ISSN 1 746-7233, England, UK
World Journal of Modelling and Simulation
Vol. 13 (2017) No. 2, pp. 94-104

Efficiency optimization of induction motor drive at steady-state using artificial neural network

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(*Received November 30 2015, Accepted November 11 2016*)

Abstract. Induction motors specially squirrel-cage type are widely used in industries because of robustness, good power/mass relation, low cost and easy maintenance throughout its life cycle. They have a low power factor at partial load if operated at rated flux, hence poor efficiency causes wastage of energy, increased operational cost and leads to significant loss of revenue if run for long durations. Because of the huge number of units operating worldwide, even a minute efficiency improvement may lead to significant environmental and economic contributions. This paper proposes an energy efficient operation of squirrel cage induction motor (SCIM) in such load conditions specially at steady-state. The good features of loss model control (LMC) and search control (SC) techniques together are used for estimation and reproduction of the optimal flux component of current (I_{ds}) for optimal efficiency operation of motor. At first, motor loss model is used to derive a loss-minimization expression considering core saturation. Based on which, optimal I_{ds} values are estimated for various load profiles and finally tabulated. Then, based on the tabulated data, an artificial neural network (ANN) controller is trained offline taking load torque and speed as inputs and optimal I_{ds} values as output. The ANN controller reproduces the optimal value of I_{ds}, based on run-time load condition, thus operate at an optimal flux level in feed-forward manner. The run-time computations and perturbations for optimal flux are eliminated, as it usually happens in conventional search control. The ANN training is performed in MATLAB and the results have shown the superb accuracy of the model. A superior efficiency performance (1-18%) at steady-state is observed in optimal flux operation, for load torque above 60% in simulation, for a wide range of speed. The proposed hybrid method is easy to implement in real-time industrial facilities, no run-time computation required and no perturbations occur. Also, it offers higher energy savings ratio, less electric demand and significant annual energy saving. Further, it seems highly suitable for applications like air conditioning, mining, marine vehicles etc., wherein load variations happen frequently, partial loading may occur for prolonged durations and maintaining accurate speed is not a critical issue.

Keywords: induction motor drive, energy efficiency, optimization, vector control, optimal control, ANN

1 Introduction

The electricity consumption is increasing day by day for fulfilling growing industrial requirements as well as for improving life standards. Most of the electricity generation is from non-renewable fuel resources like oil, coal and natural gases. The increasing load demand, limited resources, increasing prices and greenhouse effects are some of the key factors that encourage efforts for energy-saving[2, 15, 21, 23] and development of energy-efficient mechanisms. Globally, 65-70% of total electricity available to industries is consumed by electric motors[3, 5, 14, 15, 17, 27] and around 85-90% of this available electricity to industries is consumed by ac three-phase induction motors alone[9, 21] specially squirrel - cage induction motors (SCIM) of various capacities ranging up to 100 HP[27]. Also, there is an annual expansion rate of 1.5% in the industrial sector and 2.2% in another sector[14]. So induction motors can play a significant role in this energy-saving and energy-efficiency concept because of the huge number of installed units and huge amount of energy consumption done by them.

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Published by World Academic Press, World Academic Union

Due to this, the issue has been investigated for the last 35 years[2]. Even a small improvement in efficiency will contribute towards significant saving of revenue, fuel consumption and can positively impact on other associated social and environmental factors[28]. It is estimated that, every 1% improvement in motor efficiency might lead to savings of over \$1 billion per annum in energy prices, 5.4-9.1 million tons less per annum combusted coal and nearly 13.6-18.1 million tons less greenhouse emission into the atmosphere globally[27]. Surveys conducted in developing countries by various international agencies conclude that a full implementation of efficiency improvement choices might scale back worldwide electricity demand up to 7 percent[10]. Various energy efficiency audits also suggest for implementation of minimum energy performance standards (MEPS) for all operational motors worldwide. This will result 325 terawatt hours of annual electrical energy-saving and reduction of CO_2 by 206 million tons by the year 2035[12].

