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Modeling and Simulation of Flux-Optimized Induction Motor Drive

R. Al-Issa, H. Sarhan and I.D. Al-Khawaldeh
Faculty of Engineering Technology, Al-Balqa' Applied University, Amman,
P.O. Box 15008, Jordan

Abstract: The efficiency of induction motor drives under variable operating conditions can be improved by predicting the optimum flux that guarantees loss minimization. In this research, a loss-minimization scalar controller, based on determining of modulation index of IGBT inverter-based AC-to-AC converter, which corresponds to optimum flux, is proposed. For this purpose, mathematical models for total power losses as a function of magnetic flux, optimum flux as a function of operating speed and load torque, and modulation index as a function of optimum flux were analytically derived. Loss-minimized, scalar-controlled induction motor drive system was modeled, simulated and experimentally tested. The results have validated the effectiveness of this system in minimizing the motor operating losses, especially at light and medium loads. Also, the dynamic performance of the drive system has been improved. The proposed controller can be implemented in adjustable speed induction motor drive systems with variable loads, operating below rated speed.

Key words: Induction motor drive, loss minimization, modeling, optimum flux

INTRODUCTION

Induction motors are the most used in industry since they are rugged, inexpensive, and are maintenance free. It is estimated that more than 50% of the world electric energy generated is consumed by electric machines (Leonhard, 1995). Improving efficiency in electric drives is important, mainly for economic saving and reduction of environmental pollution (Anderson and Pedersen, 1996; Ta and Hori, 2001).

Induction motors have a high efficiency at rated speed and torque. However, at light loads, motor efficiency decreases dramatically due to an imbalance between the copper and the core losses. Hence, energy saving can be achieved by proper selection of the flux level in the motor (Abrahamsen *et al*., 1996; Bose *et al*., 1997; Lu and Wu, 2001).

The main induction motor losses are usually split into: stator copper losses, rotor copper losses, core (iron) losses, mechanical and stray losses. To improve the motor efficiency, the flux must be reduced, obtaining a balance between copper and core losses (Andersen *et al*., 1995; Sousa *et al*., 1995). Many minimum-loss control schemes based on scalar control or vector control of induction motor drives have been reported in literature (Abrahamsen *et al*., 2001; Lin and Yang, 2003). Basically, there are two different approaches to improve the efficiency: loss-based model approach and power measure based approach (Kirschen *et al*., 1984; Lim and Nam, 2004). In loss based model approach the loss minimization optimum flux or power factor is computed analytically, while in power measure based approach the controller searches for the operating point where the input power is at a minimum while keeping the motor output power constant. The proposed in literature various methods for loss-minimizing control of induction motors differ each other by approach, complexity, accuracy, convergence, etc., (Kioskeridis and Margaris, 1996; Yang and Lin, 2003).

In this research, a loss-minimization scalar controller of induction motor drive system, based on calculating the optimal flux for loss minimization, is developed. Then, the validity of the proposed controller was examined by simulation and experimental results. Further, the effect of loss-minimization scheme on the dynamic performance of the drive system was investigated.

ALGORITHM OF THE MINIMUM-LOSS CONTROL

The total power losses in induction motor can be calculated by the following Eq. (Kirschen *et al*., 1984; Lim, and Nam, 2004):

$$\Delta P_{tot} = 3R_1 I_1^2 + 3R_2' I_2'^2 + \Delta P_{mag.n}\varphi^2 \alpha^k \quad (1)$$

The magnetic losses at nominal operating conditions can be approximately defined as:

$$\Delta P_{mag.n} = P_{1n} - P_{ag.n} - \left(3R_1 I_{1n}^2 + 0.005 P_n\right) \quad (2)$$

Corresponding Author: I.D. Al-Khawaldeh, Faculty of Engineering Technology, Al-Balqa' Applied University, Amman, P.O. Box 15008, Jordan

The relationship between stator current, rotor current and magnetizing current is given by (Abrahamsen *et al*., 2001):

$$I_1^2 \approx I_2'^2 + I_0^2 \quad (3)$$

Also, the rotor current can be represented as:

$$I_2' = \frac{P_{ag.n}\mu}{E_{1n}\varphi} \quad (4)$$

The nominal air-gap (electromagnetic) power is:

$$P_{ag.n} = T_n \omega_s \quad (5)$$

According to analytical analysis provided in (Brodovsky and Ivanov, 1975), the magnetizing current can be expressed as:

$$I_0^2 \approx I_{0n}^2 \frac{a(1-\varphi^2)+\varphi^2}{b(1-\varphi^2)+\varphi^2} \quad (6)$$

The coefficients and are selected so as most exactly describe the segment of magnetization curve, located in the interval of optimum flux variation. Substitution of Eq. (3), (4) and (6) into Eq. (1) yields:

$$\Delta P_{tot} = B\frac{a(1-\varphi^2)+\varphi^2}{b(1-\varphi^2)+\varphi^2} + C\frac{\mu^2}{\varphi^2} + D\varphi^2\alpha^k \quad (7)$$

where;

$$B = 3R_1 I_{0n}^2 \quad (8)$$

$$C = \frac{(R_1 + R_2')P^2 ag.n}{3E^2_{In}} \quad (9)$$

$$D = \Delta P_{mag.n} \quad (10)$$

Eq. (7) shows that the total power losses at specified frequency and load torque are a function of normalized magnetic flux only.

