Research Journal of Applied Sciences, Engineering and Technology 11(5): 507-515, 2015
DOI: 10.19026/rjaset.11.1855
ISSN: 2040-7459; e-ISSN: 2040-7467

Submitted: May 11, 2015 Accepted: July 2, 2015 Published: October 15, 2015

Research Article

Optimization of Three-phase Squirrel Cage Induction Motor Drive System Using Minimum Input Power Technique

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Abstract: The efficiency of induction motor drives operating under variable conditions can be improved by predicting the optimum flux that minimizes the losses. In this study, a Loss-Minimization Controller (LMC) and a Search Controller (SC) are combined. The output from the controllers would drive the field oriented control inverter in order to achieve the optimum flux in the motor that minimizes the losses. For this purpose, a mathematical model for calculating the total power losses as a function of magnetic flux and a factor to obtain feedback as a function of optimum flux were discussed. An LMC-SC vector-controlled induction motor drive system was modelled, simulated and tested. The results have validated the effectiveness of this system in minimizing the motor operating losses, especially at light and medium loads. The proposed controller can be implemented in adjustable speed induction motor drive systems with variable loads, operating below rated speed.

Keywords: Flux vector control, flux, induction motor, loss minimization controller, optimization, search controller, variable speed drive

INTRODUCTION

No less than 50% of the total energy generated worldwide is consumed in induction motors (Kumar *et al*., 2010). Nowadays induction motor drives with cage-type machines are the most widely used machine especially in the industrial sector (Saravanan *et al*., 2012). This large share of energy consumed by induction motors has attracted researchers' attention to maximize the Induction Motor (IM) efficiency especially at light loads where the induction motor operates at low efficiency (Raj *et al*., 2009). To achieve this target there are two possible options: redesigning the induction motor in order to improve its construction or using an inverter to drive the induction motor (Kumar *et al*., 2010; Raj *et al*., 2009).

The second option can be applied by using Voltage to Frequency (V/F) ratio scalar control (Munoz-Garcia *et al*., 1998; Issa, 2010). The speed, the terminal frequency, the terminal voltage and the parameters of the motor fully describe the induction motor behaviour. Scalar controlled drives depend on the previously mentioned variables in order to operate the induction motor at the optimal V/F ratio (Raj *et al*., 2009; Mary and Subburaj, 2013).

In addition Field Oriented Control (FOC) drives can be used to control the power delivered to the induction motor (Raj *et al*., 2009; Eissa *et al*., 2013; Mary and Subburaj, 2013). Field oriented control is also referred to as flux vector control or simply as vector control. Despite the fact that vector controlled drives require more calculations than scalar controlled drives, vector controlled drives provide an ability to control the IM directly by a predetermined value of optimal flux (Elwer, 2006; Pravallika *et al*., 2015; Huerta *et al*., 2013).

The optimal flux value can be found by using the Search Controller (SC) which depends on finding the optimal flux by one of numerical methods with many iterations and mathematical equations (Kumar *et al*., 2010; Zhang *et al*., 2007). On the other hand the optimal flux can be calculated by a specific equation. It attains its optimal value when the iron losses are equal to the copper losses at any operating conditions as shown in Fig. 1. This method is known as Loss Model Control (LMC) (Mary and Subburaj, 2013).

The SC does not require prior knowledge of the motor parameters. However, the complexity and processing that are encountered with this method make it very complex and requires specialised processors in order to deal with the volume of mathematical