Induction motors are widely used in pumping, compressed gas and fan systems, heating, ventilation and air conditioning (HVAC), material handling and process, refrigeration, hoist application, traction, electric vehicles, marine vehicles, crane and aircraft launchers etc.[2, 10, 26]. As per electric power research institute (EPRI) reports, 35-40% of the motors in such applications endlessly waste electricity due to poor efficiency at partial loading[5, 23] as shown in Fig. 1. Partial loading is the major cause of poor performance as compared to other similar factors like idling, cyclic loading and overloading in motors[22, 23, 26]. Generally, induction motors are designed to run at 50-100% of rated load[23] and they possess a very good efficiency at rated load or near rated load conditions, if operated at rated flux[5]. But at partial loads, since the iron losses are excessive due to over-excitation[3], power factor becomes low and the efficiency gets badly reduced[15, 20–22] if operated at rated flux[5, 6]. As per survey report of energy information administration (EIA), the electricity consumed in HVAC applications is nearly 50% the total electricity consumed in a typical commercial construction in Malaysia[28] and most of the time induction motors used there, spend considerable time operating at partial loading[2, 21, 22]. Similarly, drives for elevators run mostly with less than a half of the rated torque[26]. Electric vehicles have limited energy storage and energy saving there could reduce the battery size[2]. Hence, they require a small, lightweight and energy-efficient motor[5]. Here, energy has to be consumed in the best possible way to increase the running distance per battery charge[6]. In, applications like traction, transportation, marine vehicles, aircraft launchers and electric cranes, power is taken out during short bursts[2]. In all these applications, there is a need of energy optimized control strategy for induction motors and the maximum potential of energy savings exists at no-load or fractional load conditions[3, 5, 25]. Optimal flux operation by adjusting the motor flux level according to the motor load requirements provides the solution in such conditions[4, 17].

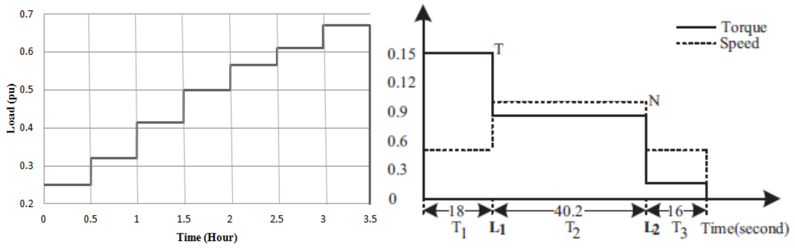

Fig. 1: (a) Load diagram of typical textile mill [18, 23]; (b) Load diagram of a typical mine hoist [15]

For any given load torque and speed condition, there is always a flux level that results in maximum efficiency where the copper and core losses become essentially equal[20] i.e. an appropriate balance between copper and iron losses[6, 21, 23]. A reduction of 60 - 90% of input power in motors are seen while operating at 15% of rated load torque[15, 25] by opting optimal flux operation. Usually, the optimum flux value exists below the rated value[6]. Also, flux reduction at partial loads gives less acoustic noise produced from converter and machine[3]. Real-time optimal control schemes are divided into three classes i.e. simple state control (SSC), loss model control (LMC) and search control (SC). LMC is a feed-forward[15] approach that treats the situation analytically[5]. The objective function is usually an analytical expression representing either the loss, the efficiency or the total power input[6]. By implementing classical or modern optimization tools and techniques, an optimal flux value is derived. Some authors have considered inverter loss (conduction and switching losses) also in total loss expression[16]. This approach is quick but suffers a drawback due to parameter variations like temperature rise, magnetic circuit saturation, skin effect etc.[3] in run-time conditions. Hence, precised information about the motor loss function parameters are essential[26] otherwise it may produce a sub-optimal solution[6, 15]. Also, the accuracy of the solution depends on the extent of correct modeling of the motor drive and the losses[5], but very complicated since the stray load loss and the mechanical loss of the machine are not strictly constant[6]. Hence, in the development of the loss model, there is always a trade-off between accuracy and complexity. Moreover, the loss-model-based controllers are more suitable for vector controlled IM drives as compared to other optimal control methods. But these controllers may cause higher pulsations in torque and flux during load transitions[5, 15]. SSC, the first method mentioned earlier, is nothing but a simpler version of LMC[20].

On the other hand SC, the third method is of a feedback nature that finds the maximum efficiency by search technique[5] i.e. an online search for optimal flux[2]. Since input power is a parabolic function of the flux[26], hence the flux is decremented in steps till the measured input power settles to lowest value. The method is fully insensitive to motor parameter variations but may suffer slow convergence problem and may never achieve the optimal point with objectionable torque ripples[3, 5, 22, 26]. There are hybrid methods also[6, 13, 24–26, 26] that combine the best features of two optimization strategies i.e. SC and LMC utilizing both the motor parameter information and feedback[2] which provides a more correct solution for efficiency optimization of induction motor drives[5, 6]. This looks to be attention-grabbing solution for efficiency optimization of induction motor drives. Both the steady-state and dynamic performances can be taken care. Fast convergence can be achieved along with removal of other drawbacks also[5, 6, 8, 15, 20, 25, 26]. One of the common approaches in hybrid method is to first estimate the flux or flux component of the current from the loss model and the subsequent adjustment of the flux using search technique. The contribution of artificial intelligence (AI) techniques such as artificial neural network (ANN), fuzzy logic, expert systems and nature inspired algorithms (NIA), genetic algorithm and differential evolution in efficiency optimization are also seen in various literatures[18, 21]. A significant utility is there in the determination of optimal flux value in offline and online both the ways[21].

