{com} = \mathrm{K_i} \int (S_{ref} - S)dt \tag{3}$$

where K=integrating constant.

C. Parameter "Bus Selector"

Table III shows the input output parameters of three phase induction motor.

TABLE III. BUS SELECTOR PARAMETER

Parameter	**Value**
Output signals	Stator measurements. Stator current is_q (A), Stator voltage vs_q (V), Stator current is_d (A), Stator voltage _d (V), Mechanical. Rotor speed (wm), Electromagnetic torque Te (N*m)
Output as bus	**Off**
	{ Rotor measurements , Rotor current ir_a (A) Rotor current ir_b (A) Rotor current ir_c (A) Rotor current iq (A) Rotor current id (A) Rotor flux phir_q (V s) Rotor flux phir_d (V s) Rotor voltage Vr_q (V) Rotor voltage Vr_d (V) } { Stator measurements , Stator current is_a (A) Stator current is_b (A) Stator current is_c (A) Stator current is_q (A) Stator current is_d (A) Stator flux is_q (V s)
	Stator flux is_d (V s) Stator voltage vs_q (V) Stator voltage vs_d (V) } { Mechanical , Rotor speed (wm) Electromagnetic torque Te (N*m) Rotor angle the tam (rad) }

IV. MATLAB MODEL

A. Induction Motor Without Slip Compensation

The SIMULINK Model for poly phase squirrel cage induction motor drive without slip compensation is show in Fig. 2. In this model four scope and six digital display are connected to show the value of output signal in analog and digital form. When run this model, than scope T_e, N and I_s,V_s given output signals. T_e represent electromagnetic torque waveform (shown in Fig. 3) for induction motor without slip compensation.

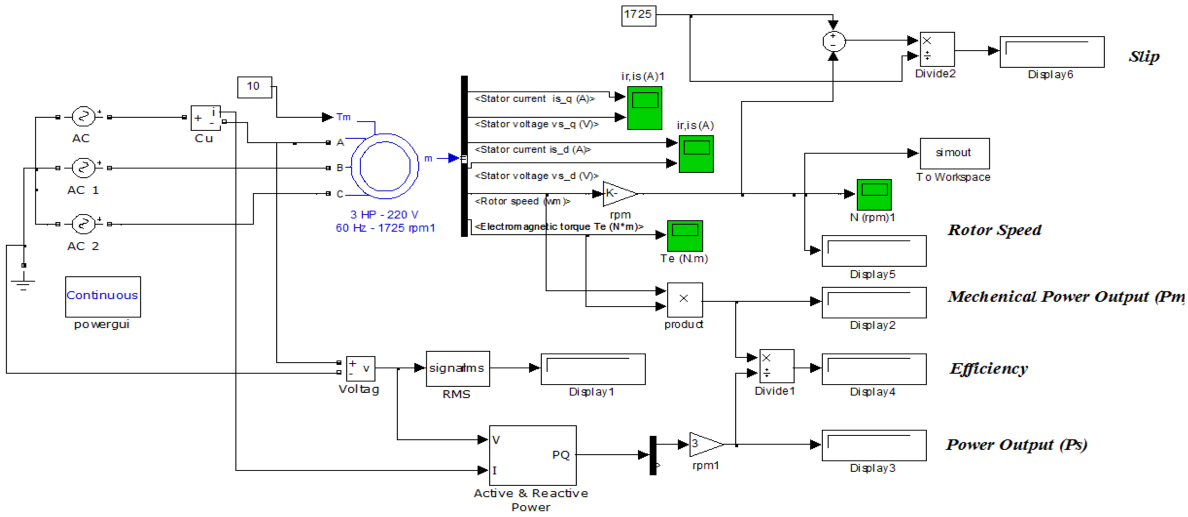

Figure. 2. SIMULINK Model for induction motor without slip compensation

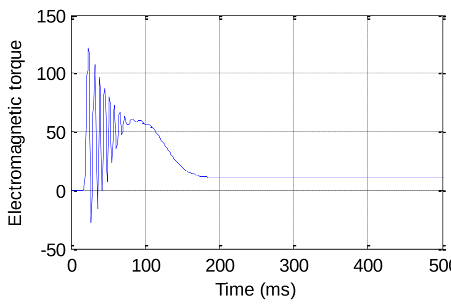

Figure 3. Electromegnatic torque waveform for induction motor without slip compensation

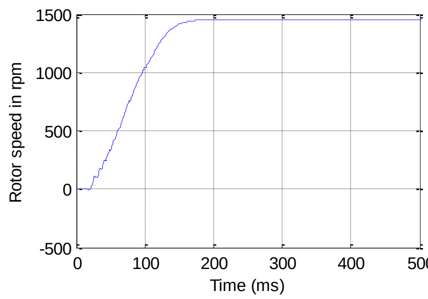

Figure 4. Rotor speed waveform for induction motor without slip compensation

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Similarly scope N and I_s,V_s represent motor speed and q-axis stator current, stator voltage waveform show in Fig. 4 and Fig. 5.