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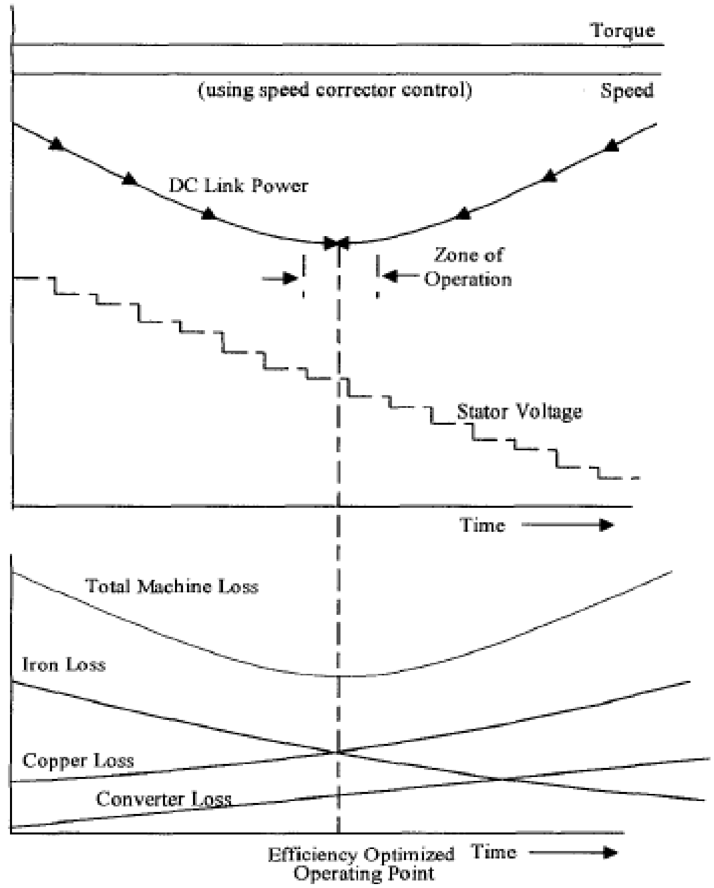

Fig. 1: Efficiency optimized operating point

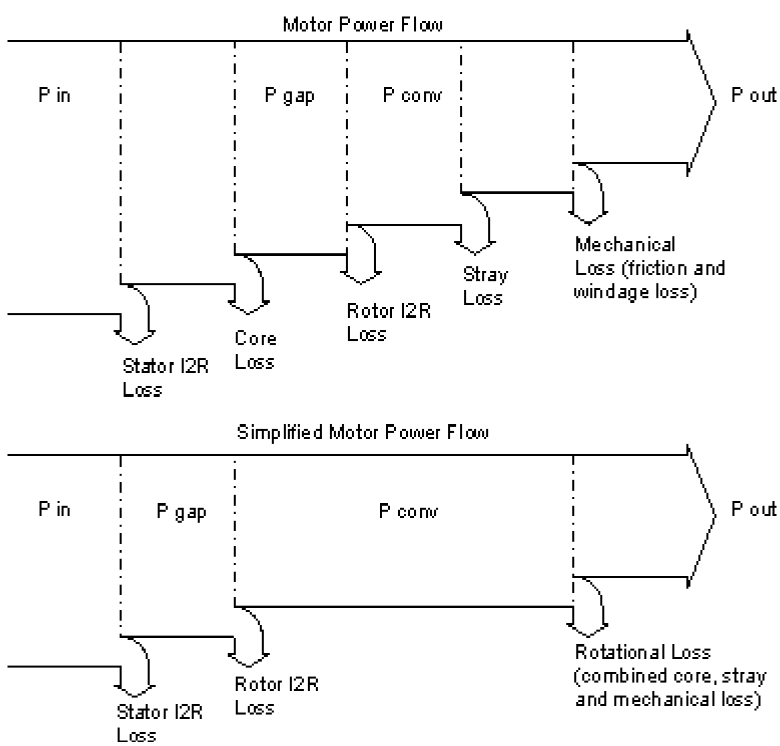

Fig. 2: Power flow in an induction motor

operation (Kioskeridis and Margaris, 1996). In this study, a hybrid system containing both methods (i.e., SC and LMC) is built and tested in order to obtain the benefits of both methods and avoid their individual disadvantages.

INDUCTION MOTOR LOSS REDUCTION

In three phase machines, the input power is part consumed by the stator, the core, the rotor as well as stray and mechanical losses as shown in Fig. 2.

Despite the fact that the core losses are incurred in both the stator and the rotor, the core losses are usually allocated to the stator as that is where the majority of these losses are incurred.

The equations that are used to determine the aforementioned types of losses are shown below (all shown as per phase values):

- Stator copper losses:

$$P_{\text{stator copper losses}} = r_s I_S^2 \tag{1}$$

- Rotor copper losses:

$$P_{\text{rotor copper losses}} = \acute{r}_r I'^2_r \tag{2}$$

- Iron losses caused by the fundamental frequency in the core (ac flux):

$$P_{Fe} = [k_e (1 + s^2) a^2 + k_h (1 + s) a] \phi_m \tag{3}$$

- Stray losses that cannot be easily calculated (including harmonics losses):

$$P_{str} = c_{zb} I_s^2 + c_s \phi^2_m I_s^2 + c_e a I_s^2 \tag{4}$$

or:

$$P_{str} = C_{str} w^2 I'^2_r \tag{5}$$

The total power losses can be calculated by the equation shown below:

$$P_{losses} = r_s I_S^2 + \acute{r}_r I'^2_r + (k_e w^2 + k_h w) \phi^2_m + C_{str} w^2 I'^2_r + c_{fw} w^2 \tag{6}$$

LOSS MODEL CONTROLLER

The minimum input power required in order to operate the IM will occur at the operating point at which the iron losses are equal to the copper losses as shown in Fig. 1 (Raj *et al*., 2009).

