EFFICIENCY OPTIMIZATION OF VECTOR-CONTROLLED INDUCTION MOTOR DRIVE

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ABSTRACT
This paper presents a new approach that minimizes total losses and optimizes the efficiency of a variable speed three-phase, squirrel-cage, vector-controlled induction motor drive through optimal control, based on combined loss-model control and search control. The motor power factor is used as the main control variable. An improvement of efficiency is obtained by online adjusting the stator current according to the value of power factor corresponding to the minimum total losses at a given operating point. The drive system is simulated using Matlab SIMULINK models. A PIC microcontroller is used as minimum loss power factor controller. Simulation results show that the proposed approach significantly improves the efficiency and dynamic performance of the drive system at all different operating conditions.

KEYWORDS: *Efficiency Optimization, Induction Motor Drive, Optimal Power Factor, Simulation, Vector Control.*

I. INTRODUCTION

Squirrel-cage three-phase induction motors IMs are the workhorse of industries for variable speed applications in a wide power range. However, the torque and speed control of these motors is difficult because of their nonlinear and complex structure. In general there are two strategies to control these drives: scalar control and vector control. Scalar control is due to magnitude variation of the control variable only. The stator voltage can be used to control the flux, and frequency or slip can be adjusted to control the torque. Different schemes for scalar control are used, such as: constant V/f ratio, constant slip, and constant air-gap flux control. Scalar controlled drives have been widely used in industry, but the inherent coupling effect (both torque and flux are function of stator voltage or current and frequency) give sluggish response and system is easily prone to instability [1-3]. To improve the performance of scalar-controlled drives, a feedback by angular rotational speed is used. However, it is expensive and destroys the mechanical robustness of the drive system. Performance analysis of scalar-controlled drives shows that scalar control can produce adequate performance in variable speed drives, where the precision control is not required. These limitations of scalar control can be overcome by implementing vector (field oriented) control.

Vector control was introduced in 1972 to realize the characteristics of separately-excited DC motor in induction motor drives by decoupling the control of torque and flux in the motor. This type of control is applicable to both induction and synchronous motors. Vector control is widely used in drive systems requiring high dynamic and static performance. The principle of vector control is to control independently the two Park components of the motor current, responsible for producing the torque and flux respectively. In that way, the IM drive operates like a separately-excited DC motor drive (where the torque and the flux are controlled by two independent orthogonal variables: the armature and field currents, respectively) [4-8].

Vector control schemes are classified according to how the field angle is acquired. If the field angle is calculated by using stator voltage and currents or hall sensors or flux sensing winding, then it is known as direct vector control DVC. The field angle can also be obtained by using rotor position measurement and partial estimation with only machine parameters, but not any other variables, such as voltages or currents. Using this field angle leads to a class of control schemes, known as indirect vector control IVC [1, 9].

From energetic point of view, it is well known that three-phase induction motors, especially the squirrel-cage type are responsible for most of energy consumed by electric motors in industry. Therefore, motor energy saving solutions by increasing its efficiency has received considerable attention during the last few decades due to the increase in energy cost. Energy saving can be achieved by proper motor selection and design, improvement of power supply parameters and utilizing a suitable optimal control technique [3-5, 10,11]

Induction motor operation under rated conditions is highly efficient. However, in many applications, when the motor works at variable speed, it has more losses and less efficiency, so it operates far from the rated point. Under these circumstances, it is not possible to improve the motor efficiency by motor design or by supply waveform shaping technique. Therefore, a suitable control algorithm that minimizes the motor losses will rather take place.

Minimum-loss control schemes have can be classified into three categories: search method, loss model, power factor control. The power factor control scheme has the advantage that the controller can be stabilized easily and the motor parameter information is not required. However, analytical generation of the optimal power factor commands remains tedious and restrictive because empirical, trial and error methods are generally used [4,5]. For this reason, search control using digital controllers is preferable.