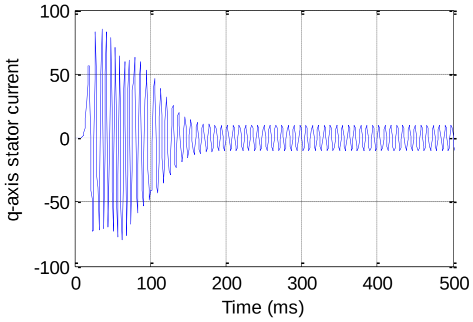

Figure 5. q-Axis stator current waveform for induction motor without slip compensation

Fig. 4 shows that when induction motor is running without slip compensation than rotor speed is 1416 rpm.

Fig. 5 and Fig. 6 shows q-Axis stator current waveform and q-Axis stator voltage waveform for induction motor without slip compensation

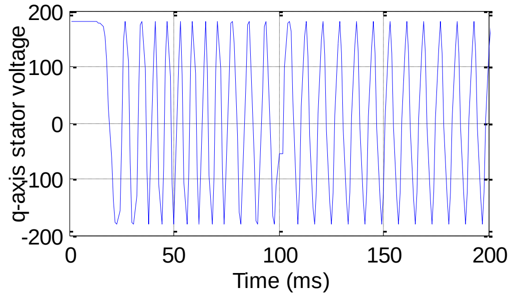

Figure 6. q-Axis stator voltage waveform for induction motor without slip compensation

B. *Induction Motor with Slip Compensation*

The SIMULINK Model for Efficiency optimization of induction motor with slip compensation is show in Fig.7.

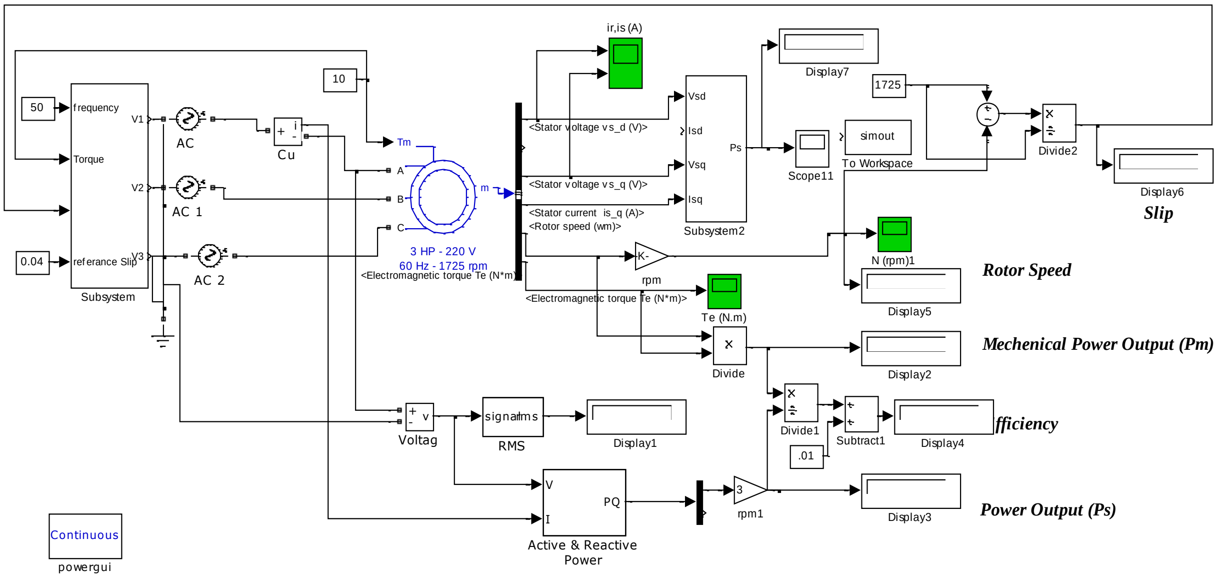

Figure7. SIMULINK Model for efficiency optimization of induction motor with slip compensation

TABLE IV. THE RELATIONSHIP BETWEEN LOAD TORQUE, FREQUENCY AND OPTIMAL VOLTAGE

		Load Torque, Nm				
		5	10	15	20	25
Frequency, Hz	5	32.8	46.4	57.6	65.6	73.6
	10	58.4	86.4	100	116	130.4
	15	83.2	116	143.2	176	190.4
	20	109.6	151.2	185.6	220	246.4
	25	137.6	196.8	236.8	267.2	308.8
	30	160.8	222.4	272.8	324	349.6
	35	189.6	276.8	326.4	369.6	400
	40	220.8	295.2	353.6	400	400
	45	243.2	340	391.2	400	400
	50	272.8	372.8	400	400	400

This model is similar to previous model. The main difference is that, in this model slip compensator has been introduced.