From Eq. (6) we can evaluate the iron losses and the copper looses separately:

$$P_{iron} = (k_e w^2 + k_h w + r_s/X^2_m) \phi^2_m \tag{7}$$

$$P_{copper} = (CL\, r_s + \acute{r}_r + C_{str} w^2) I'^2_r \tag{8}$$

In order to build a vector loss model controller a direct relationship between flux and stator current must be derived. A review of the relevant literature shows that Kioskeridis and Margaris (1996) proved that optimum flux can be evaluated by having the value of the stator current (I_s) as well as some other parameters, as shown below:

$$\Phi = I_s G_s \sqrt{\frac{1+(Ts)(w^2)}{1+(T_{ps})(w^2)}} \tag{9}$$

where,

$$G_s = X_m \sqrt{\frac{C_L r_s + \acute{r}_r}{2 C_L r_s + \acute{r}_r}} \tag{10}$$

$$\omega_{ps} - \frac{k_h C_L X_m^2}{2(k_e C_L X_m^2 + C_{str}} + \sqrt{\left[\frac{2C_L r_s + \acute{r}_r}{k_e C_L X_m^2 + C_{str}}\right] + \left[\frac{k_h C_L X_m^2}{2(k_e C_L X_m^2 + C_{str}}\right]^2} \tag{11}$$

$$T_{ps} = 1/\omega_{ps} \tag{12}$$

$$T_s = \sqrt{\frac{C_{str}}{C_L r_s + \acute{r}_r}} \tag{13}$$

$$C_L = 1 + 2 \frac{X'_{lr}}{X_m} \tag{14}$$

In this study, Eq. (9) is used to find the initial value for the optimal flux-current ratio. This value is then passed onto the SC which then starts to look for the optimal flux-current ratio in the vicinity of the suggested value received from the LMC.

The method operation of the SC is presented in the next section.

On-line search control for the optimal flux-current factor: The Search Controller (SC) represents the second stage in this optimization process within the control system. The SC will start from the suggested value of the flux-current ratio received from the LMC. It will continuously try to improve this value by comparing the input power at other flux-current values in the vicinity of the value suggested by the LMC. Following such a strategy will prevent the high oscillations that occur when applying the SC iterations. The algorithm is described in Fig. 3.

The input power flowing through the inverter is controlled by pulses that are generated by the FOC. The pulses are generated such as to achieve the target flux.

As opposed to scalar control, using FOC will make the implementation of (9) easier. The FOC transforms the stator current to direct-quadrature (d-q) model of the induction machine. In the reference frame rotating at

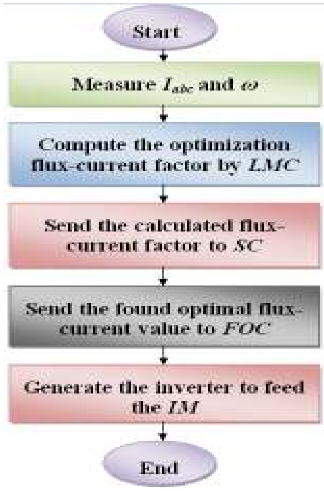

Fig. 3: The algorithm of presented optimization system

synchronous speed, the FOC presupposes that the i_{ds} component of the stator current would be aligned with the rotor field and the i_{qs} component would be perpendicular to i_{ds} (Kumar *et al*., 2014).

In order to make the implementation of this system easy to handle, the SC uses simple algorithm. With such a simple algorithm, a standard microcontroller can be programmed to implement such as simple SC using the basic mathematical and algebraic functions. Figure 4 shows a simple flowchart for the SC algorithm.

As a fixed step search method the tolerance for each step could be adjusted according to the required accuracy. In this study, based on the parameters of the selected induction motor, the initial calculated value of the flux-current ratio from the LMC was 0.03 and the tolerance was 0.005. The specifications of the selected induction motor are shown in Table 1.

