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Energy Optimisation of Sensorless Induction Motor Drives Using a Novel Robust-Adaptive Flux Simulator

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Abstract—**Modern drive systems should have improved reliability and one solution is the reduction or elimination of the number of speed sensors while maximizing the efficiency of motor and drive systems. The paper presents the development of a novel robust-adaptive-flux simulator which is used for the energy optimisation of sensorless induction motor drives. The closed loop system contains a predictive current controller and an observer which is robust against parameters variation. The estimated values of the rotor magnetic flux are used to determine the motor core losses by the robust-adaptive observer. Particle Swarm Optimisation (PSO) algorithm is used for the optimization of rotor speed so the motor losses are minimized and so the motor efficiency is increased. The simulated results show that the proposed sensorless control strategy ensures that the drive system has high dynamic performance for a wide range of rotor speeds and leads to a significant energy saving under different load operating conditions.**

Index Terms—induction motors; sensorless control; energy efficient; robust adaptive observer; field-oriented control; copper and iron losses

I. Introduction

Modern industry employs numerous drives which have a reduced number of sensors or are sensorless. The sensorless induction motor drives [1] have numerous advantages: reduced hardware complexity, cost, machine size, elimination of sensors cables, better noise immunity, increased reliability, and less maintenance requirements. Some practical solutions use Hall-effect sensors to measure the inverter input voltage and output currents while the other variables required by the control system are calculated in by the observer included in the closed-loop system.

Also nowadays an important goal for the producers and users of electrical drive systems is to maximize the efficiency of motor and drive systems so the use of fossil fuels and greenhouse gas emissions are reduced. Maximum efficiency of the induction motors is usually near 75 % of the rated load, but the studies [2] show that more than half of the industrial motors are operating below 60 % of their rated load capacity. Also idling, lightly loaded, cyclic, oversized motors consume more power than required by effective motors so it is important to increase the efficiency of electrical drive systems.

The electrical motor efficiency is the ratio between generated mechanical energy and received electrical energy. The loss segregation method shows that the motor losses must be reduced in order to increase the value for the generated mechanical energy. The components of energy loss in electrical motors are: stator and rotor copper losses; magnetic energy dissipated in the iron components; mechanical and stray losses. The core losses (copper and iron losses) depend on the rotor magnetic flux and operating frequencies values. There are various methods for minimizing the motor losses but this paper presents an observer including Particle Swarm Optimization (PSO) [3] algorithm for the optimization of rotor speed. PSO is chosen because is producing fast, accurate and reliable results when dealing with optimization problems with multiple input variables.

This paper presents the development of a novel robust-adaptive-flux simulator which is used for the energy optimisation of sensorless induction motor drives. The closed loop system contains a predictive current controller and an observer which is robust against parameters variation. The estimated values of the rotor magnetic flux are used to determine the motor core losses by the robust-adaptive observer. The observer with PSO estimates the rotor flux values and optimizes the estimated values of rotor speed. In this way the motor losses are minimized and the motor efficiency is increased (as shown by the simulated results). This paper has six sections as follows: Section two presents the block diagram of the proposed system and explains the operation of the various elements. Section three describes the need and various methods for minimization of motor losses. Section four describes the SIMULINK implementation and various blocks. Section five discusses about the simulated results and shows the comparison between the method using observer with PSO and the method without optimization. Section six contains the conclusions and suggestions for further work.

