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Efficiency Optimization with Improved Transient Performance of Indirect Vector Controlled Induction Motor Drive

Seena Thomas[1], Rinu Alice Koshy[2]

M.Tech Student, Rajagiri College of Engineering and Technology, Kakkanad, India[1]

Assistant Professor, Rajagiri College of Engineering and Technology, Kakkanad, India [2]

Abstract: This paper introduces an energy efficient induction motor drive suitable to operate at light load conditions. The iron losses in the induction motor are significant when the machine is operated below the rated conditions. The efficiency of the motor can be increased by keeping the flux level below the rated value. In this paper, the efficiency of the induction motor has been improved by incorporating an efficiency optimization algorithm. Efficiency optimization algorithm provides an optimum value of flux generating direct axis stator current, which controls the magnitude of the rotor flux. At light loads, the optimization algorithm weakens the rotor flux from its rated value, thus reducing the core losses. A 5.4-hp induction motor drive is simulated in SIMULINK to analyze the efficiency under different operating conditions of the drive. The variation of efficiency under load change and speed change is observed. Simulation results show that efficiency increases as the operation of induction motor drive shifts from unrated to rated conditions. The implemented algorithm is tested under different operating conditions of IM Drive including sudden change in load and reference speed. This paper also considers the transient performance of the drive with efficiency optimization algorithm.

Keywords: Vector control, Optimization, Indirect field oriented control, Simulink

I. INTRODUCTION

It is estimated that electric machines consume more than 50% of the world electric energy generated. Economic saving and reduction of environmental pollution are the two factors that highlight the importance of analyzing the efficiency in electric drives. The induction motors are widely used in the electrical drives and are responsible for most of the energy consumed by electric motors [1]. In recent years the control of high-performance induction motor drives for general industry applications and production automation has received widespread research interests [2]. Many schemes have been proposed for the control of induction motor drives, among which the field oriented control, or vector control, has been accepted as one of the most effective methods [3]. Vector control offers a number of benefits including speed control over a wide range, precise speed regulation, fast dynamic response, and operation above base speed [4].

Induction motor operating at rated conditions is a high efficiency electrical machine. However, at light loads, IM drive shows considerable reduction in the efficiency. It is possible to obtain an optimum value of efficiency for any load condition with the introduction of efficiency optimization algorithm in the control technique of the induction motor [5]. Efficiency optimization is relevant in applications where the load torque is not constant and may vary from full load to light load conditions. Optimization can conserve energy by minimizing the iron losses in the machine. For industrial applications such as electrical vehicles, high efficiency is essential to extend the running distance per battery charge under all operating conditions [6]. Efficiency optimization is particularly applicable in marine vehicles where the light running conditions persist for long period of time.

The focus of this paper is to obtain optimum efficiency for an induction motor (IM) drive especially at light loads, by minimizing the core losses which are considerable at these load conditions. This paper analyzes the performance of an induction motor drive with the implementation of efficiency optimization algorithm for different operating conditions. Simulation study of the proposed optimization algorithm is done in MATLAB/Simulink environment. The efficiency measurement for the induction motor drive will be carried out with and without efficiency optimization control at different speed and load conditions.

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Also the dynamic performance of the drive with optimization algorithm has been investigated. The paper introduces a technique to improve the transient behavior of the drive in which optimization algorithm is implemented.

II. INDIRECT FIELD ORIENTED CONTROL

By using field oriented control, torque and flux of the induction motors can be controlled independently as in dc motors. The power circuit consists of a front end diode rectifier and a hysteresis band current control pulse width modulation (PWM) inverter. Fig. 1 shows the block diagram of a typical IFOC of induction motor.

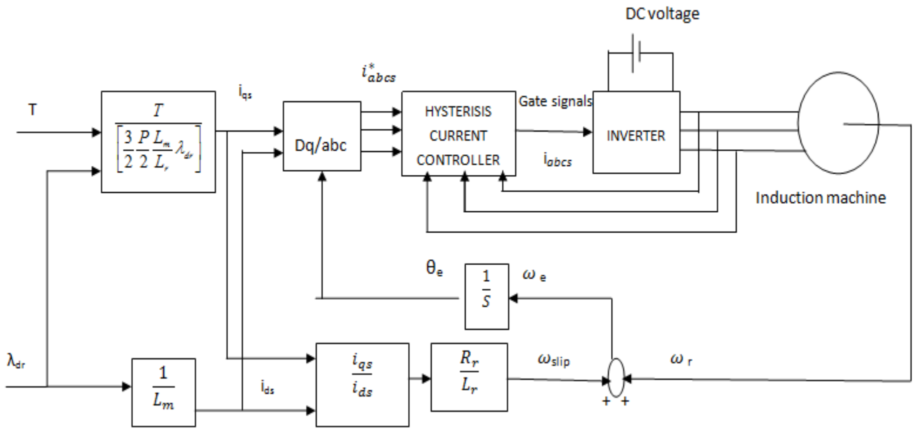

Fig. 1 Typical IFOC block diagram

The speed PI controller generates the reference torque command:

$$T = (K_{p\_speed} + \frac{K_{i\_speed}}{s})(N_{ref} - N) \tag{1}$$

where N_{ref} is the speed command and N is the actual rotor speed.
The torque and rotor flux reference commands are utilized to generate the motor $d-q$ reference currents:

$$i_{ds}^{e} = \frac{\lambda_{dr}}{L_m} \tag{2}$$

$$i_{qs}^{e} = \frac{T}{\left[\frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}\lambda_{dr}\right]} \tag{3}$$