Table 1: Twenty hp motor parameters

r_s	0.214700
$\acute{r}_r$	0.220500
Ls	0.000991
Lr'	0.000991
Lm	0.064190
k_e	0.038000
k_h	0.038000
C_{str}	0.015000

Each load and operating condition has its own optimal flux-current ratio. The actual value of the load does have an effect on the time required to find the optimal value of the flux current ratio.

There exists a compromise between the number of iteration and the selection of the step size; using a large step size could reduce the search time, but could result in oscillations in the output value. On the other hand, using a small step size would avoid oscillations but will result in a larger search time.

A constant step size was used within this research. Using the LMC allows us to start from the appropriate initial value and is then complemented by the SC that will fine tune the result.

OPTIMIZATION CONTROL SYSTEM MODELING USING MATLAB/SIMULINK

In order to test the improvements that can be achieved by applying the proposed combined system, MATLAB/SIMULINK was used to simulate a 20-hp

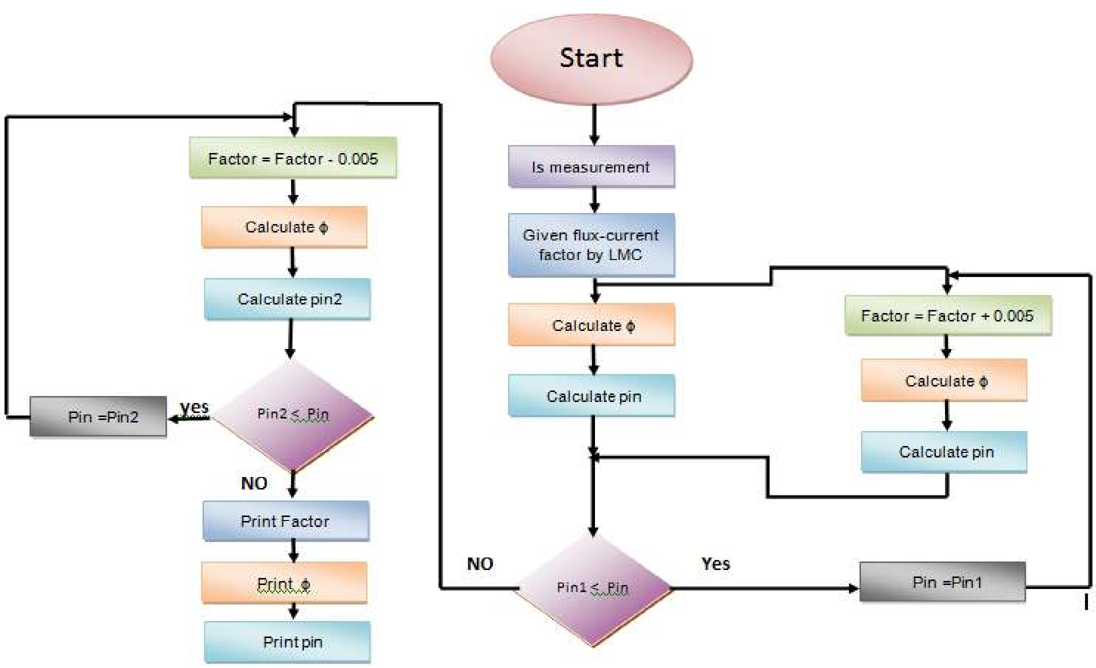

Fig. 4: SC algorithm