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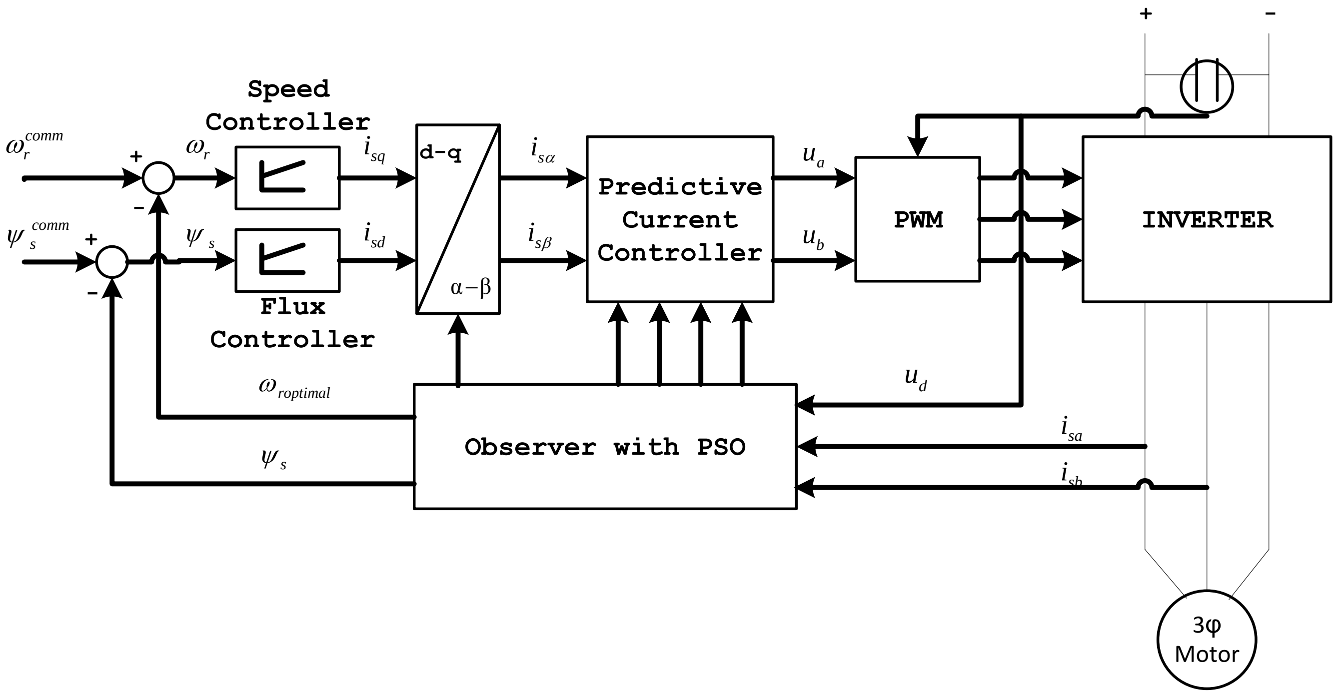

Fig. 1. Block diagram for the proposed method

II. Proposed System

The Stator Field Oriented Control (SFOC) method ensures that torque control can be achieved by controlling the direct and quadrature (d, q) currents separately. The controller reference (d, q) coordinate system must be aligned with the synchronous dq-coordinate system formed by the flux linkage vector $\hat{\psi}_M$ and back-EMF vector $\hat{e}_M = j\omega_s\hat{\psi}_M$. Both systems are rotated by the angle θ_M (angle in electrical degrees) and θ_M^c (reference angle in electrical degrees) respectively. Doncker et al [4] describe the method of Direct Field Oriented Control where the angles θ_M^c and θ_M are determined by using the linkage vector or voltage vector. This may be achieved by an observer which makes use of measured electrical quantities from the electrical motor terminals. The authors are naming this control approach as 'sensorless' because it does not require position sensors or encoders.

Figure 1 shows the block diagram of the proposed system. The speed and flux controllers are PI controllers which contain proportional and integrative elements to regulate the rotor speed and flux [5].

The theoretical analysis of the induction motor operation employs the Clarke-Park transformation where space vectors from the three-phase stationary system (a, b, c) are converted into space vectors placed into two-phase moving reference frame (α, β) which depends on time and rotor speed (Clarke-Park transformation).

Assuming that α-axis and a-axis are in the same direction, the space vectors for (α, β) system are:

$$\begin{aligned} i_{s\alpha} &= i_a \\ i_{s\beta} &= \frac{1}{\sqrt{3}} i_a + \frac{2}{\sqrt{3}} i_b \end{aligned} \tag{1}$$

where $i_{s\alpha}$ and $i_{s\beta}$ are stator currents in (α, β) system.

Park transformation projects the rotating (α, β) system into stationary (d, q) frame. It is considered that the d-axis is in line with rotor flux where θ is the rotor flux position. The direct and quadrature components of the current vector are determined by the following equations:

$$\begin{aligned} i_{sd} &= i_{s\alpha}\cos\theta + i_{s\beta}\sin\theta \\ i_{sq} &= -i_{s\alpha}\sin\theta + i_{s\beta}\cos\theta \end{aligned} \tag{2}$$

where i_{sd} and i_{sq} are direct and quadrature components. These components depend on the (α, β) components and rotor flux position [6].