This paper proposes an optimal control scheme for HVAC and mining applications when motors utilized there operate at partial loading for prolonged durations by simply adapting optimal flux operation instead of rated flux specially in steady-state conditions. In the present work, the concepts of LMC and SC both are utilized along with the benefits of ANN for performing the optimal operation of motor. The proposed way of implementing ANN controller for efficiency optimization is straightforward, makes machine intelligent and easy to implement using micro-controllers, digital signal processor (DSP) and dSPACE controller as compared to similar works done earlier.

2 Proposed methodology

The flux - producing current (Ids) is controlled to control the magnetic loading of the machine according to the motor load to yield maximum efficiency[5, 23]. LMC is used for development of optimal Ids[15] values for efficiency optimization. An offline trained ANN controller reproduces appropriate optimal Ids value in the conventional vector control loop, instead of its constant value, as per load conditions and hence operates the machine at optimal flux level. The conventional vector control is used below 60% of rated load with the help of a logical switching circuit since no efficiency improvement margin is attained by the proposed technique. The efficiency validation is done in MATLAB with the help of the model shown in Fig. 3(b). The block diagram of proposed control method as well as its realization in MATLAB is shown in Figs. 4 & 5.

2.1 Estimation of optimal ids value

The proposed work utilizes the loss model and loss minimization algorithm developed in[11] for the development of optimal Ids expression. The condition for minimum losses, that minimizes the copper and iron losses as a function of speed and torque are fulfilled if relations (1) and (2) holds good.

$$i_{ds} = \sqrt{\frac{R_q}{R_d(\omega)}} i_{qs} = K_m in(\omega)|i_{qs}|, \tag{1}$$

where,

$$K_{\min}(\omega) \triangleq \sqrt{\frac{R_s(R_{qls}+R_r)+R_{qls}R_r}{R_s(R_{qls}+R_r)+M_d^2\omega^2}},$$

is called Loss Minimization Factor (LMF),

$$R_q \triangleq R_s + \frac{R_{qls}R_r}{R_{qls}+R_r} \& R_d(\omega) \triangleq R_s + [\frac{M_d^2}{R_{qls}+R_r}]\omega^2. \tag{2}$$

At first, LMF is estimated, based on Eq. (2), for all possible combinations of torque and speed, based on which optimal Ids values are estimated for steady-state conditions. The effect of speed values in the calculation of LMF is seen negligible, almost for all the speeds, and taken 0.58, which may produce some error in speed tracking. The values of optimal Ids for improved efficiency operation of a 50 HP, 460V, 60 Hz induction motor, for various load conditions are shown in Tab. 1. The torque values are considered only from 60% of rated to rated value, as the proposed method does not perform well below this torque range, for any possible speed range. Conventional vector control is suggested there. The ANN controller is trained offline on the data available in Tab. 2, discussed in subtopic 1.2.

2.2 Design of ann controller for optimal operation

ANN has been widely used for efficiency optimization of induction motor drives, in many previous works [1, 7, 19, 29]. The proposed method also involves ANN to perform as optimal flux controller at partial load situation. The ANN controller has been trained offline for torque, speed and optimal value of flux component of current (I_{ds}). Torque and speed values are taken as input and optimal I_{ds} values as output for training in MATLAB. Network topology, training efforts statistics and target accuracy are shown in Fig. 2 and Tab. 2 respectively.

Table 1: Optimal I_{ds} Values at Steady-State, at Different Load Conditions

Torque (N-m)	110	120	130	140	150	160	170	180	190	200
I_{ds}^* at 30 rad/s	23.32	25.59	27.45	29.54	31.66	33.63	35.82	38.22	39.92	41.96
I_{ds}^* at 60 rad/s	24.88	26.84	28.68	30.53	32.31	34.75	36.76	38.86	40.68	42.75
I_{ds}^* at 90 rad/s	25.58	27.63	29.64	31.59	33.62	35.69	37.74	39.63	41.68	43.59
I_{ds}^* at 120 rad/s	25.42	27.45	29.49	31.53	33.57	35.58	37.63	39.67	41.7	43.73
I_{ds}^* at 150 rad/s	25.84	27.74	29.82	31.83	33.96	36.05	38.08	40.19	41.94	44.19
I_{ds}^* at 180 rad/s	26.8	28.82	30.93	33.02	34.96	36.5	38.62	40.36	42.45	44.33