The flux is kept at rated value up to rated speed. Hence i_{ds}^{e}, the d-axis component of stator current is constant depending on the rated flux value. The i_{qs}^{e}, q-axis component of stator current determines the electromagnetic torque developed. The slip frequency ω_{slip}, is generated from i_{qs}^{e} and i_{ds}^{e}.

$$\omega_{slip} = \frac{R_r}{L_r}.\frac{i_{qs}^{e}}{i_{ds}^{e}} \tag{4}$$

where Rr is the rotor resistance and Lr is rotor inductance.
The synchronous speed, ω_e is the sum of slip frequency, ω_{slip} and electrical angular rotor frequency, ω_r.

$$\omega_e = \omega_{slip} + \omega_r \tag{5}$$

The integration of ω_e yields the rotor pole position, θ_e.

$$\theta_e = \int \omega_e \tag{6}$$

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The hysteresis PWM attempts to force the actual motor currents (i_{as} i_{bs}, i_{cs}) to the reference currents(i_{as}^*, i_{bs}^*, i_{cs}^*) values. The error between the reference currents and the actual currents are used to switch the PWM inverter. The output of the inverter is supplied to the stator of the induction motor.

III. INDUCTION MOTOR DRIVE EFFICIENCY

Minimum power loss operation in induction motor drives brings about significant global energy savings, since machines consume approximately two-thirds of all electricity generation worldwide. The three main components of a motor drive system are the control, machine, and power electronics. Control is based on analog or digital circuits and usually consumes a negligible amount of power; its power consumption is relatively constant. Machine and power electronics dominate the system losses.

Machines are normally designed to operate at rated flux conditions so that the developed torque per ampere is high and transient response is fast. If the flux component of the stator current in the d-q synchronously rotating frame is set to the rated field flux for the full range of base speed (i.e. from zero to rated value), as is done in conventional vector control method of an induction motor, it results in production of very fast and precise torque response. However, most of the time, industrial drives operate at light loads. If rated flux is maintained at light load the core loss is excessive resulting in poor efficiency of the drive. In addition, in low frequency operations, core loss is rather low compared to copper loss. As the speed increases the contribution of eddy current loss increases and finally becomes dominant, hence optimal combination of direct axis (d-axis) and quadrature axis (q-axis) current vary depending on the required torque and speed.

The operating loss of an induction motor is composed of the stator and rotor copper losses, the core losses and the mechanical losses. The copper loss is due to the flow of current through stator and rotor windings and is given by

$$W_{Cu} = \frac{3}{2}\left[\left(i_{qs}^{e\,2} + i_{ds}^{e\,2}\right)r_s + \left(i_{qr}^{e\,2} + i_{dr}^{e\,2}\right)r_r\right] \tag{7}$$

where i_{qs}^e and i_{ds}^e are q-axis and d-axis stator current respectively and i_{qr}^e and i_{dr}^e are q-axis and d-axis rotor currents respectively.

The core (iron) losses due to hysteresis and eddy currents are related as

$$W_{Fe} = \frac{3}{2}\left[K_h \omega_e \lambda_m^{e\,2} + K_e \omega_e^2 \lambda_m^{e\,2}\right] \tag{8}$$

where K_h and K_e are the eddy current and hysteresis loss coefficients and λ_m is the flux linkage.

The mechanical losses are dependent on the rotor speed and is given by

$$W_{mech} = K_m \omega_r^2 \tag{9}$$

where K_m is the mechanical loss coefficient.

Thus the total operating losses are given by

$$W_{total} = \frac{3}{2}\left[\left(i_{qs}^{e\,2} + i_{ds}^{e\,2}\right)r_s + \left(i_{qr}^{e\,2} + i_{dr}^{e\,2}\right)r_r\right] + \frac{3}{2}\left[K_h \omega_e \lambda_m^{e\,2} + K_e \omega_e^2 \lambda_m^{e\,2}\right] + K_m \omega_r^2 \tag{10}$$

Efficiency of the induction motor is given by

$$\eta = \frac{T_e \omega_r}{T_e \omega_r + W_{total}} \tag{11}$$

where T_e is the electromagnetic torque developed.