Taking the derivative of ΔP_{tot} with respect to φ in Eq. (7) and equating the derivative to zero yields:

$$\varphi^8 + a_1\varphi^6 + a_2\varphi^4 + a_3\varphi^2 + a_4 = 0 \quad (11)$$

where;

$$a_1 = \frac{2b}{1-b} \quad (12)$$

$$a_2 = \left(\frac{b}{b-1}\right)^2 + \frac{2B(b-a) - C\mu^2(b-1)^2}{D\alpha^k(b-1)^2} \quad (13)$$

$$a_3 = \frac{2C\mu^2 b}{D\alpha^k(b-1)} \quad (14)$$

$$a_4 = -\frac{C\mu^2 b}{D\alpha^k(b-1)^2} \quad (15)$$

Eq. (11) has 8 roots, 6 of them are complex, one real negative root, and one real positive root. The complex roots and the negative root have no physical meaning and should be ignored. The remaining real positive root will be the optimal normalized flux φ_{opt} , which corresponds to minimum power losses.

The optimum value of control command, modulation index m_{opt}, can be defined as:

$$m_{opt} = a\varphi_{opt} \quad (16)$$

The last equation shows how the magnetic flux should be changed to achieve energy saving at different operating conditions. Also, it is the control algorithm of the proposed loss-minimization controller. The optimal value of modulation index is always.

The optimal value of stator voltage V_{opt} that minimizes the total power losses is:

$$V_{opt} = m_{opt} V_n \quad (17)$$

MODELING AND SIMULATION OF OPTIMIZED DRIVE SYSTEM

The studied drive system consists of IGBT-inverter-based AC to AC converter, three-phase squirrel cage induction motor and controller. In order to analyze the system performance, all of these components should be modeled (mathematically described). According to the analysis done in (Saleem *et al*., 2010; Sarhan and Issa, 2005; Vivek and Sandhu, 2009), the converter will be modeled through its input-output equation based on the modulation index, and the standard state-space model will be used to model the induction motor. Equation 16 represents the mathematical model of the controller.

The block diagram of the drive system studied using MATLAB Simulink is shown in Fig. 1. The parameters of

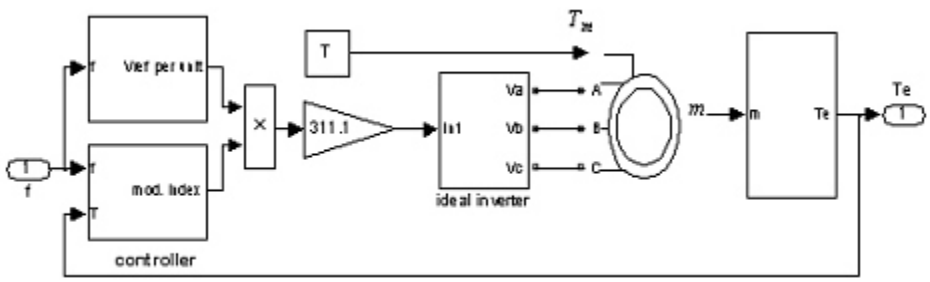


Fig. 1: Model of optimized drive system

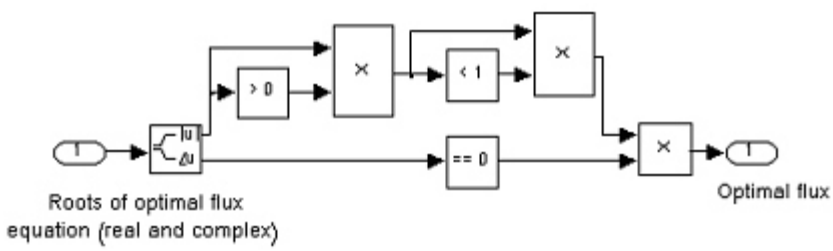


Fig. 2: Model of optimal flux

Table 1: Induction motor data

Parameter	Value
Stator resistance R_1	1.230
Stator reactance X_1	1.500
Mutual reactance X_m	53.700
Rotor resistance referred to the stator R'_2	0.787
Rotor reactance referred to the stator X'_2	2.490
Nominal voltage V_n	220/380
Nominal torque T_n	36.340
Nominal output power P_n	5.500
Nominal stator current I_{1n}	11.500
Nominal power factor $\cos\varphi_n$	0.850
Nominal frequency f_n	50
Number of poles P	4
Nominal slip s_n	0.036
Synchronous rotational speed n_s	1500
Synchronous angular speed ω_s	157
Nominal rotational speed n_n	1446
Nominal angular speed ω_n	151.348
Moment of inertia J	0.017
Constant a	0.0327
Constant b	3.112
Coefficient k	1.400

modeled and simulated induction motor are given in Table 1.

The MATLAB Simulink model of optimal flux φ_{opt} is shown in Fig. 2. The model is used to define the real positive root of Eq. (11). The condition $0 < \varphi_{opt} \leq 1$ was considered in the model. The required coefficients in Eq. (1) were simulated according to Eq. (12-15).