The next block is the Predictive Current Controller (PCC) which has $i_{s\alpha}$ and $i_{s\beta}$ as input signals. Guzinski et al [5] described the basic structure of the PCC implemented in the closed-loop system. The stator current dynamic system is described by the following equation:

$$di_s/dt = (u_s^{com} - e)/(\sigma L_s)\hat{e} = d\hat{\psi}_r/d\tau \tag{3}$$

where
subscripts *s* and *r* are stator and rotor respectively
i_s – stator current vector
e – motor EMF
u_s – stator voltage vector

$\sigma = 1-L_m^2/(L_sL_r)$
L_s – stator inductance
ψ_r – rotor flux

Assuming that T_{imp} is a small period of time, the discrete form of Equation (3) is as follows:

$$[i_s(k)-i_s(k-1)]/T_{imp} = [u_s^{com}(k-1)-e(k-1)]/(\sigma L_s) \quad (4)$$

where the known values are the commanded voltage $u_s^{com}(k-1)$ and measured current $i_s(k-1)$. The variables $i_s(k)$ and $e(k-1)$ are unknown and should be predicted.

The observer calculates EMF according to (4) where the samples of $\hat{e}(k-2)$ and $\hat{e}(k-3)$ are memorized and used in the successive calculations. The change of position of the EMF vector is described by the following relation:

$$\Delta\varphi_e[(k-2),(k-3)] = \Delta\varphi_e = \varphi_e(k-2)-\varphi_e(k-3) \quad (5)$$

Generally two arc tangent are required to calculate $\varphi_e(k-2)$ and $\varphi_e(k-3)$. Guzinski et al [5] used only one arc tangent function to determine these variables:

$$\Delta\varphi_e = \tan^{-1}\frac{\hat{e}_\alpha(k-2)\hat{e}_\beta(k-3)-\hat{e}_\alpha(k-2)\hat{e}_\beta(k-3)}{\hat{e}_\alpha(k-2)\hat{e}_\beta(k-3)+\hat{e}_\alpha(k-2)\hat{e}_\beta(k-3)} \quad (6)$$

The EMF speed changes slowly in the motor so it is possible to predict $e(k-1)$ for small T_{imp} by rotating EMF vector with small $\Delta\varphi_e$ angle calculated by (6)

The predicted value of $e(k-1)$ is:

$$e^{pred}(k-1) = C_{EMF}\hat{e}(k-2)$$
$$C_{EMF} = \begin{bmatrix} \cos(\Delta\varphi_e) & \sin(\Delta\varphi_e) \\ -\sin(\Delta\varphi_e) & \cos(\Delta\varphi_e) \end{bmatrix} \quad (7)$$

The motor stator current sample at instant (k) is predicted:

$$i_s^{pred}(k) = i_s(k-1) + [u_s^{com}(k-1)-e^{pred}(k-1)]T_{imp}/(\sigma L_s) \quad (8)$$

Pulse Width Modulator (PWM) receives the voltage signals from PCC and generates command pulses for the inverter. The motor flux and speed should stay within their hysteresis bands so it is necessary to apply appropriate combinations of the inverter semiconductor switches [7].

The inverter is used to produce a high power waveform with average voltage varying sinusoidal in a manner suitable for driving the induction motor. It is considered that the closed loop system from Figure 1 contains a voltage-source inverter with full-sinusoidal bridge using insulated gate bipolar transistors (IGBTs) [8]. This type of inverter is readily available in MATLAB SimPower software package.

The closed loop system contains a three-phase two-symmetrical-windings induction motor with output power of 750W, 2-poles, 220V. The electrical properties of the motor are as follows [9]:

Rated power = 750W; Voltage = 220V; frequency = 50 Hz; main stator winding resistance r_m = 4.6 Ω; auxiliary stator winding resistance r_a = 10.6 Ω; main stator leakage reactance X_{lm} = 4.31 Ω; auxiliary stator leakage reactance X_{la} = 7.1472 Ω; rotor winding resistance r_r = 3.455 Ω; rotor leakage reactance X_{lr} = 4.284 Ω; q-axis magnetizing reactance X_{mq} = 89.65 Ω; d-axis magnetizing reactance X_{md} = 169.43 Ω; q-axis equivalent iron loss resistance R_{qfe} = 1050 Ω; d-axis equivalent iron loss resistance R_{dfe} = 1450 Ω; motor inertia J = 0.005776 kg.m2; flux density B = 0.00328 N.m.s/r; Pole pair p = 2.