IV. EFFICIENCY OPTIMIZATION ALGORITHM

Fig.2 shows the block diagram of indirect vector controlled induction motor drive with efficiency optimization algorithm providing the optimum value of direct axis stator current, $i_{ds\text{-}opt}$. The machine can be operated with and without the optimization algorithm.

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When the motor is running under the rotor flux field orientation, at steady state, $\lambda_{dr} = \lambda_r$ and $\lambda_{qr} = 0$, since d-axis is locked on the rotor flux vector . Hence, $i_{dr}^e = 0$ and $i_{qr}^e = -L_m L_r\, i_{qs}^e$ and thus λ_m^e can be eliminated from Eq. (10), and the loss becomes

- Total losses can be expressed as:

$$W_{total} = \frac{3}{2}\left[x\left(i_{ds}^2\right) + y\left(\frac{T_e}{Ki_{ds}}\right)^2 \right] + k_m \omega_r^2 \qquad (12)$$

where

$$x = r_s + \left(k_h \omega_e + k_e \omega_e^{\,2}\right) L_m^{\,2}$$

$$y = r_s + r_r \frac{L_m^{\,2}}{L_r^2} + \left(k_h \omega_e + k_e \omega_e^{\,2}\right) \frac{L_m^{\,2}}{L_r^2} \left(L_r - L_m\right)^2$$

$$K = \frac{3}{2}\frac{P}{2}\frac{L_m^{\,2}}{L_r}$$

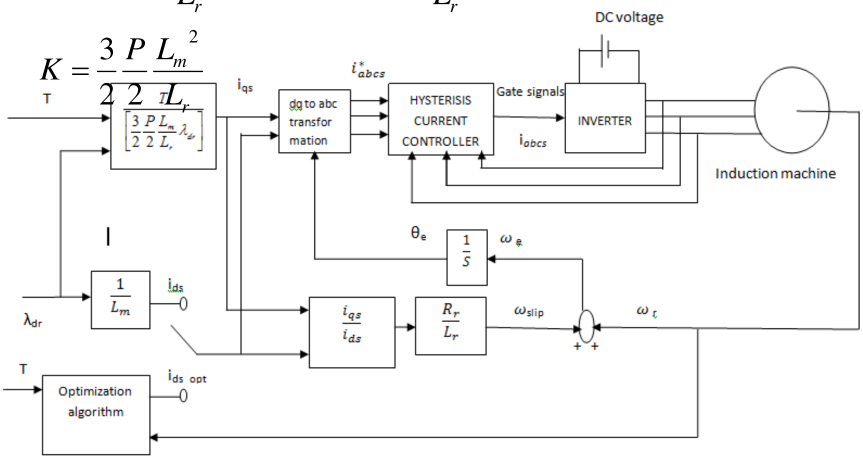

Fig.2 Block diagram of the induction motor drive with optimization

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Differentiating the total losses with respect to i_{ds} and equating it to zero yields the optimal d-axis current that minimizes the total power loss:

$$\frac{dW_{total}}{di_{ds}} = \frac{3}{2}\left[2xi_{ds} - \left(\frac{T_e}{K}\right)^2 \frac{2y}{i_{ds}^3} \right] = 0 \qquad (13)$$

$$i_{ds\_optimum} = \sqrt[4]{\frac{y}{x}\left(\frac{T_e}{K}\right)^2} \qquad (14)$$

Substituting (14) in (12)

$$W_{total} = \frac{3T_e\sqrt{xy}}{K} + k_m \omega_r^{\,2} \qquad (15)$$

Optimum efficiency can thus be obtained as,

$$\eta = \frac{KT_e\omega_r}{KT_e\omega_r + k_m K\omega_r^2 + 3T_e\sqrt{xy}} \qquad (16)$$

V. SIMULATION RESULTS

An indirect field oriented controlled induction motor drive is simulated using MATLAB / SIMULINK. Simulations have been carried on a 5.4 hp induction motor drive, the ratings of which are summarized in the Table I. Fig. 3 shows the Simulink model of the indirect field oriented control of IM which includes an efficiency optimization algorithm.