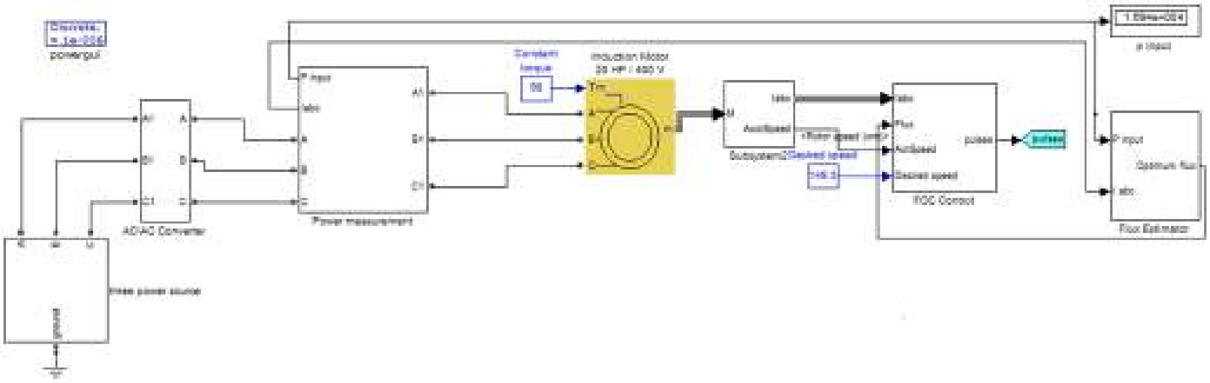

Fig. 5: MATLAB simulation model of optimal control

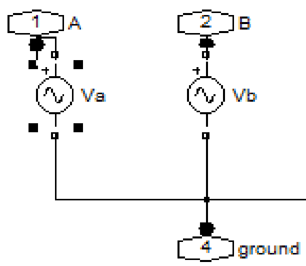

Fig. 6: Three phase power source modelling

motor with the suggested control system as shown in Fig. 5.

The main components of this model are as follows:

- A three phase power source with 231 V phase voltage (rms) and 50 Hz frequency. Figure 6 shows the diagram of three power source.
- An AC-DC-AC converter that includes a rectifier, an intermediate low pass filter and a six pulse IGBT inverter. This converter is shown in Fig. 7.

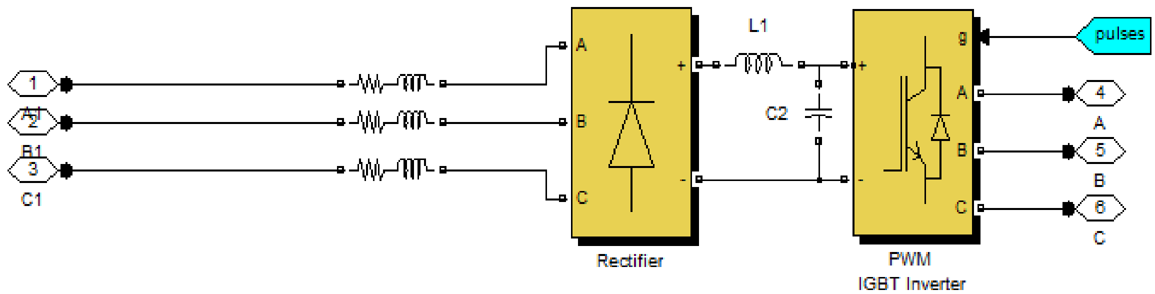

Fig. 7: AC to AC converter modelling

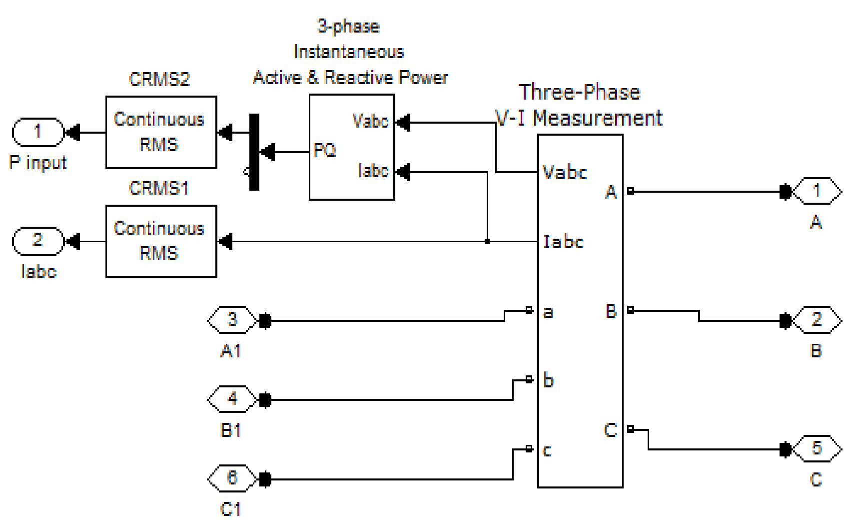

Fig. 8: Power measurement block

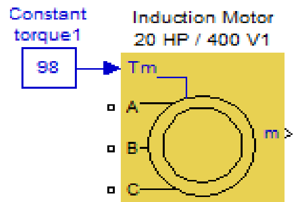

Fig. 9: Twenty hp induction motor modelling

- A power measurement block that measures the current, voltage and input power as shown in Fig. 8.
- A 20 hp induction motor; with the specifications mentioned in Table 1 and shown in Fig. 9.
- A FOC controller that has the aforementioned function. It has four inputs: actual speed, desired speed, current and flux-current ratio (feedback