In this paper, a combined minimum-loss control and search control approach is used to find the power factor, corresponding to the minimum losses in the drive system at a specified operating point. A PIC microcontroller is used as an optimal power factor controller to online adjust the stator current (voltage) to achieve the maximum efficiency of the drive system.

II. EFFICIENCY OPTIMIZATION OF VECTOR-CONTROLLED DRIVE SYSTEM

The generalized block diagram of vector-controlled induction motor drive is shown in Figure 1.

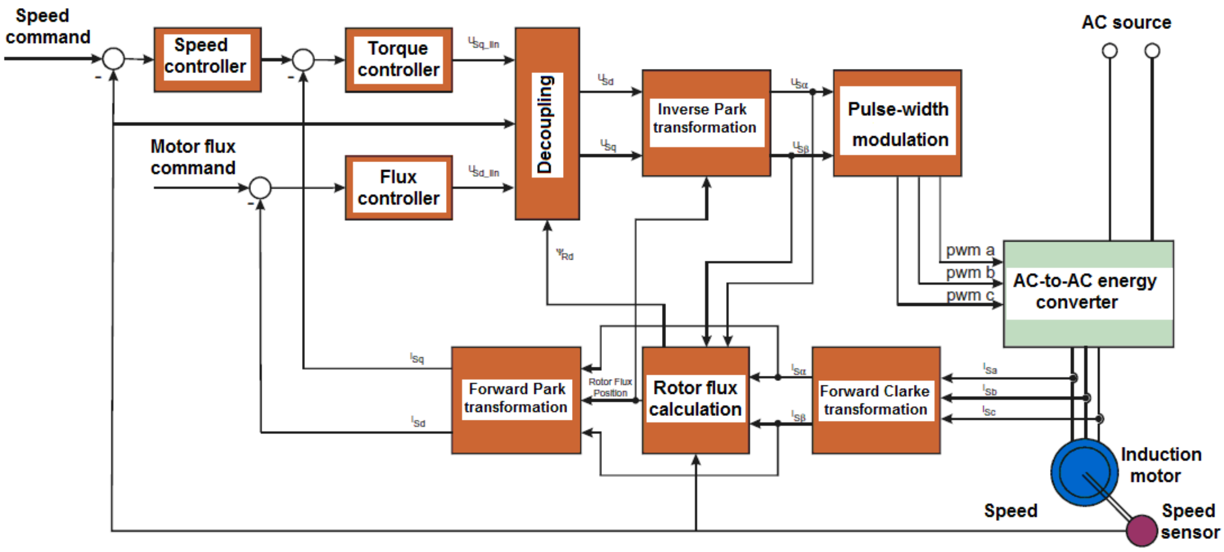

Figure 1. Generalized block diagram of vector-controlled induction motor drive.

To perform vector control, the following steps are required [1]:

1. Measurements of motor phase voltages and currents.
2. Transformation motor phase voltages and currents to 2-phase system (α, β) using Clarke transformation, according to the following equation:

$$i_{s\alpha} = k[i_{sa} - \frac{1}{2}i_{sb} - \frac{1}{2}i_{sc}],$$
$$i_{s\beta} = k\frac{\sqrt{3}}{2}(i_{sb} - i_{sc}) \quad (1)$$

where:

$i_{sa} =$ actual stator current of the motor phase A

$i_{sb} =$ actual stator current of the motor phase B

$i_{sc} =$ actual current of the motor phase C

$k = const$

3. Calculation of rotor flux space vector magnitude and position angle through the components of rotor flux.

4. Transformation of stator currents to $d-q$ coordinate system using Park transformation, according to:

$$i_{sd} = i_{s\alpha}\cos\theta_{field} + i_{s\beta}\sin\theta_{field},$$
$$i_{sq} = -i_{s\alpha}\sin\theta_{field} + i_{s\beta}\cos\theta_{field} \quad (2)$$

where θ_{field} is the rotor flux position.

The component i_{sd} is called the direct axis component (the flux-producing component) and i_{sq} is called the quadrature axis component (the torque-producing component). They are time invariant; flux and torque control with them is easy.