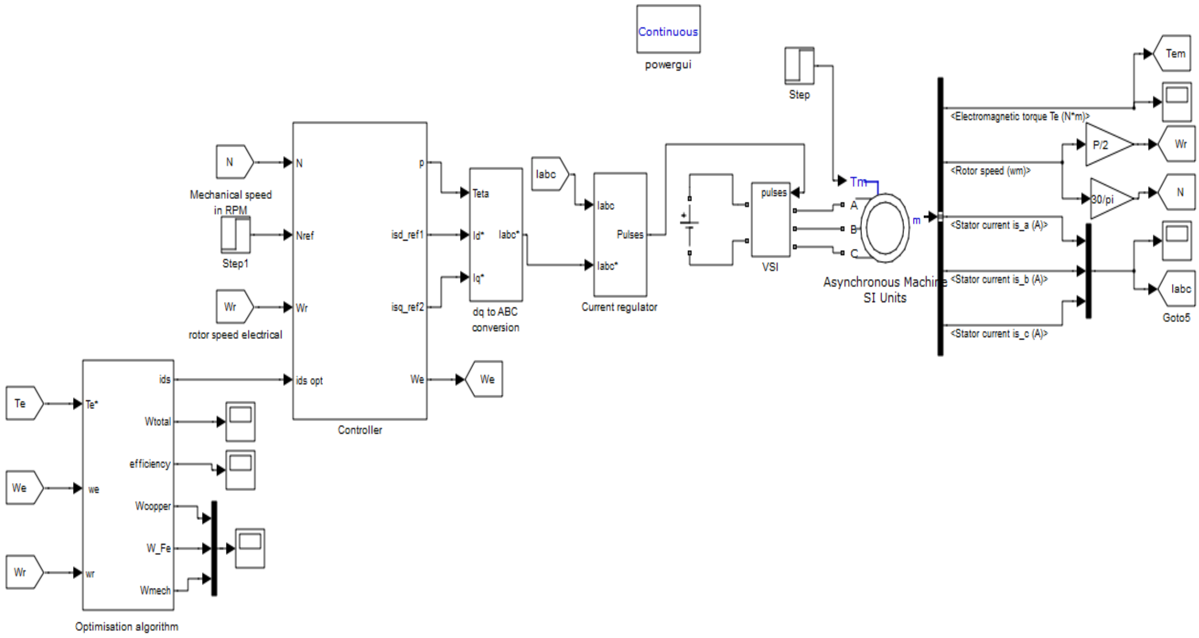

Fig. 3 Simulink model of indirect field oriented control of induction motor with optimization

TABLE I

MOTOR PARAMETERS

Rated power	5.4 hp
Rated speed	1430 rpm
Rated current	9.1 A
Rated torque	26.7 Nm
Number of poles	4
Rs	1.405 Ω
Rr	1.395 Ω
Lls	5.839 mH
Llr	5.839 mH
Lm	172.2mH
Ke	0.002
Kh	0.002
Km	0.0075

The performance of the drive under different operating conditions is observed. Table II shows the efficiency of IM at different speed and load conditions. It is observed that the iron losses are almost constant for the conventional

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method without optimization at different load condition for a given constant speed. When the machine operates at lower loads or at non rated speeds, its efficiency decreases due to unbalance between the two main losses components, with the iron losses dominating at light loads. At rated speed, the efficiency changes from 60% to 82% as load is increased from 20%(5.34 Nm) to 100%(26.7 Nm) of the rated load torque. The mechanical losses are constant for a given speed and vary proportionally as the speed varies.

Table III shows the efficiency of IM with optimization at different speed and load conditions. It is observed that the iron losses are considerably reduced at light load conditions while operating in the base speed range with optimization control. Even though there is a marginal increase in the copper losses in the optimization method during rated speed operation, it is considerably reduced at light load and below rated speed operation. It is also observed that the implemented method results in the overall reduction of the total losses and hence efficiency is greatly improved particularly at light loads. As compared to the conventional method without optimization, the efficiency of the IM drive is improved by almost 10% under light load condition with optimization control.

TABLE II
EFFICIENCY OF 5.4HP INDUCTION MOTOR WITHOUT OPTIMIZATION

Speed(rpm)	**Load (% of rated torque)**	**Cu loss(W)**	**Fe loss(W)**	**Mech loss(W)**	**Total loss(W)**	**Efficiency(%)**
1430(rated speed)	100	404	287	168	852	82
	80	290	283	168	737	81
	60	195	278	168	637	78.7
	40	126	273	168	564	73.5
	20	84	271	168.6	524	60
1144(80% of rated speed)	100	394	188	107.6	690	81.71
	80	277	186	107.5	573	81.2
	60	188	183	107.6	480	79.6
	40	122	179	107.8	411	75.21
	20	83	177	108.3	370	63.2
858(60% of rated speed)	100	390	106	60.82	558	80.27
	80	280	104	60.82	444	80
	60	187	102	60.82	348	79.8
	40	124.4	100.4	60.82	285	76.7
	20	83	99.1	60.82	244	65
572(40% of rated speed)	100	386	52.37	27	470	76.6
	80	276	51	27	352	77.8
	60	187	48.8	27	263	76.7
	40	123	47.2	27	195	76
	20	83	45.8	27	157	66.7
286(20% of rated speed)	100	384	15	6.728	407	67.4
	80	274	14	6.749	292	67.3
	60	184	13.3	6.747	204	68.5
	40	120	12.5	6.73	141	66.7
	20	82	11.6	6.728	94	60

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(An ISO 3297: 2007 Certified Organization)