Table 2: Optimal Ids Values at Steady-State, at Different Load Conditions

Number of Inputs	2 (T, ω)
Number of Outputs	1 ($I_{ds\text{Optimal}}$)
Maximum input value	$\omega_{\max} = 1$ (p.u) $T_{max} = 1$(p.u)
Maximum output value	$I_{ds\text{Optimal}} = 1$(p.u)
Minimum output value	$I_{ds\text{Optimal}} = 0$(p.u)
Number of Hidden Layers	3
Functions	Logsigmoidal
Number of Training patterns	50,000
Learning step	0.1

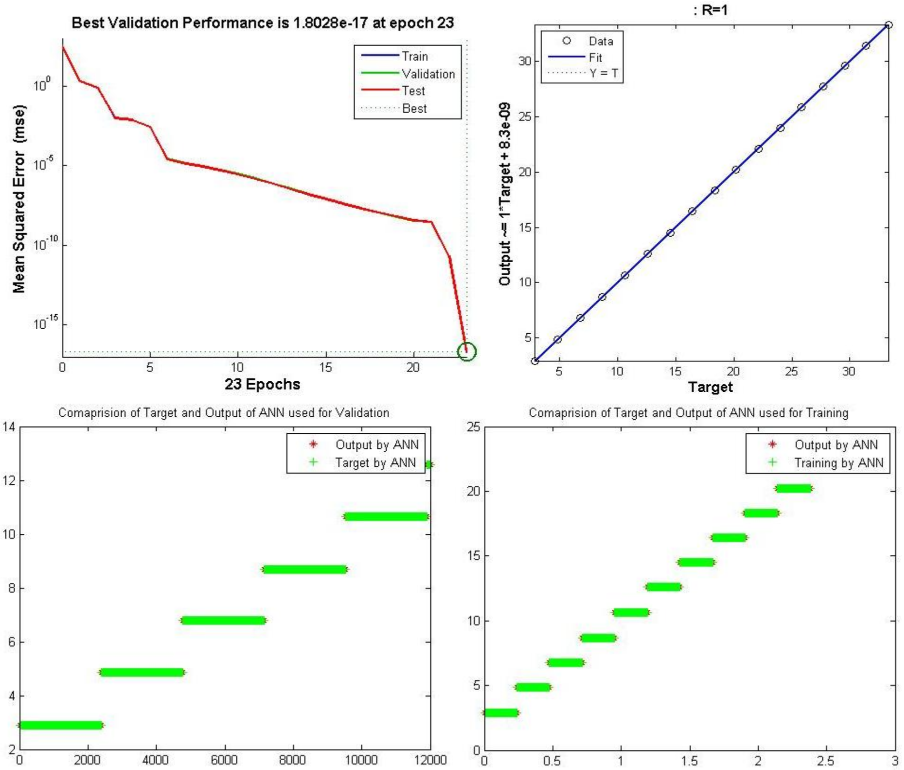

Fig. 2: ANN training and validation

The proposed scheme uses run-time load torque information at a particular speed, and generates an appropriate value of optimal Ids current, which maximizes the motor efficiency at that given load condition, with the help of this offline trained ANN controller, which basically serves as reference value (Ids*) generator in the conventional vector control loop as shown in Fig. 3(a).

3 Result and discussion

For the optimal flux operation at partial load, the proposed hybrid scheme uses load torque and speed information and generates the optimal value of flux component of current (Ids) with the help of an offline trained ANN controller, which in actual serves as reference value (Ids*) generator in the conventional vector control loop. Once optimal Ids* command is available, it is fed to the stator reference - current generation block that further generates pulses for inverter, resulting in optimum efficiency operation of induction motor. Improvements up to 18% are observed on 50 HP, 460V, 60 Hz motor at various load conditions (above 60% of rated). The efficiency improvement margin and other associated parameters for different load torques and speeds are shown in table 3, Fig. 7. For sample, two load torque values are only considered (200 N-m and 150 N-m). The efficiency performance along with torque and speed tracking are shown in figure 6 at a speed of 120 rad/s only.

For rated load torque (200 N-m), with the optimal efficiency operation, a reduction of 8.19 kW (from 45.24 kW at rated flux to about 37.05 kW at optimal flux) has been noticed. Thus, a saving of about 18.10% of input power is assured along with an annual energy saving equivalent to $2235 for 5200 hours of operation at an electricity tariff of $0.07 per kWh in U.S. Similarly, for 3/4th of rated load torque (150 N-m) with the optimal efficiency operation, a reduction of 3.41 kW (from 35.88 kW at rated flux to about 32.37 kW at optimal flux) has been noticed. Thus, a saving of about 9.50% of input power is assured along with an annual energy saving equivalent to $958 for the same operational hours at same tariff.