The relationship between optimal flux, frequency, and load torque is shown in Fig. 3. It is clear from Fig. 3 that there is certain value of optimal flux for each operating point. In order to validate the effectiveness of the proposed controller, a motor loss model is required. This model is shown in Fig. 4. The model was constructed according to Eq. (7-10). Examples of total power losses plots as a function of stator voltage (flux) under various load torques and frequencies are shown in Fig. 5 and 6. It can be seen from Fig. 5 and 6 that there is an optimal value of stator voltage (flux) for each operating point, where the total power losses are minimum.

For quantitative analysis, the total power losses in the optimized system were compared with those in the original (non-optimized) system under the same operating conditions. The original system is considered that one, in which the stator voltage (flux) remains constant and equals the nominal value for all operating conditions. Examples of total power losses plots in original and optimized systems are shown in Fig. 7 and 8. From Fig. 7 and 8, it is easy to notice that the proposed optimization approach has significant effect at light loads.

Effect of optimization on the system dynamics has been investigated. Simulation results show that the dynamic responses of stator current, electromagnetic torque, and angular speed had been improved. Examples of dynamic responses of both optimized and original systems are shown in Fig. 9, 10 and 11. Also, it was noticed in some cases, that there is a small increase in

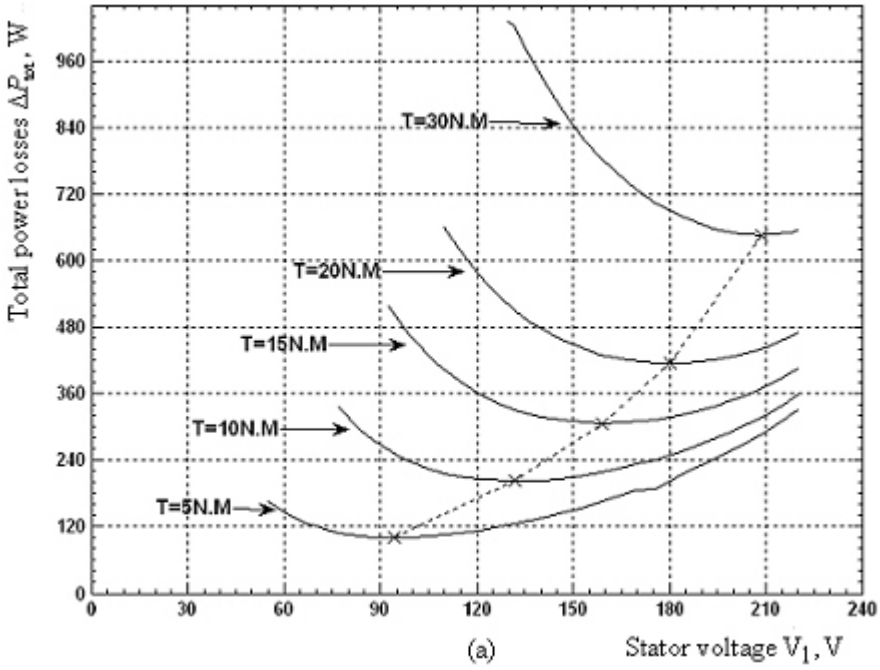


Fig. 3: Optimal flux as a function of load torque at variable frequency

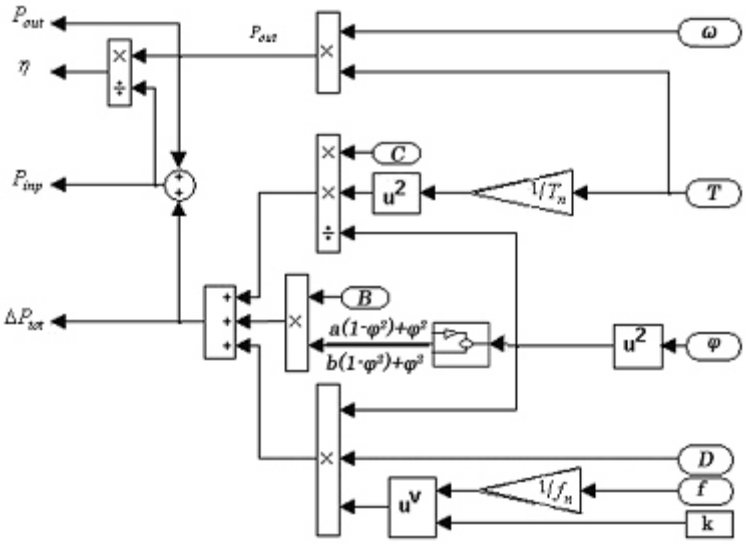


Fig. 4: Motor loss model

slip, as shown in Fig. 11. This can be explained as a result of decrease in dynamic torque causing motor acceleration due to decrease in magnetic flux.

EXPERIMENTAL RESULTS

To verify the use of the proposed loss-minimization controller some experiments have been carried out with the same drive system that was simulated. The total power losses were experimentally obtained for different operating conditions as the difference between the input power and the output power. The input power was measured for each operating point, while the corresponding output power was calculated as $P_{out}=.T\omega$ The experimental results were compared with theoretical results. Some of these results are represented in Fig. 12.