Vol. 2, Special Issue 1, December 2013

TABLE III
EFFICIENCY OF 5.4HP INDUCTION MOTOR WITH OPTIMIZATION

Speed(rpm)	Load (% of rated torque)	Cu loss(W)	Fe loss(W)	Mech loss(W)	Total loss(W)	Efficiency(%)
1430(rated speed)	100	408	276	168	852	81.91
	80	330	220	168	729	81.2
	60	247	167	168	581	80.1
	40	149.8	101.4	168	419.5	77.17
	20	77.88	51.55	168.4	297.8	72.59
1144(80% of rated speed)	100	375.2	214.8	107	697.6	81.89
	80	286.9	164.2	107	558.7	81.19
	60	220	126	107	453	80.31
	40	145.2	83.1	107	336	78.42
	20	76.62	43.87	107.7	228.2	73.85
858(60% of rated speed)	100	338.5	146	60.54	545	81.15
	80	261.9	112.9	60.55	435.4	80.65
	60	194.9	84.04	60.55	339.5	79.91
	40	129.2	55.72	60.54	245.5	78.49
	20	70.05	30.21	60.55	160.8	75.12
572(40% of rated speed)	100	323.4	82.78	26.91	433.1	78.69
	80	246.3	63.07	26.91	336.2	78.37
	60	188.3	48.2	26.91	263.4	77.95
	40	127.2	32.57	26.91	186.6	77.12
	20	60.6	15.53	26.91	103	74.42
286(20% of rated speed)	100	306.2	25.9	6.615	337.8	69.6
	80	242.9	20.7	6.717	270.3	69.5
	60	183.7	15.71	6.729	206.1	69.43
	40	118.5	10.14	6.726	135.3	69.06
	20	60.88	5.211	6.73	72.82	68.06

A. *Operation of Induction Motor Drive with Efficiency Optimization Algorithm (EOA)*

When Efficiency Optimization Algorithm is activated:
- The iron loss can be minimized by using a minimum possible field flux corresponding to a given torque and motor speed. The flux can be reduced by decreasing the flux component current.
- Torque component of stator current must be increased in order to maintain the same torque with a reduced rotor flux.
-The flux component current decreases while the torque component current increases; however, the total stator current is reduced.
-As a result, the optimal balance between the iron and copper loss is achieved.

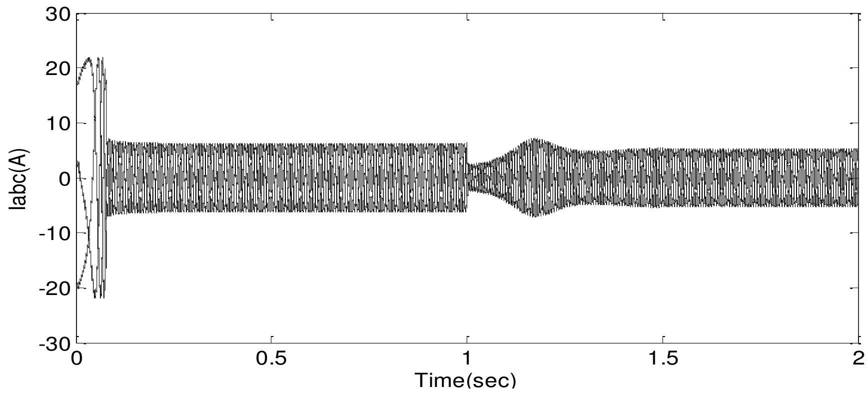

Fig. 4 Three phase currents

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Vol. 2, Special Issue 1, December 2013