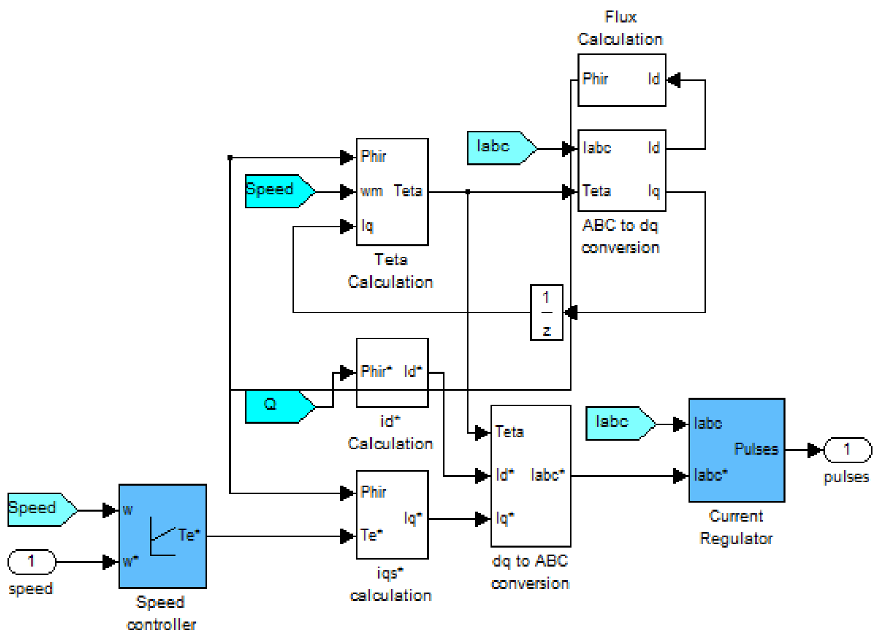

Fig. 10: FOC control modelling

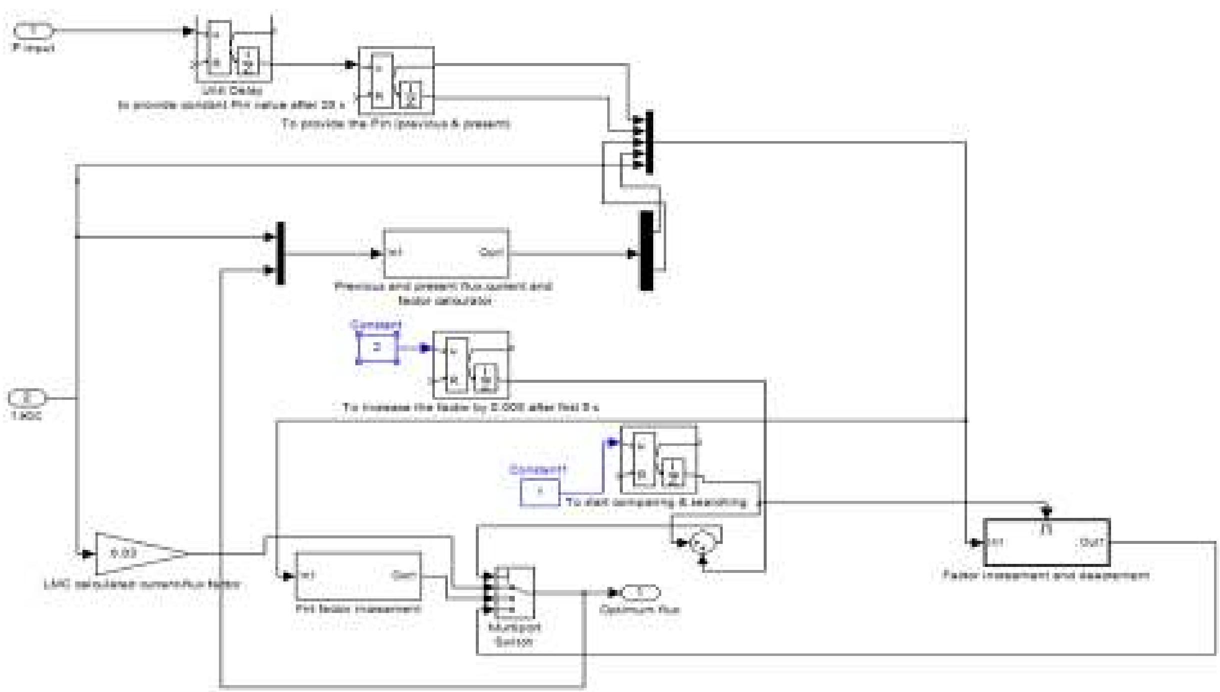

Fig. 11: Online SC modelling

value). The first two inputs are subtracted to find the error in speed and the error is then applied to a PI controller (with specific value of Kp and Ki). This error is representative of the required torque necessary to eliminate the error between the actual and the desired speeds.

The other two inputs are required in order to calculate the desired current that guarantees attaining the desired speed based on the pre-detected value of flux.

The last step in the FOC function is to generate suitable pulses to drive the six pulse IGBT inverter. The pulses are generated within the current regulator by applying the hysteresis current method (within a specific band). The parameters of 20 hp motor have been inserted into the FOC equations. The FOC control modeling is shown in Fig. 10.

- A flux estimator that represents the online SC. This block has two inputs: The input power and the current. The input power is required in order to compare the present and past value of the input power and check whether there is a reduction or increase in the value of the input power. Based on the comparison of the two values, the SC will decide to increase the flux-current ratio by 0.005, reduce by 0.005 or stop the search and accept the final value.