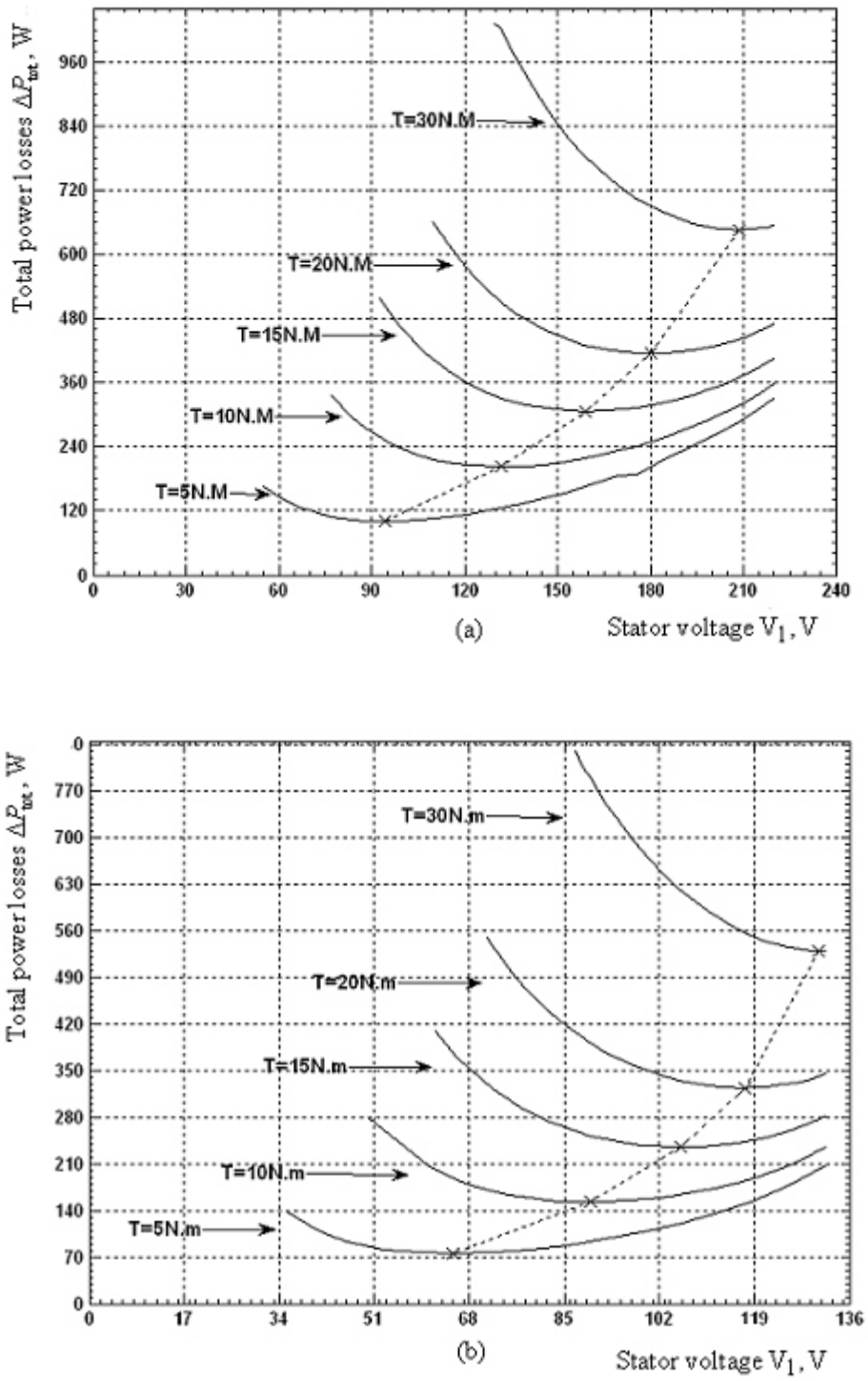
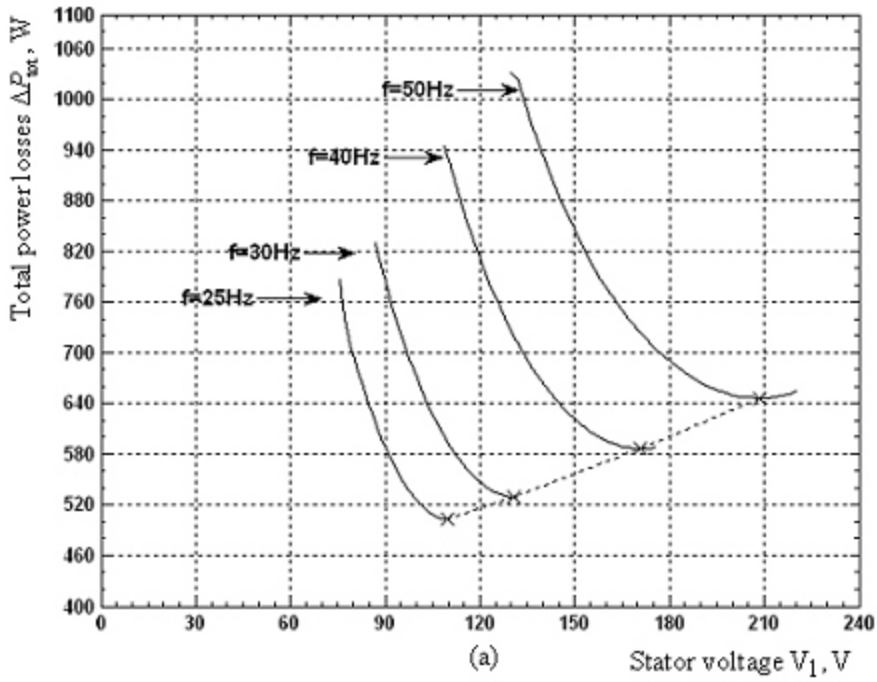