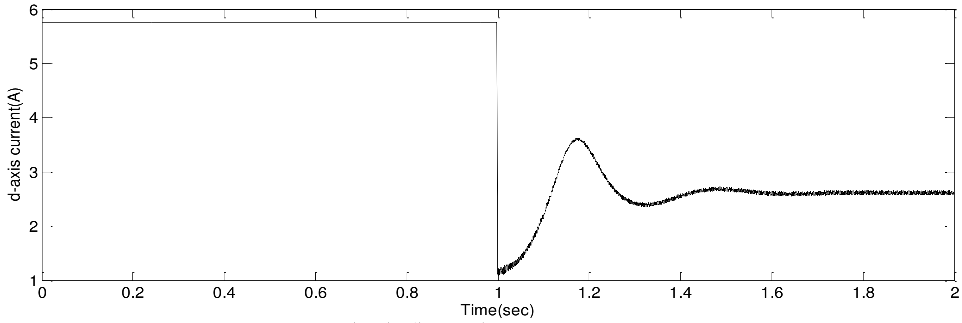

Fig. 5 direct axis stator current

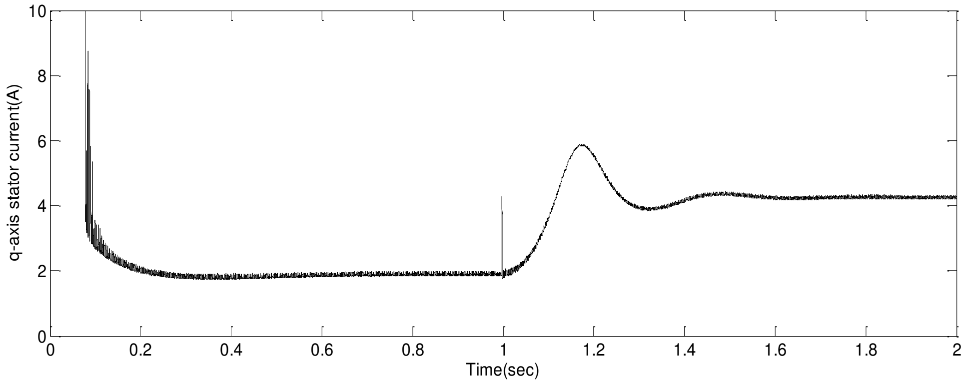

Fig. 6 q-axis stator current

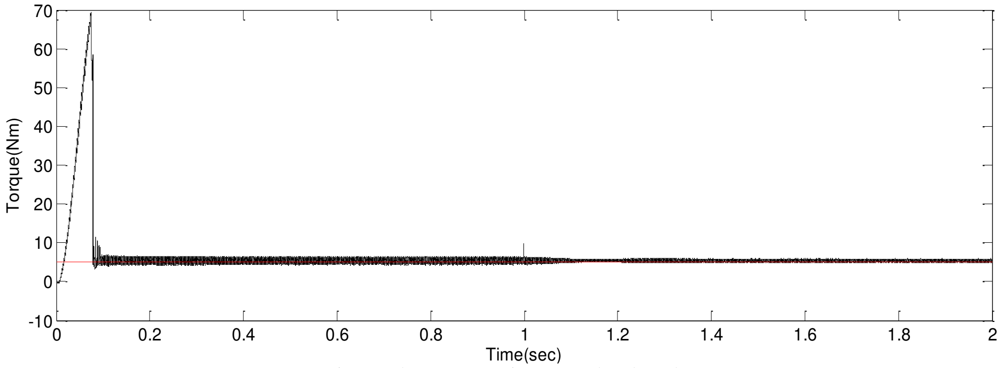

Fig. 7 Electromagnetic torque developed

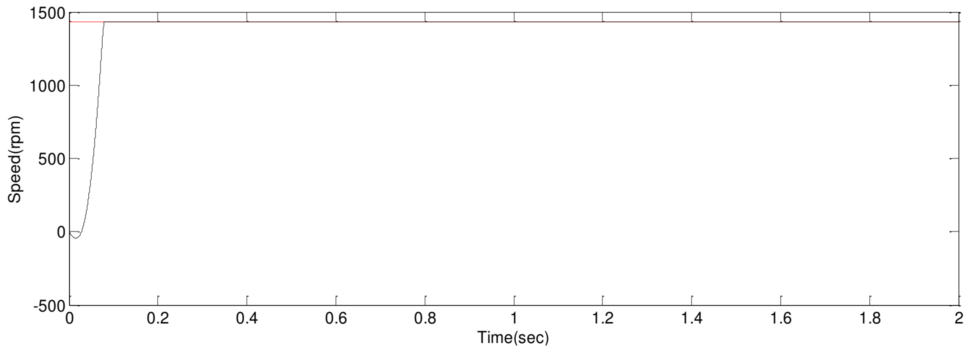

Fig. 8 Speed

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(An ISO 3297: 2007 Certified Organization)

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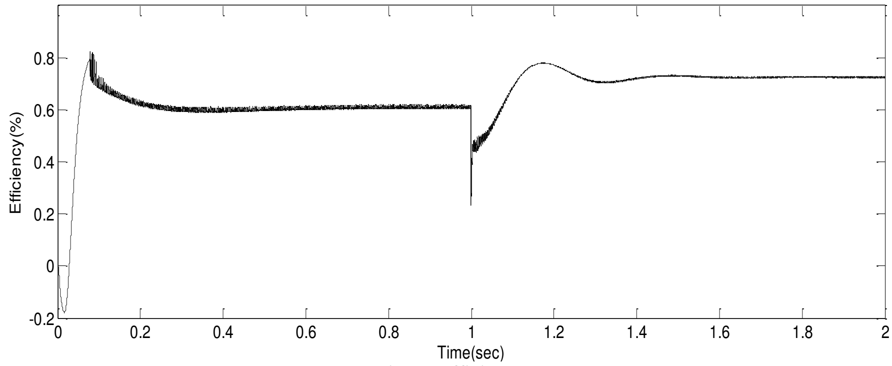

Fig. 9 Efficiency

B. *Performance Analysis of Efficiency Optimization Algorithm (EOA)*

Efficiency optimization algorithm is switched ON only after a certain period of time during which the system reaches the steady state conditions recovering from its initial transients. Till then d-axis current is kept constant at the rated value. As the EOA is activated the direct axis current, i_{ds} reduces in order to provide an optimum value of flux required to maintain the operation as before, but with improved efficiency. The i_{ds} reduces from 5.76A to 2.56 A. However the current takes 0.5 sec to settle to the optimum value. The quadrature axis current, i_{qs} changes accordingly so that the torque required is provided.