The values of $\sin\theta_{field}$ and $\cos\theta_{field}$ can be calculated by:

$$\sin\theta_{field} = \frac{\Psi_{r\beta}}{\Psi_{rd}},$$
$$\cos\theta_{field} = \frac{\Psi_{r\alpha}}{\Psi_{rd}} \quad (3)$$

where:

$$\Psi_{rd} = \sqrt{\Psi^2{}_{r\alpha} + \Psi^2{}_{r\beta}} \quad (4)$$

The rotor flux linkages can be expressed as:

$$\Psi_{r\beta} = L_r i_{r\beta} + L_m i_{s\alpha},$$
$$\Psi_{r\alpha} = L_r i_{r\alpha} + L_m i_{s\alpha} \quad (5)$$

5. The stator current torque- i_{sq} and flux- i_{sd} producing components are separately controlled.

6. Calculation of the output stator voltage space vector using decoupling block.

7. Transformation of stator space vector back from $d-q$ coordinate system to 2-phase system fixed with the stator using inverse Park transformation by:

$$i_{s\alpha} = i_{sd}\cos\theta_{field} - isq\sin\theta field,$$
$$i_{s\beta} = i_{sd}\sin\theta_{field} + i_{sq}\cos\theta_{field} \quad (6)$$

8. Generation of the output 3-phase voltage using space modulation.

The developed electromagnetic torque of the motor T can be defined as:

$$T = \frac{3}{4}P\frac{L_m}{L_r}\phi_{dr}i_{qs} \quad (7)$$

where P is the number of poles of the motor.

From Equation (7) it is clear that the torque is proportional to the product of the rotor flux linkages and *q*-component of the stator current. This resembles the developed torque expression of the DC motor, which is proportional to the product of the field flux linkages and the armature current. If the rotor flux linkage is maintained constant, then the torque is simply proportional to the torque producing component of the stator current, as in the case of the separately excited DC machine with armature current control, where the torque is proportional to the armature current when the field is constant.

The power factor *p.f* is also a function of developed torque, motor speed and rotor flux, and can be calculated as the ratio of input power to apparent power [3-4]:

$$p.f = \frac{v_{qs} i_{qs} + v_{ds} i_{ds}}{\sqrt{v^2_{qs} + v^2_{ds}}\sqrt{i^2_{qs} + i^2_{ds}}} \qquad (8)$$

The power factor can be used as a criterion for efficiency optimization. The optimal power factor corresponding to minimum power losses in the drive system can be found analytically or by using search method of control. To avoid tedious analytical calculations of power factor, a search control is implemented in this paper. The stator voltage is incrementally adjusted until the controller detects the minimum total losses at a given operating point. The total power losses $\sum\Delta P$ can be calculated as the difference between the input power P_{in} and the output mechanical power P_{out}:

$$\sum\Delta P = \frac{3}{2}(v_{qs} i_{qs} + v_{ds} i_{ds}) - T\omega \qquad (9)$$

The block diagram of proposed efficiency optimization system for vector-controlled induction motor is shown in Fig. 2. The system consists of 400V,4kW, 1430 rpm, 50Hz three-phase, squirrel-cage induction motor. The motor is fed from three phase AC-to-AC energy converter, based on voltage controlled pulse-width modulated inverter. A PIC 16f877A microcontroller is used as a controller in the system.