III. Observer with PSO

Particle swarm optimization (PSO) is a population based stochastic optimization technique, inspired by social behavior of bird flocking or fish schooling. Like other evolutionary computation technique, PSO has similarities with Genetic Algorithm (GA) [10]. The initialization of the system begins with a population of random solution and searches for optimal results by updating generations. The PSO does not have an evolution operator such as crossover and mutation. Potential solution (called particles) flies through the problem space by following the current optimum particles. The PSO is easy to implement, fast and requires a reduced number of parameters. The PSO algorithm implemented in the proposed observer has the following steps as described by Hamid et al [11]:

1. Initialize a population of particles with random positions and velocities in the problem space and fly them.
2. Evaluate fitness of each particle in swarm.
3. For every iteration, compare each particle's fitness with previous best fitness (pbest) obtained. If the current value is better than the pbest, then set pbest equal to the current value and the pbest local equal to the current location in the d-dimensional problem space.
4. Compare pbest of particles with each other and update the swarm global best location with the greatest fitness (gbest).
5. Change the velocity and position of particle according to following equations:

$$V_{id}^{n+1} = W * v_{id}^n + c_1 * rand_1^n * (P_{id}^n - X_{id}^n) + c_2 * rand_2^n * (P_{gd}^n - X_{id}^n) \quad (9)$$

$$X_{id}^{n+1} = X_{id}^n + V_{id}^{n+1} \quad (10)$$

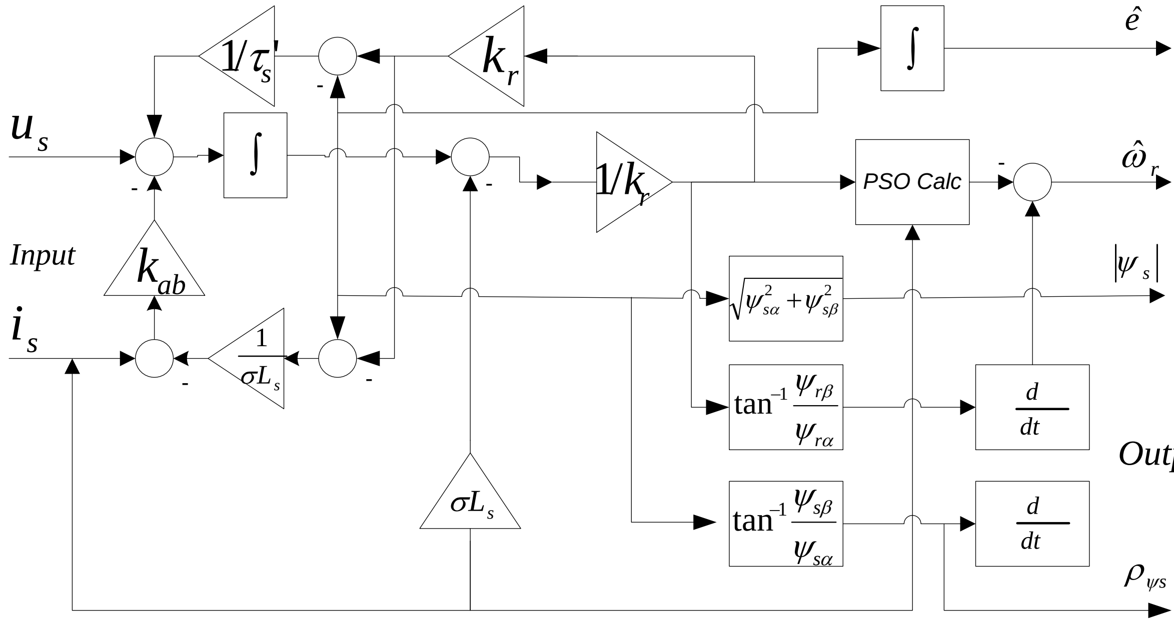

Fig. 2. Block Diagram for Observer with PSO

where

V_{id}^{n+1}, V_{id}^{n} represent the velocity of the next and present particles with d dimensions; X_{id}^{n+1} , X_{id}^{n} represent the position of the next and present particles with d dimensions; *c1* and *c2* cognitive and social accelerations respectively; $rand_1$ and $rand_2$ are two uniform random functions between 0 to 1; P_{id} and P_{gd} are local and global best positions; and *W* is the inertia weight.

6. Repeat steps (1) to (5) until convergence is reached based on some desired single or multiple criteria.

The proposed Observer with Particle Swarm Optimization (PSO) (see Figure 2) performs two major tasks:

a. Optimizes the rotor speed ($\omega_{roptimal}$) by using stator current ($i_{s\alpha}$) and motor direct voltage (u_d).
b. Estimates the stator flux demand (ψ_s) which is the input signal of the flux controller.