Fig. 5 shows variation in the direct axis stator current when the optimization algorithm is activated as the motor operates at a light load (20% of rated load torque). The d-axis current decreases from its rated value to a reduced value provided by the optimization algorithm. At the same time, q-axis current slightly increases as in Fig. 6. However the net effect is to reduce the three phase stator currents. The torque and speed is unaffected with the activation of optimization algorithm as seen from Fig. 7 and Fig. 8. The efficiency increases from 60% to 72.59% with the activation of optimization algorithm as in Fig. 9.

C. *Smooth Starting performance with EOA*

The starting of the induction motor drive with EOA is usually associated with the following issues:

-The speed takes longer settling time to reach the reference value.

-Starting current persists for considerable time period which is not good for the windings as these currents are usually high.

-Starting torque would show high ripple factor.

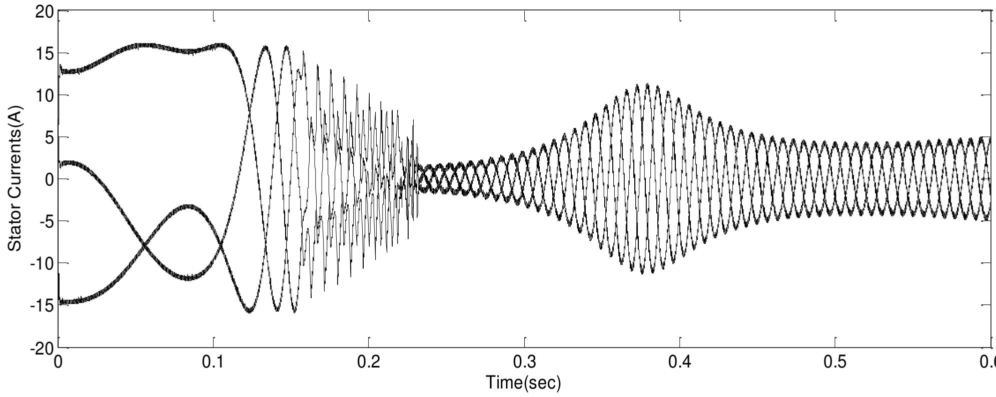

Fig. 10(a) Stator Currents

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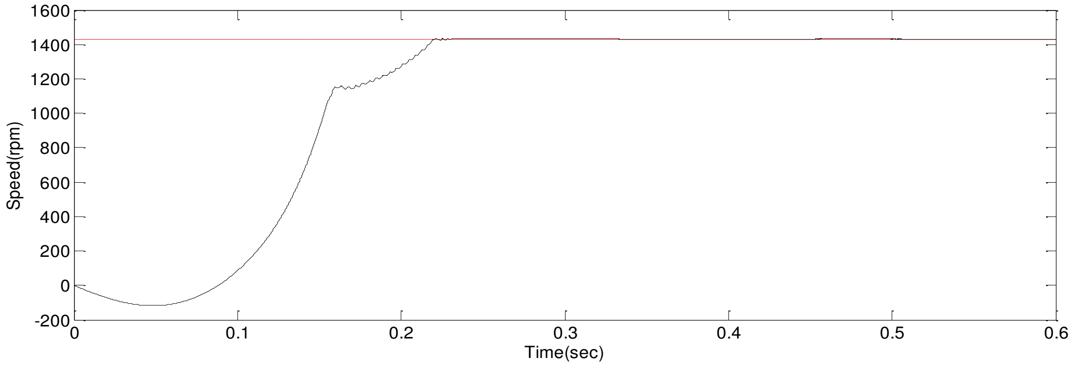