With the help of equation 3 we find the value of (V_{com}) compensated voltage. This model consist four scopes and seven display blocks. The output of scope T_e ,N and I_s,V_s

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is shown in Fig. 9, Fig. 10, Fig. 11 and Fig. 12 respectively.

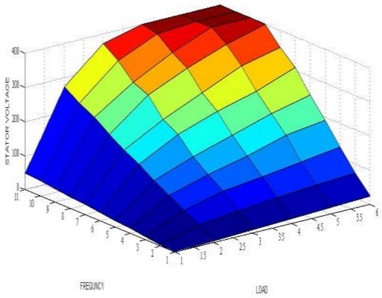

Figure 8. The relationship between load torque, frequency and optimal voltage (graphical representation)

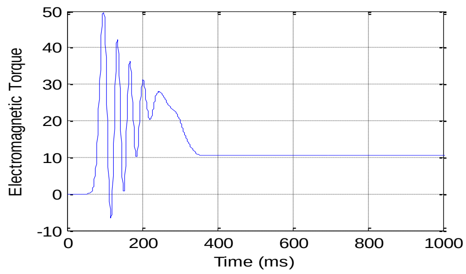

Figure 9. Electromegnatic torque waveform for induction motor with slip compensation

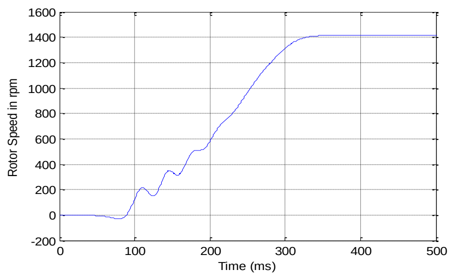

Figure 10. Rotor speed waveform for induction motor with slip compensation

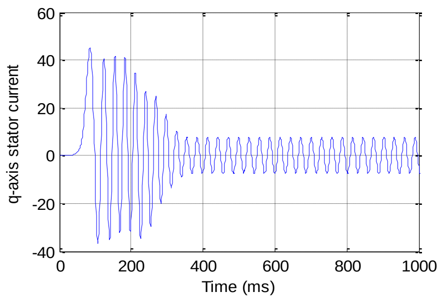

Figure 11. q-Axis stator current waveform for induction motor with slip compensation

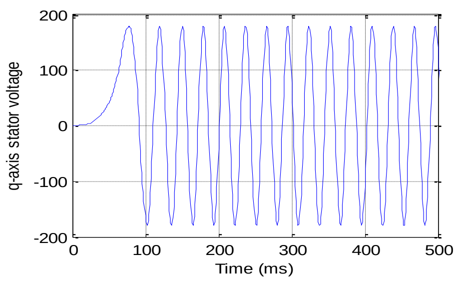

Figure 12. q-Axis stator voltage waveform for induction motor with slip compensation

The relationship between load torque, frequency and optimal voltage is shown in Table IV (numeric representation) and Fig. 4 (graphical representation).

Finally after comparing all the output waveform of uncompensated model to compensated model (as shown in Table V.) it is clear that the value of rotor speed and efficiency of induction motor is increased by reducing the value of slip, with the help of slip compensator.

TABLE V. COMPARISON OF BOTH MODELS (WITH SLIP COMPENSATION AND WITHOUT SLIP COMPENSATION)

Comparison of induction motor parameter on 10N load			
Parameters	Efficiency	Slip	Rotor Speed
Without compensation	0.813	0.178	1416
With slip compensation	0.842	0.154	1458

V. CONCLUSSION

The conclusion of this thesis efficiency optimization controller, based on search method will be developed. The proposed controller manipulates the value of stator voltage that maximizes the efficiency at any given operating point. To reduce the slip to a certain value, a slip compensator has been inserted into the drive system. The suggested technique can be used in variable frequency, variable load electrical drive systems. Based on simulation analysis, it will be noticed that the compensated optimized system gives significant results at low frequencies and light loads.

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