Performances at a predefined load cycle are also investigated. A load cycle of 150 N-m at 120 rad/s, 200 N-m at 150 rad/s and 150 N-m, 90 rad/s is applied at time $t = 0$, $t = 4$ and $t = 7$ seconds and various

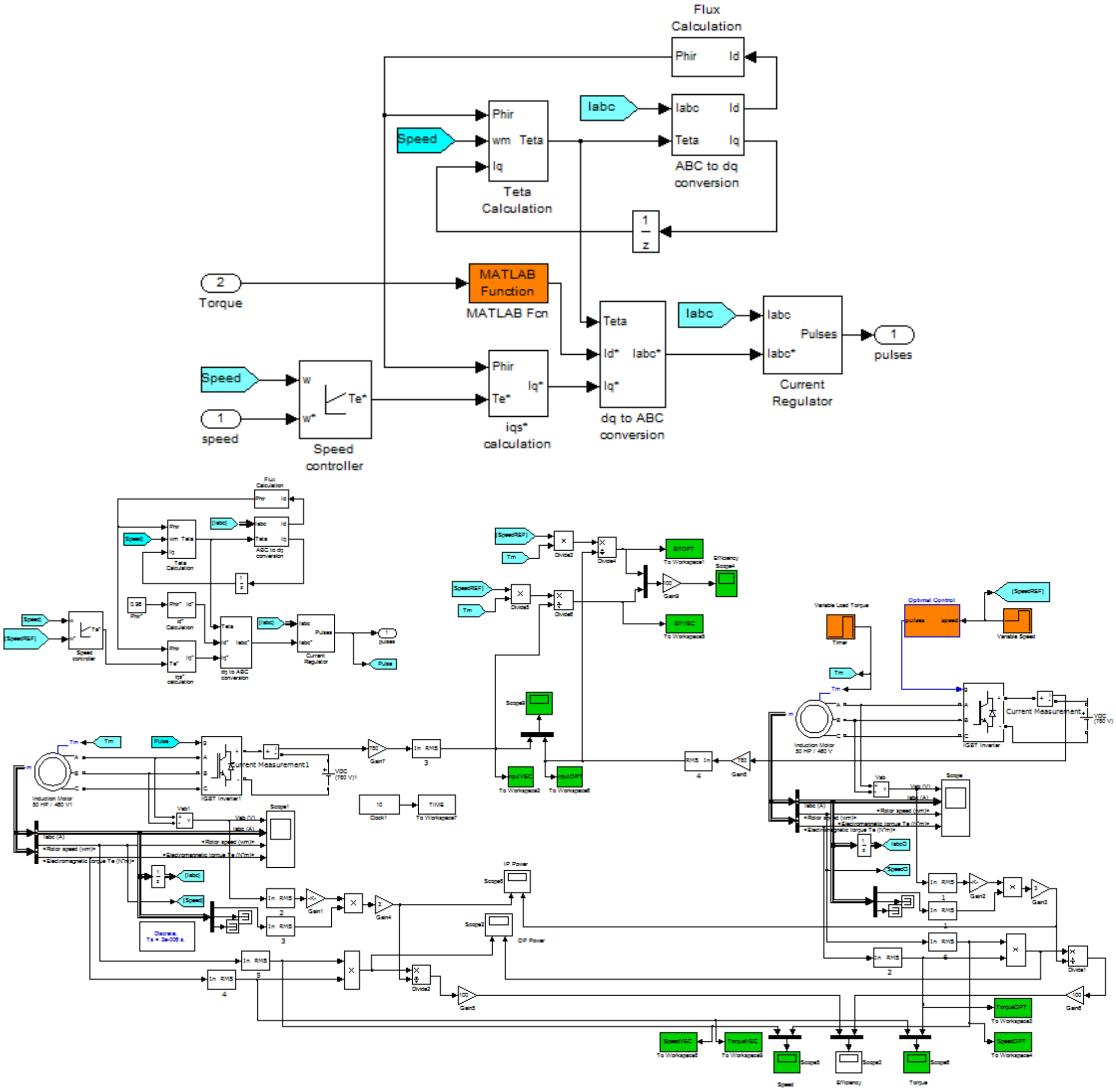

Fig. 3: (a) ANN controller for reproduction of I^*_{ds}; (b) MALAB model for efficiency validation