Fig. 10(b) Speed

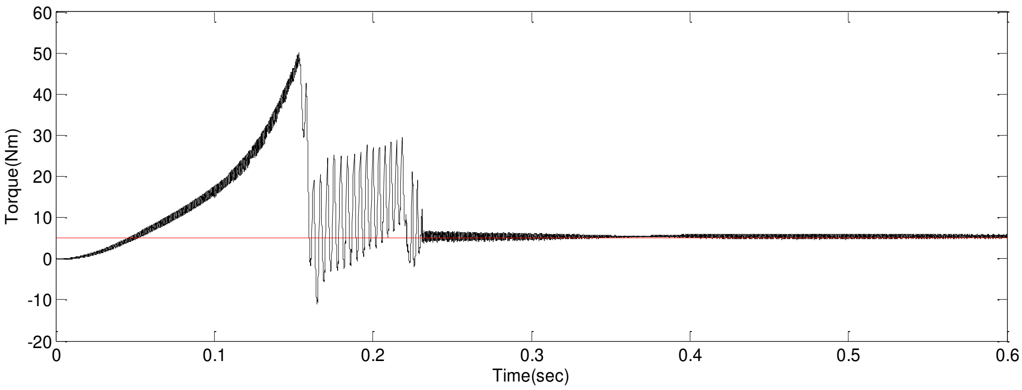

Fig. 10(c) Torque

To ensure good dynamic performance of the system, the rated value of the flux current is used in the transient states when there is a change in the speed command or in the load torque. During starting of the IM drive, it undergoes a transient state. Transient state can easily detected by using the speed error signal. Speed error signal can be used to switch between the rated value and optimum value of direct axis stator current. Also the dynamic performance of the drive during sudden change in load and speed, can thus be improved. When a transient state occurs, the flux current reference is immediately restored to its rated value. After the system has arrived in the steady state, the EOA is activated.

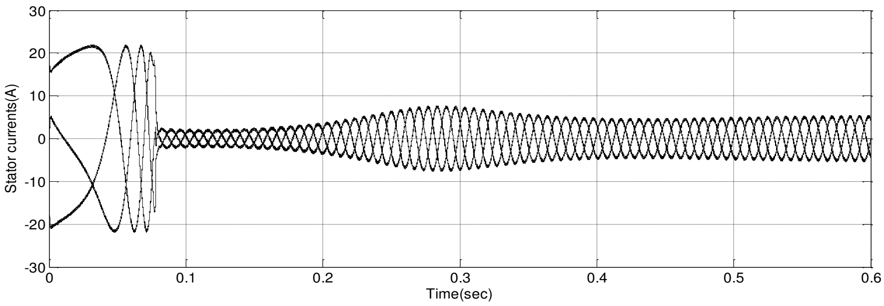

Fig. 11(a) Stator currents

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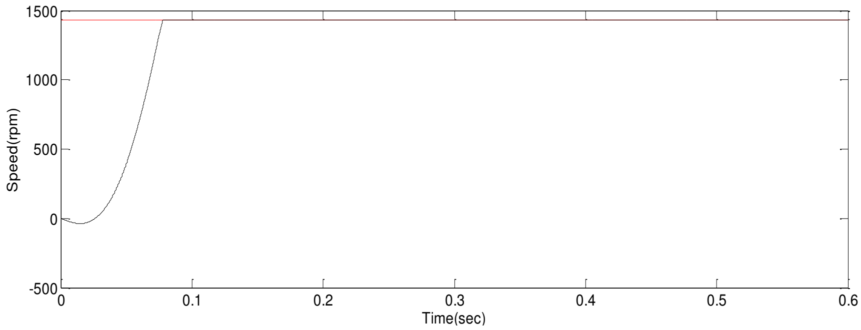

Fig. 11(b) Speed

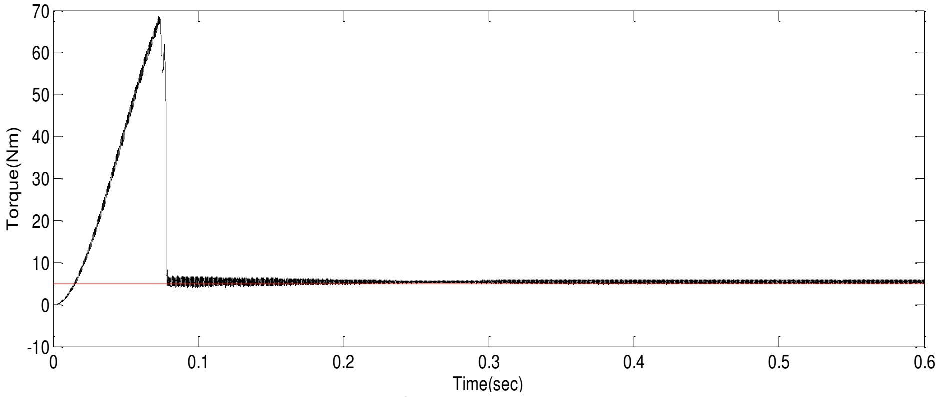

Fig. 11(c) Torque

Fig. 10(a), Fig. 10(b), Fig. 10(c) shows the phase currents, speed, and torque waveforms of the induction motor drive with EOA activated at the starting time. It can be seen that the transient performance of the drive is poor. However when the speed error signal is used to switch from optimization algorithm during transients, the drive starts smoothly as seen from Fig. 11(a), Fig. 11(b), Fig. 11(c).

VI. CONCLUSION

The proposed algorithm maximizes the efficiency of the induction machine and is highly desirable when the motor operates at light loads. The incorporation of the algorithm has improved the efficiency by 10% at light load condition in a 5.4 hp induction motor drive. However the induction motor drive with efficiency optimization algorithm exhibited poor starting characteristics with high torque ripple. Inorder to improve the dynamic behavior of the drive and provide a smooth starting, the speed error signal is sensed to switch from the optimization algorithm during transients. Thus a highly efficient induction motor drive with improved transient performance is developed.

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