Guzinski et al [5] determined the stator flux by using the following equations:

$$d\hat{\psi}_s / dt = (-\hat{\psi}_s + k_r\hat{\psi}_r)/\tau_s' + \hat{u}_s - k_{ab}(i_s - \hat{i}_s) \quad (11)$$

It is obvious that the flux calculation does not require a value for motor speed so any errors associated with the measurement or estimation of these signals are eliminated.

The rotor flux yields:

$$\hat{\psi}_r = (\hat{\psi}_s - \sigma L_s \hat{i}_s)/k_r \quad (12)$$

where

$k_r = L_m / L_r$

$\sigma = 1 - L_m^2/(L_s L_r)$

$\tau_s' = \sigma L_s / R_s$

k_{ab} – observer gain
R_s – stator resistance
L_m – magnetic linkage inductance;
L_s – stator inductance
L_r – rotor inductance
$\hat{\psi}_s$ – estimated stator flux vector
$\hat{\psi}_r$ – estimated rotor flux vector
$\hat{i}_s$ – estimated stator current vector
i_s – predicted stator current vector
u_s – predicted stator voltage.

The magnitude of the stator flux yields:

$$|\hat{\psi}_s| = \sqrt{\psi_{s\alpha}^2 + \psi_{s\beta}^2} \quad (13)$$

The angle position of the stator flux vector is:

$$\hat{\rho}_{\psi s} = \tan^{-1}\left(\hat{\psi}_{s\beta} / \hat{\psi}_{s\alpha}\right) \quad (14)$$

The angle position of the rotor flux vector yields:

$$\hat{\rho}_{\psi r} = \tan^{-1}\left(\hat{\psi}_{r\beta} / \hat{\psi}_{r\alpha}\right) \quad (15)$$

The estimated stator current vector for feedback correction is:

$$i_s = (\hat{\psi}_s - k_r\hat{\psi}_r)/(\sigma L_s) \quad (16)$$

The rotor mechanical speed $\hat{\omega}_r$ is the difference between the rotor flux synchronous speed $\hat{\omega}_{\psi r}$ and slip speed $\hat{\omega}_2$:

$$\hat{\omega}_r = \hat{\omega}_{\psi r} - \hat{\omega}_2 \quad (17)$$

The rotor flux synchronous speed $\hat{\omega}_{\psi r}$ yields:

$$\hat{\omega}_{\psi r} = d\hat{\rho}_{\psi r} / d\tau \quad (18)$$

The rotor flux slip speed $\hat{\omega}_2$ has the following equation:

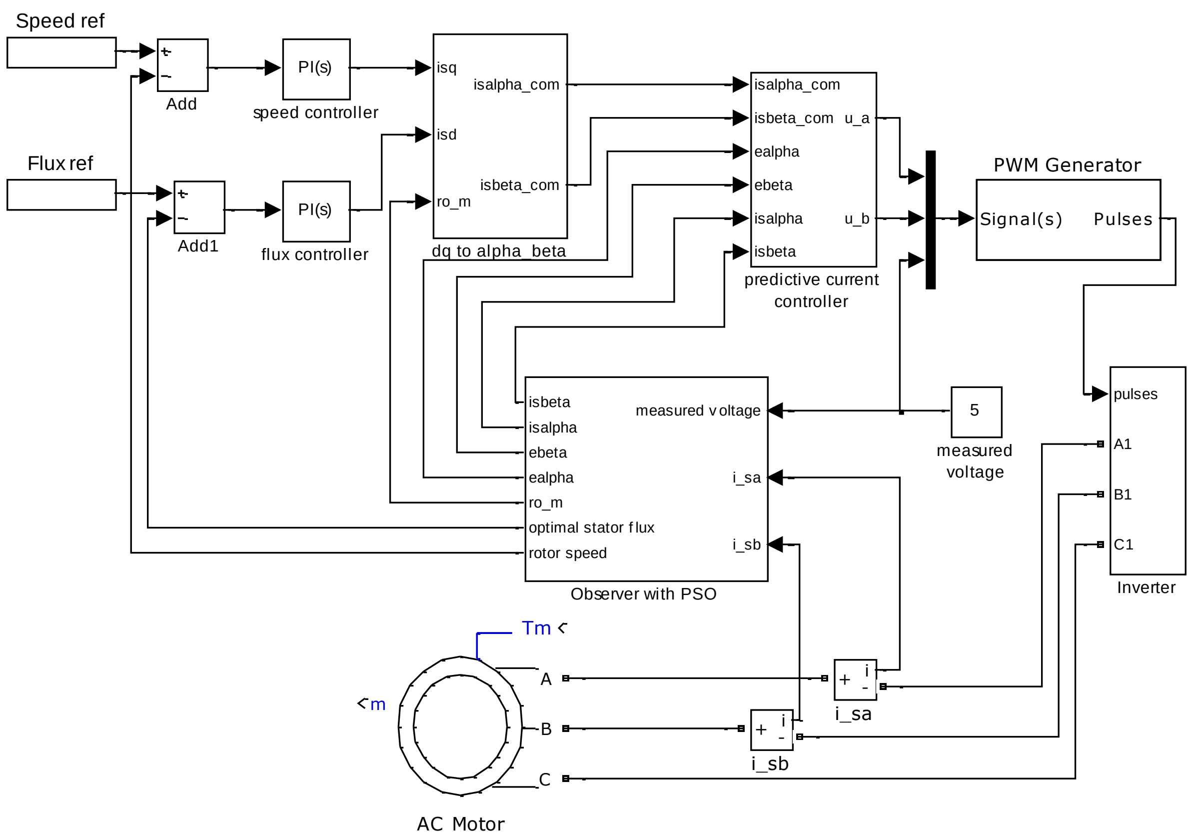

Fig. 3. Simulink representation of the whole system

$$\hat{\omega}_2 = \hat{\psi}_{r\alpha} i_{s\beta} - \hat{\psi}_{r\beta} i_{s\alpha} / \left|\hat{\psi}_r\right|^2 \tag{19}$$

Substituting (18) and (19) into (17) yields:

The rotor flux synchronous speed $\hat{\omega}_{\psi r}$ yields:

$$\hat{\omega}_r = d\hat{\rho}_{\psi r} / d\tau - \hat{\psi}_{r\alpha} i_{s\beta} - \hat{\psi}_{r\beta} i_{s\alpha} / \left|\hat{\psi}_r\right|^2 \tag{20}$$

where

$\hat{\rho}_{\psi s,\psi r}$ is an estimated angle position of stator/rotor flux vector

$\hat{\psi}_{s\alpha,s\beta}$ is an estimated stator flux at α/β-component

$i_{s\alpha,s\beta}$ is an estimated stator current at α/β-component

The numerical values included in Equations (17-26) contain normalized values for variables.

The output $\hat{\omega}_r$ in (20) is optimized using PSO algorithm described before and this optimized value will be used to determine the motor losses as described in the next chapter.

IV. Minimization of Motor Losses with Optimal Speed

According to Amin [9] the distribution of motor losses varies with the variation of flux and torque. The core losses decrease and the copper losses increase when the flux reduces from the rated value.

The motor equations are developed [9] as follows:

$$\begin{aligned} v_{qs}^e &= r_m i_{qs}^e + L_{lm}\frac{di_{qs}^e}{dt} + L_{mq}\frac{di_{qm}^e}{dt} \\ &+ \omega_e (L_{la} i_{ds}^e + L_{md} i_{dm}^e) \\ v_{ds}^e &= r_a i_{ds}^e + L_{la}\frac{di_{ds}^e}{dt} + L_{md}\frac{di_{dm}^e}{dt} \\ &- \omega_e (L_{lm} i_{qs}^e + L_{mq} i_{qm}^e) \end{aligned} \tag{21}$$

$$\begin{aligned} 0 &= r_r i_{qr}^e + L_{lr}\frac{di_{qr}^e}{dt} + L_{mq}\frac{di_{qm}^e}{dt} \\ &+ \frac{\omega_{sl}}{k}(L_{lR} i_{dr}^e + L_{md} i_{dm}^e) \end{aligned} \tag{22}$$

$$\begin{aligned} 0 &= r_R i_{dr}^e + L_{lR}\frac{di_{dr}^e}{dt} + L_{md}\frac{di_{dm}^e}{dt} \\ &- k\omega_{sl}(L_{lR} i_{qr}^e + L_{mq} i_{qm}^e) \end{aligned} \tag{23}$$

$$i_{qs}^e + i_{qr}^e = i_{qfe}^e + i_{qm}^e \tag{24}$$

$$i_{ds}^e + i_{dr}^e = i_{dfe}^e + i_{dm}^e \tag{25}$$

where

$$i_{dfe}^e = \frac{v_{qm}^e}{R_{qfe}}$$

$$i_{qfe}^{e} = \frac{v_{dm}^{e}}{R_{dfe}}$$

$$v_{dm}^{e} = -\frac{\omega_e L_{lr} L_{mqs}}{L_r} i_{qs}^{e}$$

$$v_{qm}^{e} = \omega_e L_{mds} i_{ds}^{e}$$

and superscript e denotes synchronous reference frame

$i_{ds,qs}$ – stator current (d- and q-axes)

k – turns ratio auxiliary/main windings

$v_{ds,qs}$ – stator voltage (d- and q-axes)