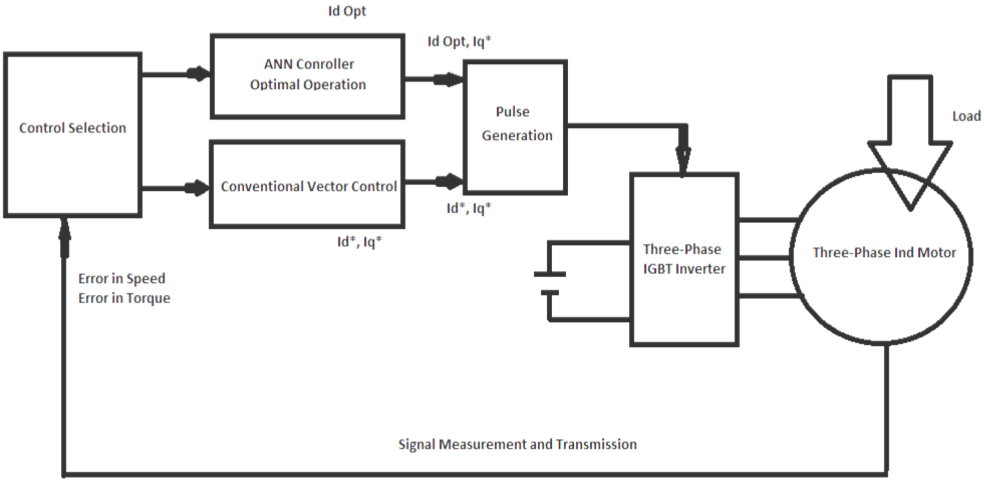

Fig. 4: Block diagram of proposed control scheme

performances are observed, which seem satisfactory. No or lesser overshoots or undershoots along-with same

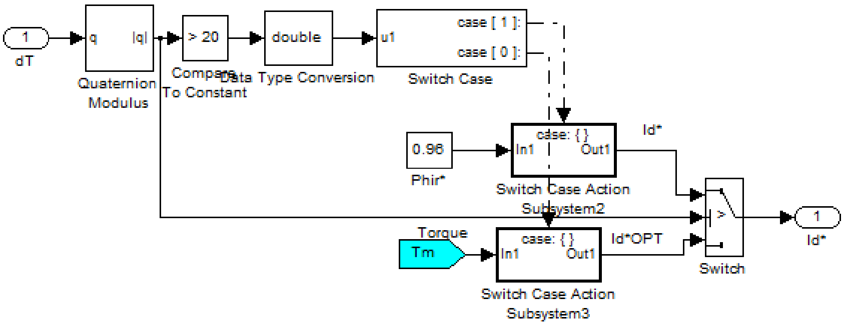

Fig. 5: Control mode selection model

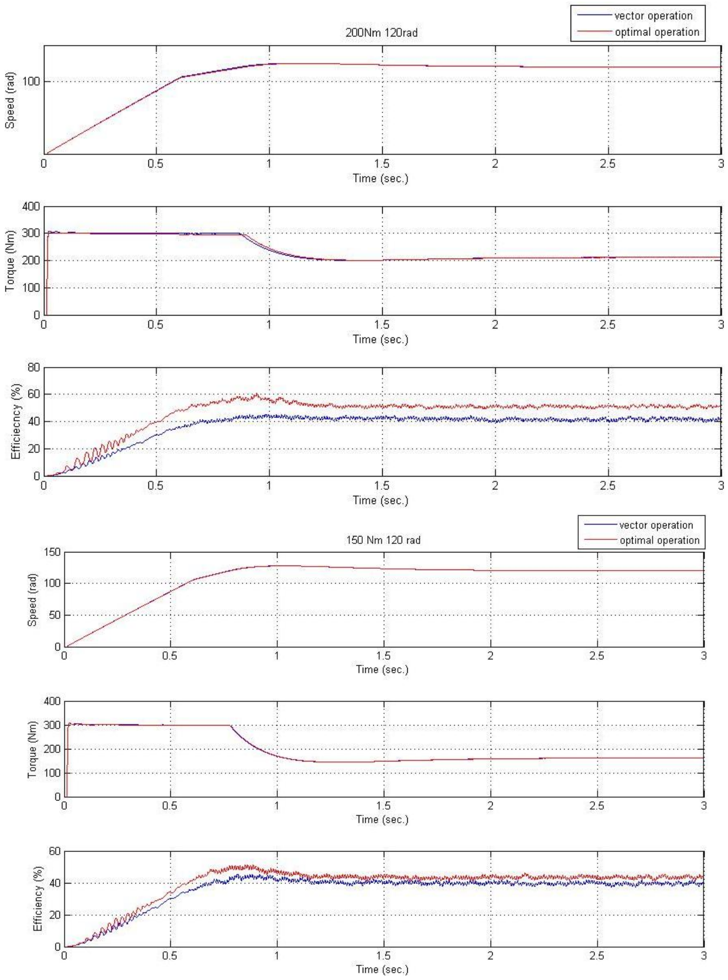

Fig. 6: Speed, Torque and Efficiency performance at rated load torque and 3/4th of rated load torque (200N-m and 150 N-m) at 120 rad/s speed, with corresponding 12% and 5% efficiency rise

or better settling time as compared to that in vector control is seen in speed and torque tracking by the proposed controller shown in figure 8.