The second input (current) is multiplied by the calculated flux-current ratio from the LMC in order to provide the initial value of optimum flux.

For each applied flux-current ratio the motor will be operated for 2.5 sec in to ensure that the steady state level is attained, after which it measures the input power. The diagram of the proposed online SC is presented in Fig. 11.

SIMULATION RESULTS

The initial calculated flux-current ratio was 0.03 based on the aforementioned equations. The value of 0.03 is in fact an approximation of the exact value obtained (which was 0.026) in order to make the calculation simpler and due to the fact that the step size is 0.005. Such an approximation does not change the final value.

The initial value of 0.03 for the flux-current ratio was passed onto the SC to allow to check the optimality or otherwise of such a value. It will adjust the value in order to achieve the most optimal result.

Each load has its own optimal flux-current ratio as shown in Fig. 12. It is worth mentioning that the input power, the current, the flux and the flux-current ratio values are affected by the variation in the load. This can be easily noticed in Fig. 13 and 14.

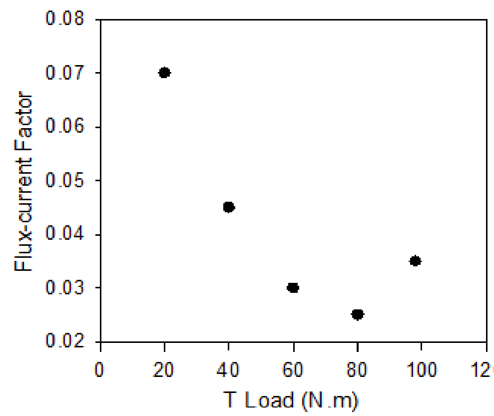

Fig. 12: Optimal flux-current factor versus load (N.m)