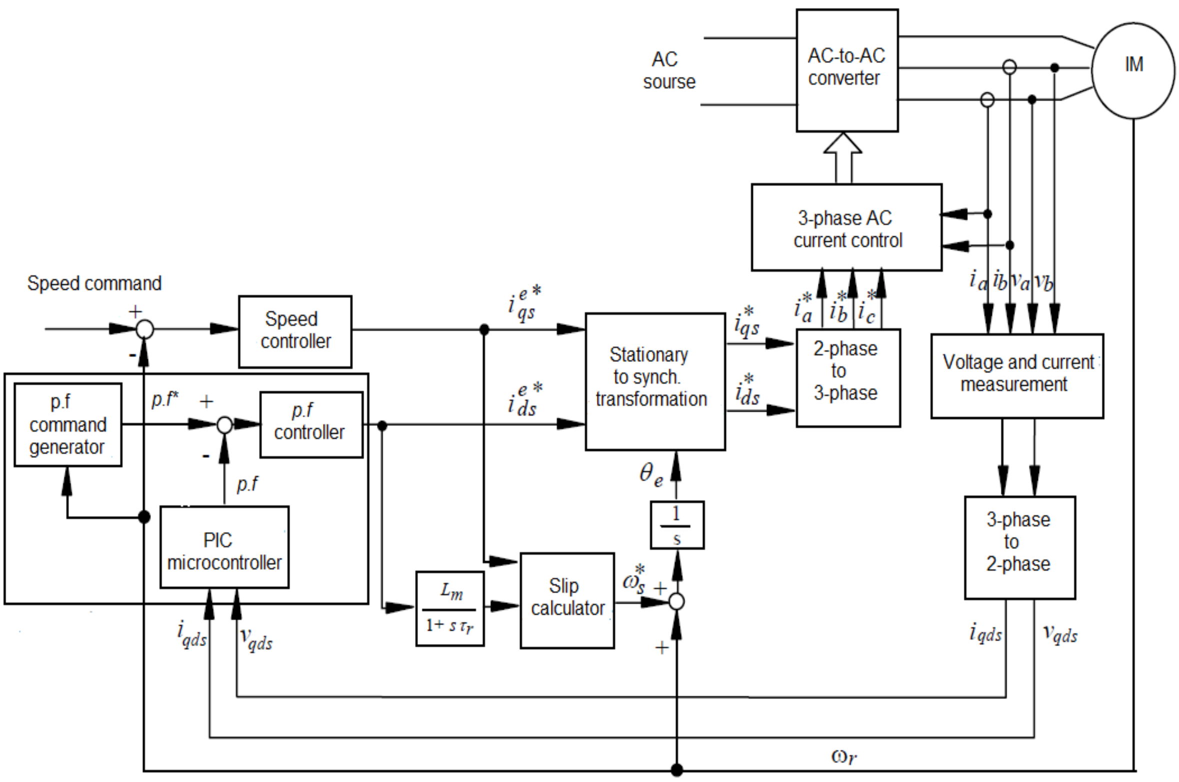

Figure 2. Block diagram of vector-controlled optimized system.

To investigate the proposed optimized system, two Matlab SIMULINK models were constructed. The first model, which is shown in Figure 3, represents the original vector-controlled drive system without efficiency optimization. The second model, Figure 4, illustrates the efficiency-optimized, vector-controlled system.