Two common problems on lightly loaded motor happen in general, while running at optimal flux, one is large speed drop when increasing sudden load torque and the other is slow acceleration. These two are entirely eliminated in the proposed method. Hence, primarily it is verified that the optimal flux operation is superior in terms of energy saving and efficiency improvement than conventional vector control method at partial loading and steady - state condition. But the proposed efficiency optimization technique does not perform satisfactory for load torque below 60% of the rated value. Here conventional rated flux operation performs better. The present work also offers two different modes of operations based on amount of load put on the motor, first is

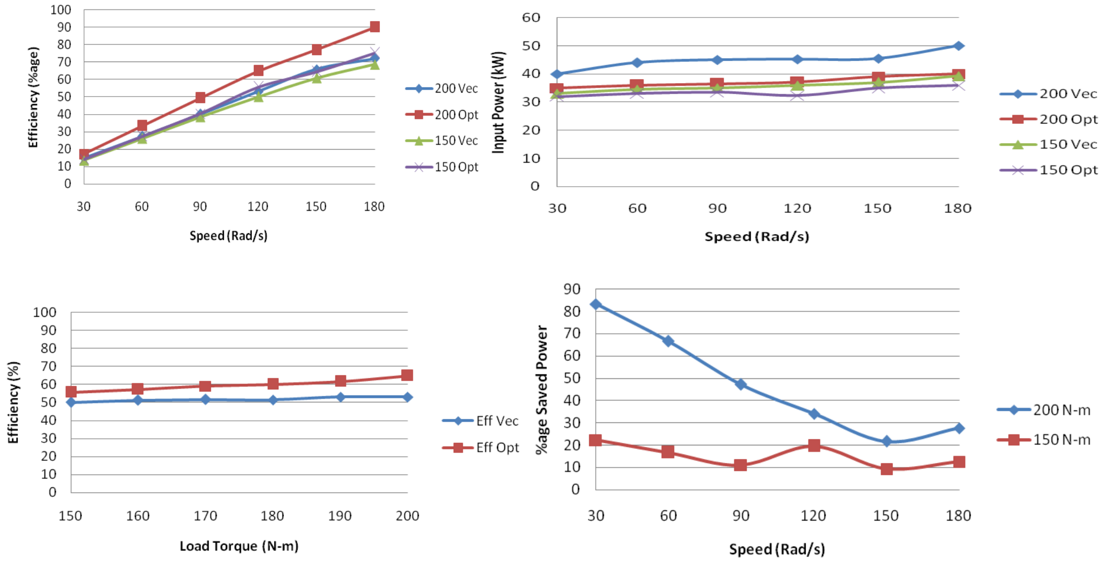

Fig. 7: (a) Efficiency- vs- Speed, (b) Input Power - vs- speed, (c) Sample Efficiency- vs- Load-Torque at 120 rad/s, (d) % age Power Saving - vs- Speed

Table 3: Efficiency Rise and Saving Percentage by Flux Optimization for 50 HP Motor

Speed	30 rad/s		60 rad/s		90 rad/s		120 rad/s		150 rad/s		180 rad/s	
Flux programming	Rated	Optimal	Rated	Optimal	Rated	Optimal	Rated	Optimal	Rated	Optimal	Rated	Optimal
Energy efficiency at 200 Nm (%age)	15	17.14	27.27	33.33	40	49.3	53.05	64.77	65.9	76.92	72	90
Input power (kW)	40	35	44	36	45	36.5	45.24	37.05	45.5	39	50	40
Electric demand saving	5kW		8kW		8.5 kW		8.19 kW		6 kW		10 Kw	
Savings/output (%age)	83.33		66.67		47.22		34.12		21.66		27.77	
Annual energy saving for 5200 hrs @.007$ tariff	1363$		2184$		2317$		2235$		1780$		2702$	
Energy efficiency at 150 Nm (%age)	13.63	14.06	26.08	27.27	38.57	40.29	50.16	55.6	60.81	64.47	68.7	75.2
Input power (kW)	33	32	34.5	33	35	33.5	35.88	32.37	37	34.9	39.3	35.9
Electric demand saving	1 kW		1.5 kW		1.5 kW		3.41 kW		2.1 kW		3.4 kW	
Savings/output (%age)	22.22		16.67		11.11		19.5		9.33		12.59	
Annual energy saving for 5200 hrs @.007$ tariff	276$		411$		408$		958$		574$		927$	

optimal flux operation if load is above 60% of rated load and second is rated flux operation if load is below 60% of rated load, with the help of logical switching.