Fig. 5: Total power losses as a function of stator voltage under variable load torques (a) frequency f = 50 Hz and (b) frequency f = 30 Hz



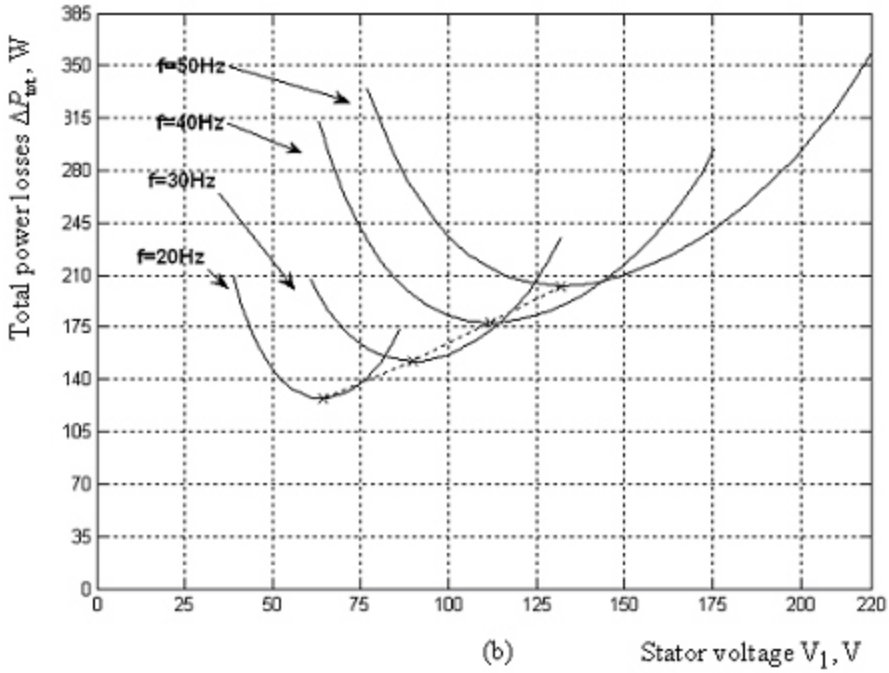


Fig. 6: Total power losses as a function of stator voltage under variable frequencies (a) load torque T = 30 N.m and (b) load torque T = 10 N.m