The total electrical losses can be expressed as follows:

$$P_{losses} = P_{cu1} + P_{cu2} + P_{core} \tag{26}$$

where

P_{cu1} - stator copper losses;

P_{cu2} - rotor copper losses;

P_{cor} - core losses.

Stator copper losses is expressed as:

$$P_{cu1} = r_m i_{qs}^{e^2} + r_a i_{ds}^{e^2} \tag{27}$$

whereas Rotor copper losses is stated as:

$$P_{cu2} = r_r i_{qr}^{e^2} + r_R i_{dr}^{e^2} \tag{28}$$

and Core losses is:

$$P_{core} = \frac{v_{qm}^{e^2}}{R_{qfe}} + \frac{v_{dm}^{e^2}}{R_{dfe}} \tag{29}$$

The stator copper losses are caused by electric currents flowing through the stator windings, whereas the core losses due to hysteresis and eddy currents in stator. The total electrical losses of motor can be rewritten as:

$$P_{losses} = r_m i_{qs}^{e^2} + r_a i_{ds}^{e^2} + r_r i_{qr}^{e^2} + r_R i_{dr}^{e^2} + \frac{v_{qm}^{e^2}}{R_{qfe}} + \frac{v_{dm}^{e^2}}{R_{dfe}} \tag{30}$$

The total electrical losses are obtained as follows:

$$P_{losses} = \left[r_m + \frac{r_r L_{mqs}^2}{L_r^2} + \frac{\omega_e^2 L_{lr}^2 L_{mqs}^2}{L_r^2 R_{dfe}} \right] \left(\frac{T_e^2 L_r^2}{P^2 \left(\frac{L_{mds}}{K} \right)^2 \psi_r^2} \right) + \left(r_a + \frac{\omega_e^2 L_{mds}^2}{R_{qfe}} \right) \frac{\psi_r^2}{L_{mds}^2} \tag{31}$$

where

$\omega_e = \omega_r + \omega_{sl1}$ and ω_{sl1} is the slip speed r/sec.

From (31) the loss formula depends on rotor flux ψ_r and certain operating point of Torque T_e and rotor speed ω_r .

Winding losses could be by optimising both the shape and the dimensions of the external fans. Iron losses could be kept low by an optimally designed magnetic circuit.

The total power losses for the induction motor are:

$$TotalP_{losses} = P_{in} - P_{out} \tag{32}$$

The motor efficiency yields:

$$Efficiency\ (\eta) = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{P_{out} + TotalP_{losses}} \tag{33}$$

The optimised value of rotor speed ω_r is included in Equation (31) so the motor losses are minimised. These motor losses are used to determine the motor efficiency values (see Equation (33)) which are compared with the values obtained for the case of observer with PSO in TABLE I.

V. SIMULINK MODEL

The SIMULINK implementation of the proposed system is shown on Figure 3 and contains the following blocks:

- Subsystem *'dq to alpha_beta'* includes the mathematical equations for the Park transformation which projects the rotating (α, β) system into stationary (d, q) frame.
- Subsystem 'Predictive current controller' – implements the equations presented by Guzinski et al [5]. The output signals are used by PWM generator to generate command pulses.
- The block *'PWM generator'* is available in MATLAB SimPower software package. This PWM generator is used to fire the forced-commutated devices (IGBTs) of two-level three-phase bridges included in inverter.
- The block *'Inverter'* is available in MATLAB SimPower software package. The direct current (DC) in converted into alternative current (AC) using two-level IGBT converter. Two pulses are sent to the upper and lower IGBT of each arm of the bridge and a time delay is used in practice to avoid a short circuit result on the DC bus when the gate is not completely off. The inverter converts from 600 V DC to a balanced three-phase 380 V line voltage.
- Subsystem *'Observer with PSO'* – contains the elements presented in Figure 2. The output signals are stator currents and EMF components in (α, β) rotational frame, rotor angular position, stator flux and optimised rotor speed using PSO algorithm presented in Section III.
- The block *'AC motor'* is available in MATLAB SimPower software package. The numerical values for the parameters are included in Section II.