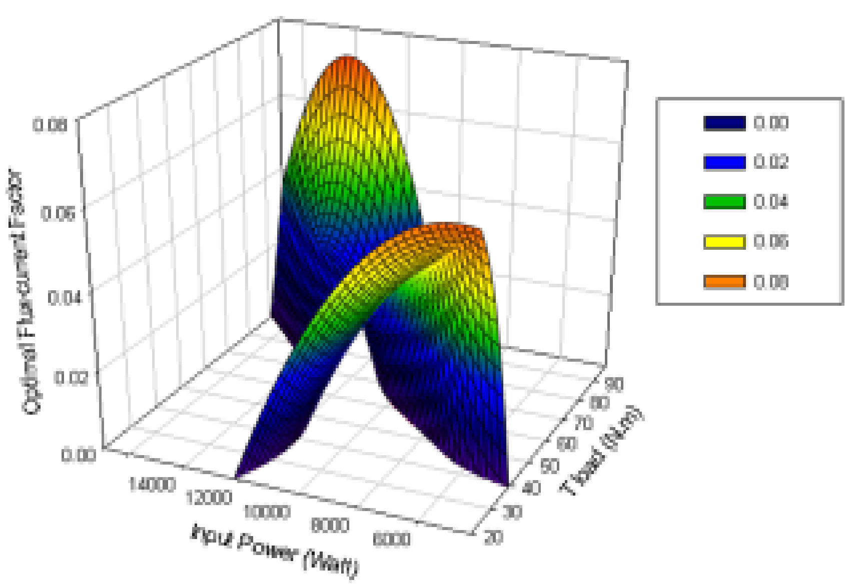

Fig. 13: The optimal flux-current vs. power input for various loads

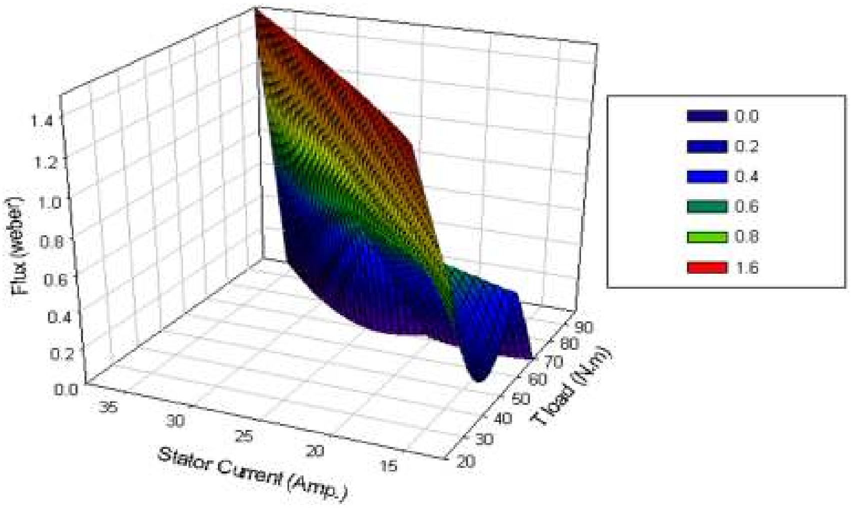

Fig. 14: The optimal flux vs. stator current for various loads

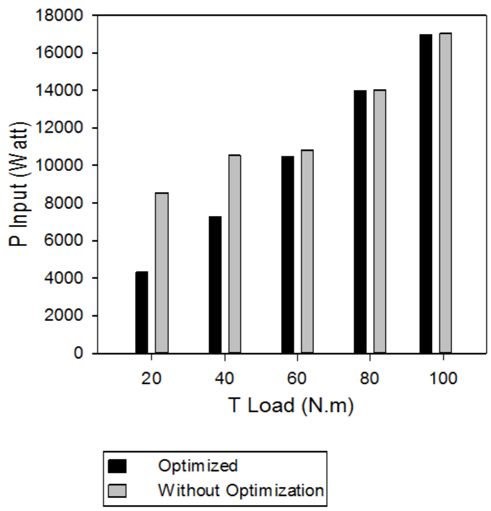

Fig. 15: Comparison of the input power at different loads

Figure 15 shows the total power saving at each load. It can be seen that the improvement is larger at light loads.

CONCLUSION

In order to minimize the input power to an induction motor, an optimization drive system has been presented in this study. This drive system combines LMC and SC techniques in order to provide accurate values for the calculated optimal flux-current ratio.

The LMC will provide the SC with the initial approximate value for the flux-current ratio. This value when applied will minimize the total input power needed to operate the induction motor. The SC will then continue searching for another optimal operating point in the vicinity of the initial value calculated by the LMC, in order to arrive at the optimal operating point for the IM.

The optimal flux value can be deduced simply by measuring the stator current and the motor rotational speed. Thus, one of the main advantages of this method is that its application does not require any additional tools or costs. Moreover, the SC algorithm can be easily programmed on the common microcontroller.

NOMENCLATURE

r_s	:	Stator resistance
$\acute{r}_r$	:	Rotor resistance
X_m	:	Magnetizing reactance
X_{ls}	:	Stator leakage reactance
X'_{ls}	:	Rotor leakage reactance
s	:	Slip
w	:	Speed
ϕ_m	:	Air-gap flux
P_{Fe}	:	Iron losses
P_{str}	:	Stray losses
k_e, k_h	:	Eddy current and hysteresis coefficient
C_{str}, C_{zb}	:	Stray loss coefficient Ce, Cs
T_{ps}	:	Filter cut-off time constant
T_s	:	Filter corner time constant

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