4 Conclusion

In this work, it is verified that the optimal flux operation is superior to that of rated flux operation at partial load in steady - state condition, in terms of efficiency enhancement and hence energy-saving. In general 1 - 18% efficiency improvement is observed on 50 HP, 60 Hz motor, at different load-torques (above 60%) and various speeds in the simulink environment. High energy saving ratio, less electric demand and good annual

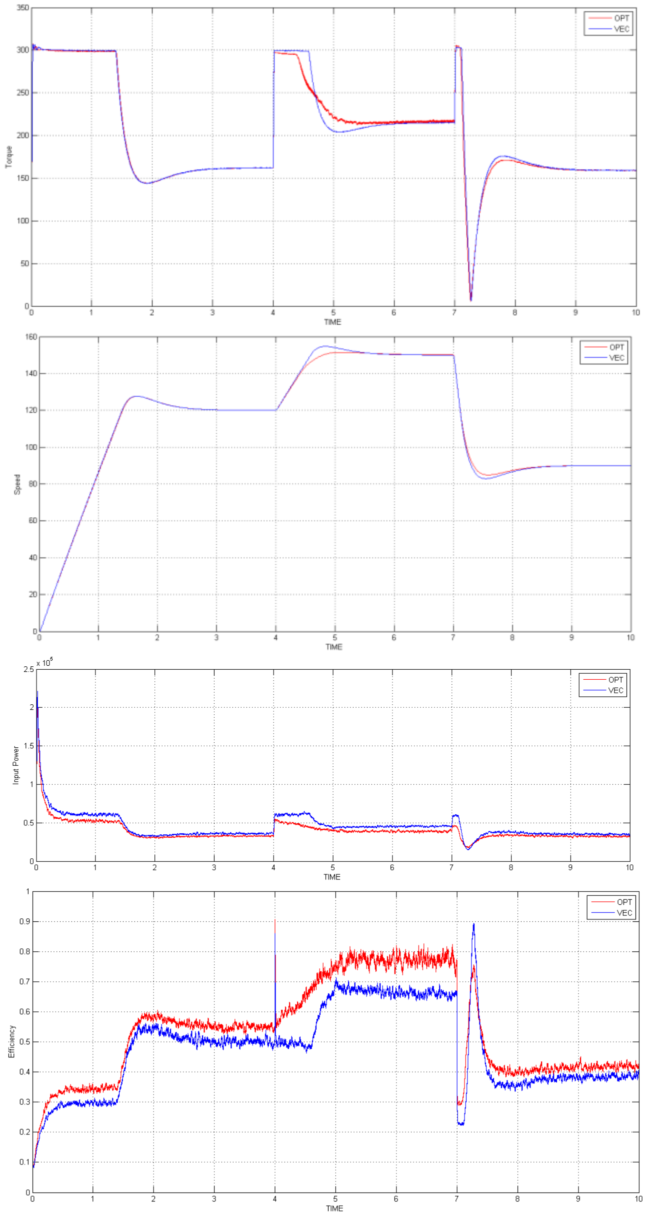

Fig. 8: Torque, Speed, Input Power and Efficiency performance at for a load cycle of (150 N-m, 120 rad/s) for 4 sec, (200 N-m, 150 rad/s) for 3 sec, and (150 N-m, 90 rad/s) for 3 sec

energy savings are offered by the proposed hybrid controller. The dynamic performance is seen satisfactory, similar to vector control or even better, in terms of overshoot, undershoot and settling time. Accuracy in speed tracking is little bit deviated but still the proposed approach is extremely suitable for applications like HVAC and mining sectors where maintaining speed very precisely is not a critical issue. The proposed method can be easily implemented on other induction motor drive systems for which the steady-state speed-vs-torque load characteristics are already known or can be predicted. The offline optimization process as performed in the present work, is a limitation as the optimal flux trajectories are only valid for one specific application and thus, it can also be considered as a drawback. But, the proposed hybrid approach eliminates the need of run-time computation complexity in traditional loss model controller (LMC) and hence less hardware installations will be required in implementation, making it a cost-effective method. Also, since no run-time perturbations happen, as it usually happen in conventional search control (SC), so no torque ripples will exist and hence wear and tear of induction motor drive will be lesser. The proposed scheme needs simple modifications in existing variable frequency drive only making it easily adaptable in industries. But, one of the major drawback of the proposed technique is the unavailability of efficiency improvement below 60% of rated load for which conventional vector (i.e. rated flux operation) is suggested. A logical switching is required for decision making which increases a little bit of computation.

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