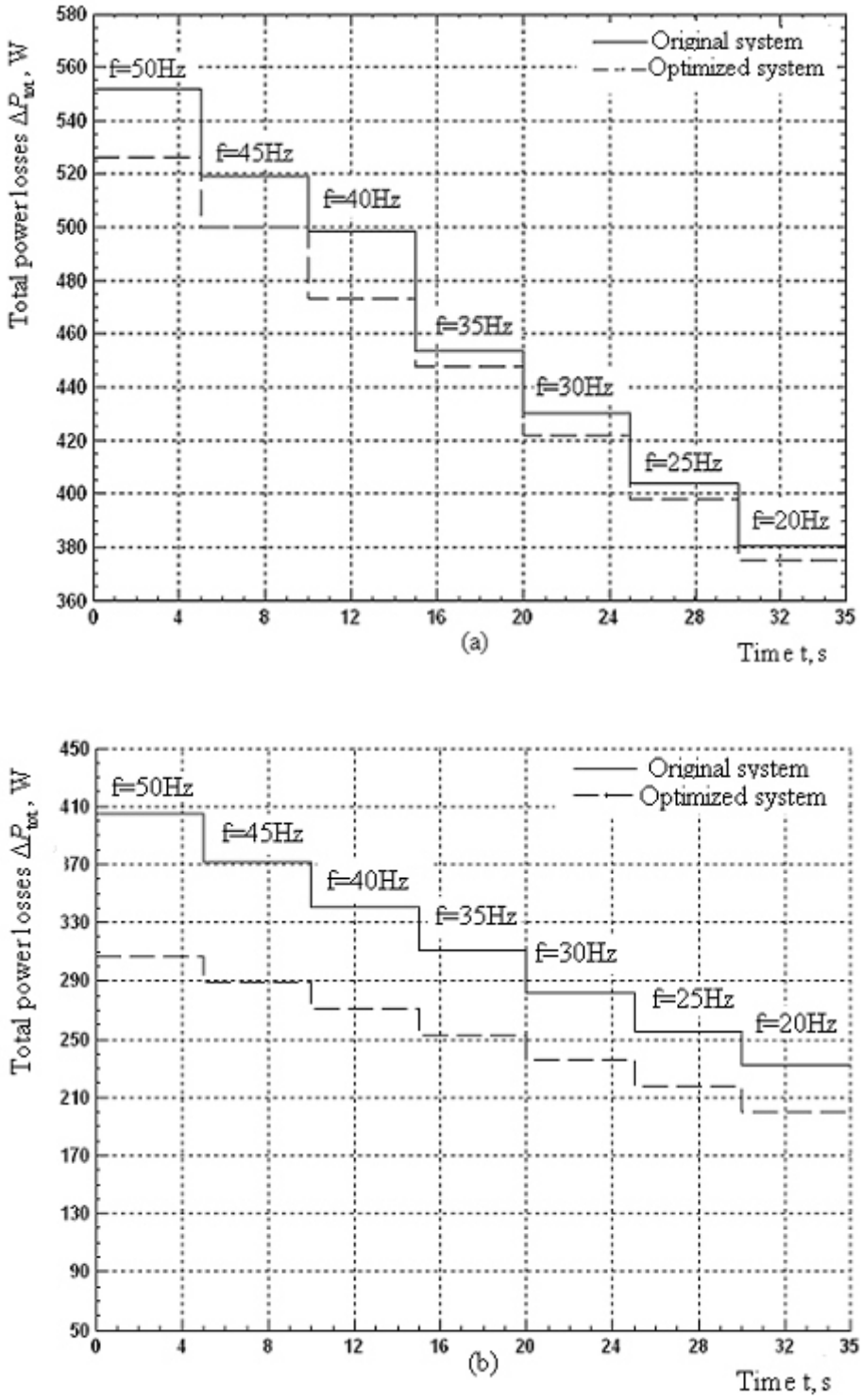
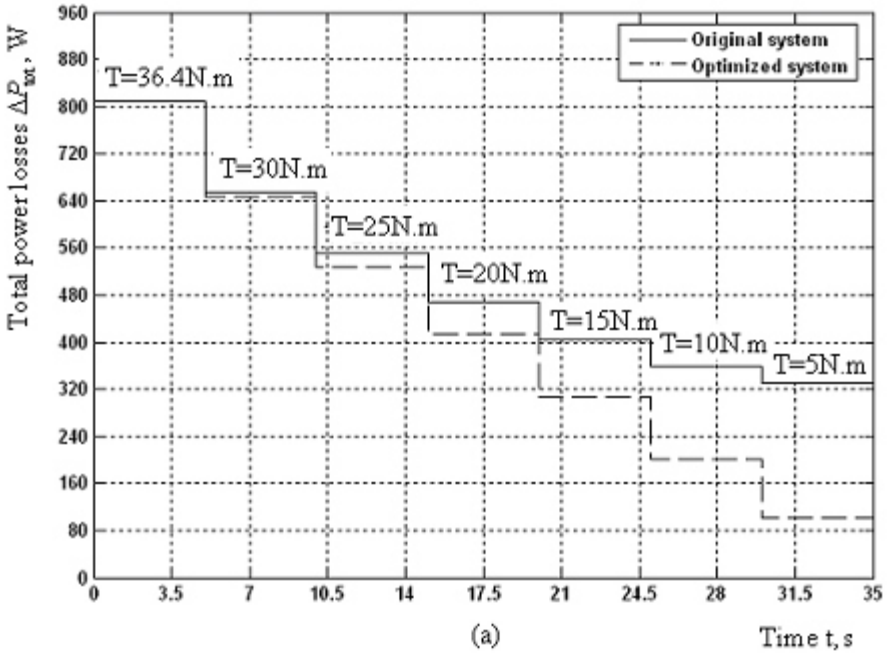


Fig. 7: Total power losses in original system and optimized system under variable frequencies (a) Load torque T = 25 N.m and (b) load torque T = 15 N.m



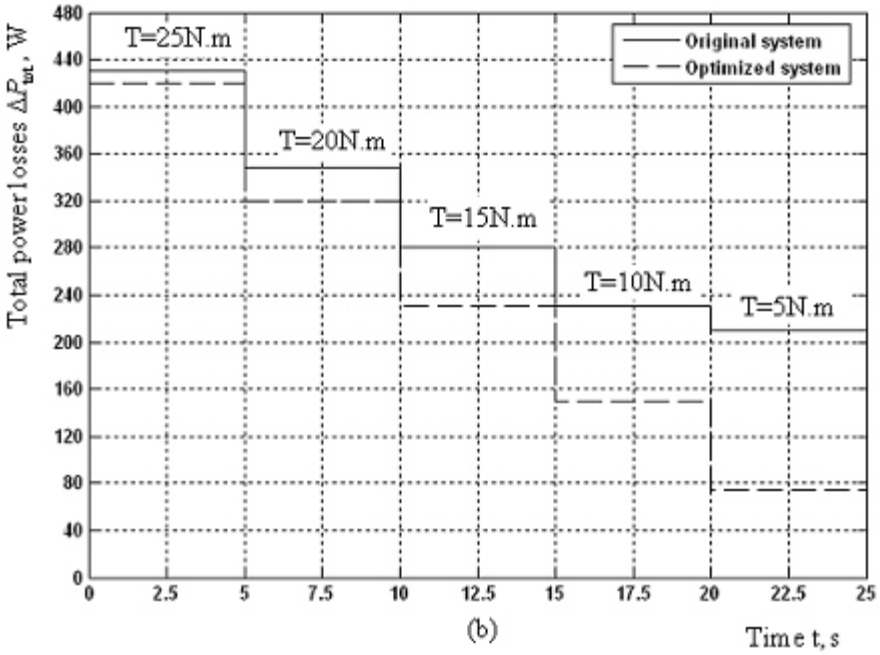


Fig. 8: Total power losses in original system and optimized system under variable loads (a) Frequency f = 50 Hz and (b) frequency f = 30 Hz