VI. SIMULATED RESULTS

Fig. 4 shows the variation of motor efficiency when the load torque varies between 0.2 and 1 p.u. This is an effective technique for estimating efficiency of three-phase induction motor. It is not necessary to disconnect the motor from the driven equipment and make connections at the motor terminal box. The motor losses are considered when determining its performance curve containing both motor efficiency and output load information. However this method has several shortcomings: the nameplate data could be rounded; the error in estimated efficiency can be very high; the motor may have been rewound.

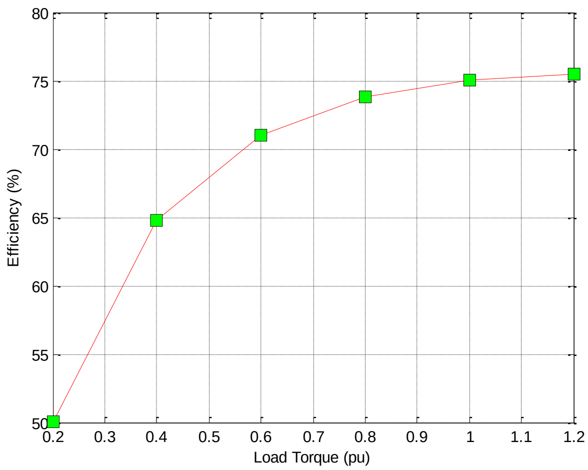

Fig. 4. Efficiency versus load – method without optimisation

TABLE I shows the comparison between the motor efficiency without PSO optimisation and with PSO optimisation, as the motor dynamic performance is greatly improved particularly over the light load region where the efficiency values are relatively low.

TABLE I
COMPARISON OF MOTOR EFFICIENCY BETWEEN WITHOUT AND WITH PSO

Load (pu)	Without optimisation	With PSO
0.2	70.78	92.93
0.4	71.18	92.88
0.6	71.88	93.34
0.8	72.80	93.82
1.0	73.97	94.38

Fig. 5 shows the variation of motor efficiency for various loads (20, 40, 60, 80, 100%). It is clear that for low torque load, the motor exhibits low efficiency than for the higher torque load. The proposed method is improving the efficiency of induction motors (which are the most energy consuming electric machines) so it optimises the energy consumption of sensorless induction motor drives.

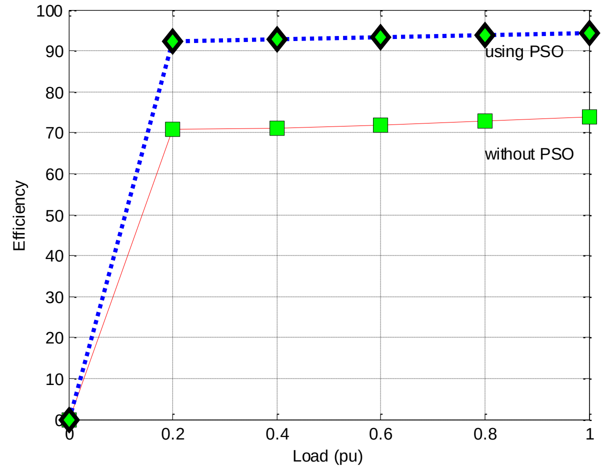

Fig. 5 Comparison on motor efficiency with and without PSO

VII. CONCLUSIONS

The paper presents the mathematical equations and SIMULINK implementation of a novel robust-adaptive-flux simulator. The system contains a PCC and robust observer which estimates the values of the rotor magnetic flux and optimizes the estimated values of the rotor speed so the motor core losses are minimized. The mathematical model of the system is implemented in SIMULINK and the simulated results show that the motor efficiency increases when the observer with PSO is used in comparison with the values corresponding to the case when the estimated rotor speeds were not optimized. So the drive system has high dynamic performance for a wide range of rotor speeds and leads to a significant energy saving under different load operating conditions when the observer with PSO is included in the proposed sensorless control strategy.

PSO calculates the global minimum values and more research will be performed in order to determine the influence of PSO algorithm on the velocity of the regulation system.

This novel robust-adaptive flux simulator using an artificial intelligence algorithm represents an important contribution to the development of intelligent energy management systems that will help attain high energy efficiency of variable speed drives by interacting dynamically with motor loads and available power sources.

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