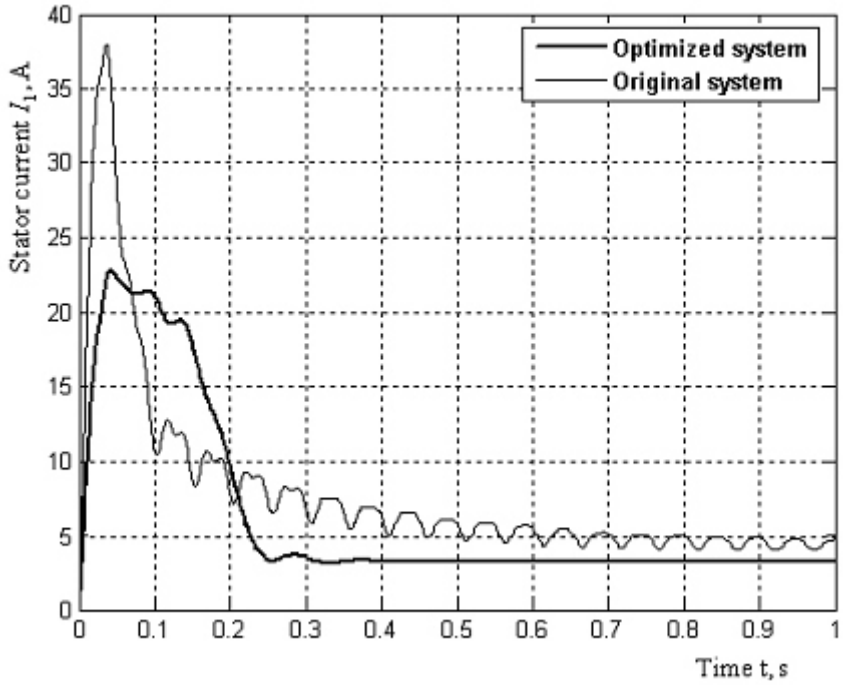


Fig. 9: Dynamic response of stator current at load torque T = 5 N.m and frequency f = 30 Hz

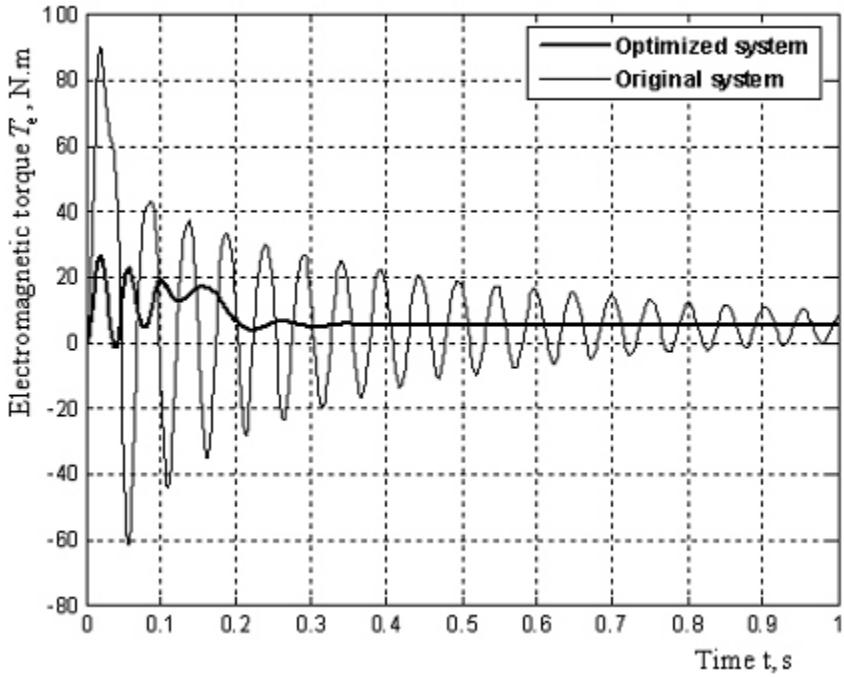


Fig. 10: Dynamic response of electromagnetic torque at load torque T = 5 N.m and frequency f = 30 Hz

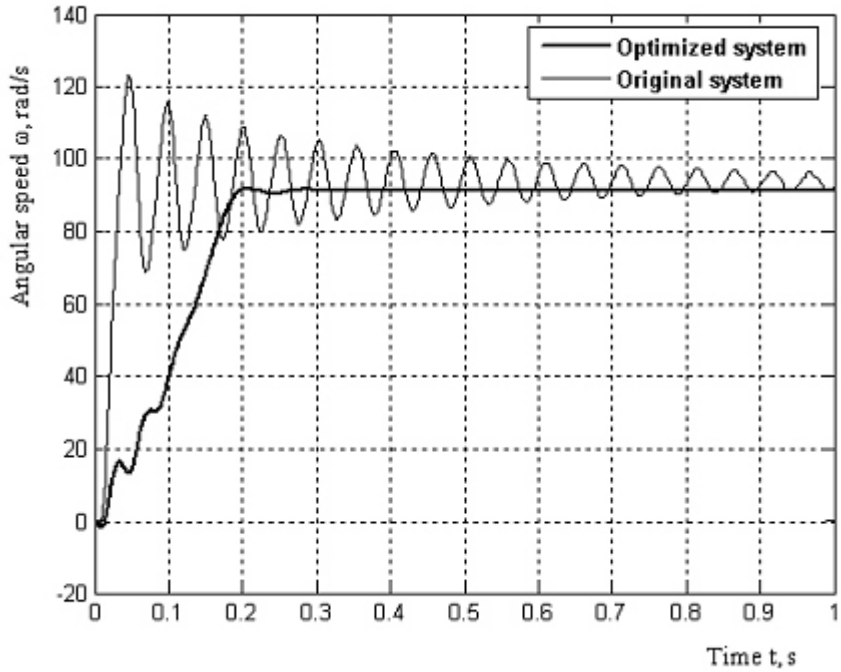


Fig.11: Dynamic response of angular speed at load torque T = 5 N.m and frequency *f* = 30 Hz

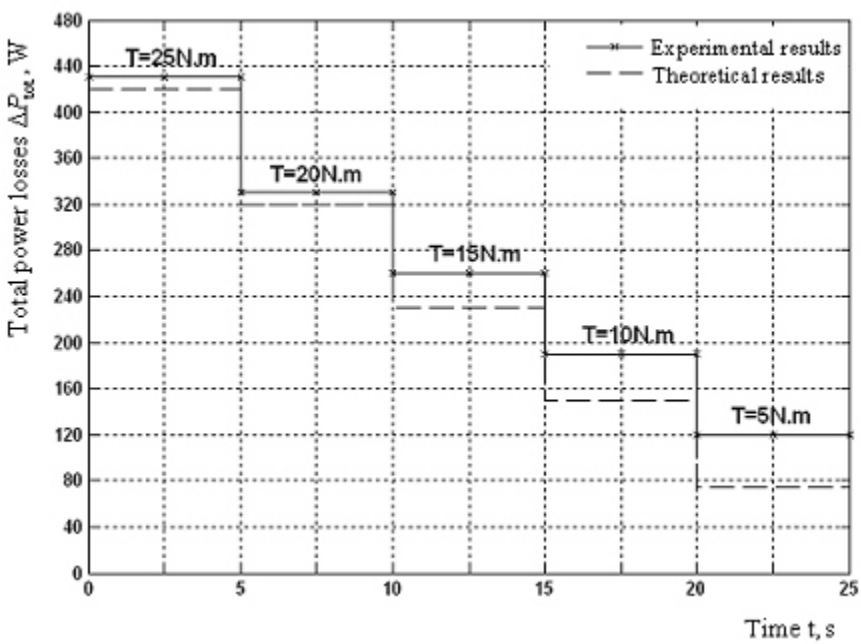


Fig.12: Experimental and theoretical power losses in the drive system for variable load torque and constant frequency 30 Hz

It is clear from Fig. 12 that there is some deviation between experimental and theoretical results. This is due to the assumptions and approximations done during loss model derivation and due to the losses in other components of the drive system.

CONCLUSION

In this research, the loss minimization in induction motor drive systems through the magnetic flux has been derived and examined. The control scheme utilizes

modulation index of IGBT-inverter-based AC to AC converter as the main control variable and manipulates the stator voltage in order for the motor to operate at its minimum-loss point. The proposed controller can be used in adjustable speed induction motor drive systems operating with variable loads. The total power losses can be decreased significantly at light loads. However, in some cases, slip compensation is required. Simulation results show that the dynamic performance of the optimized system has been improved.

NOMENCLATURE

ΔP_{tot} = Total power losses, W
R_1 = Stator resistance, Ω
R_2' = Rotor resistance referred to the stator, Ω
I_1 = Stator current, A
I_2' = Rotor current referred to the stator, A
I_0 = Magnetizing current, A
I_{0n} = Nominal magnetizing current
$\Delta p_{mag.n}$ = Magnetic losses at nominal operating conditions, W
$\varphi = \frac{\phi}{\phi_n}$ = Normalized (relative) flux, p.u
ϕ = Operating flux, Wb
ϕ_n = Nominal flux, Wb
$\alpha = \frac{f}{f_n}$ = Normalized (relative) frequency, p.u
f = Operating frequency, Hz
f_n = Nominal frequency, Hz
k = Coefficient depending on the type of steel used in core construction, usually = 1.3-1.5
$\mu = \frac{T}{T_n}$ = Normalized torque, p.u
T = Load torque, N.m
T_n = Nominal load torque, N.m
$P_{ag.n}$ = Nominal air-gap (electromagnetic) power, W
E_{1n} = Nominal e.m.f., V
P_{1n} = Nominal input power, W
I_{1n} = Nominal stator current, A
P_n = Nominal output power, W
ω_s = Synchronous speed, rad/s
a,b = Coefficients of analytical approximation of magnetization curve
V_n = Nominal stator voltage, V

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