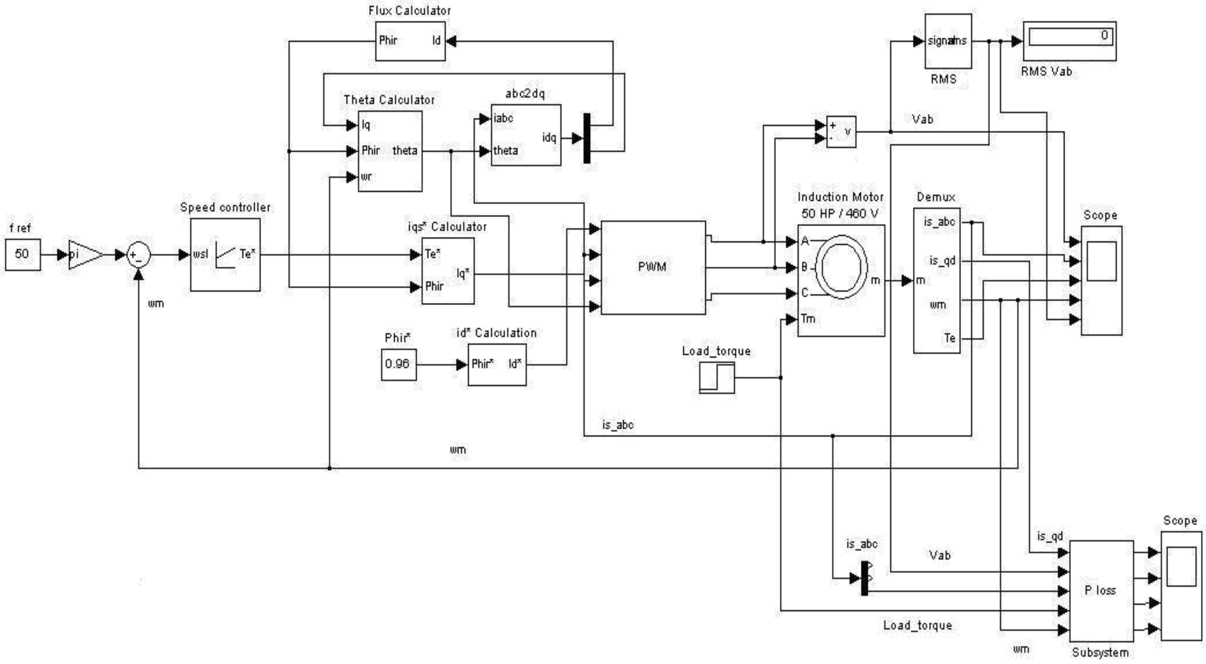

Figure 3. Matlab SIMULINK model of vector–controlled drive system.

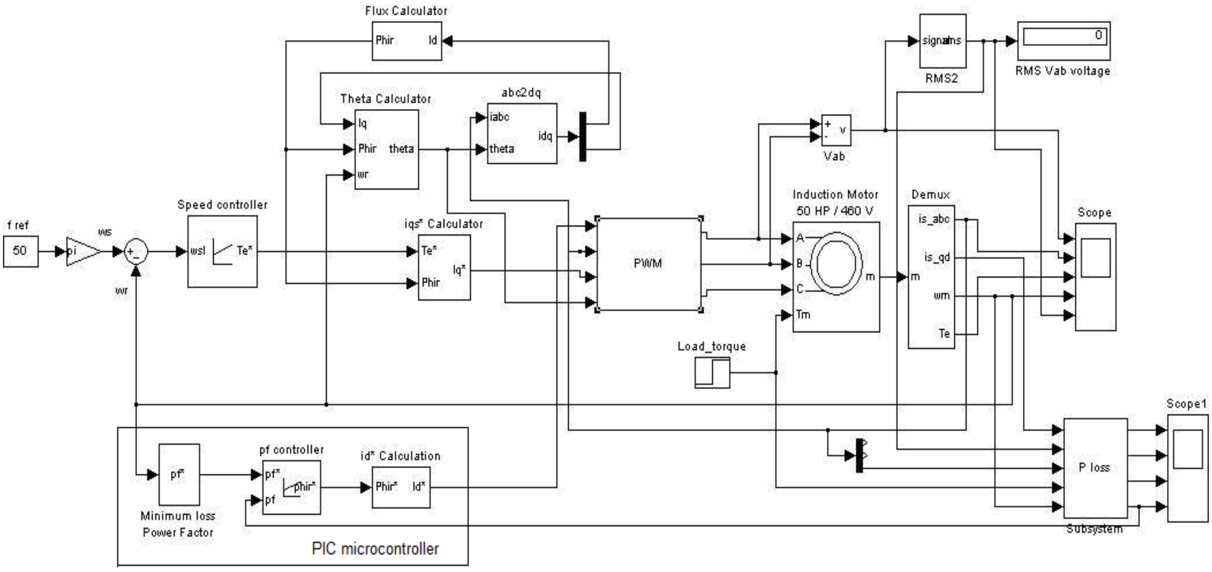

Figure 4. Matlab SIMULINK model of efficiency-optimized, vector-controlled drive system.

The PIC microcontroller was linked to the Matlab model by interface circuit shown in Figure 5.

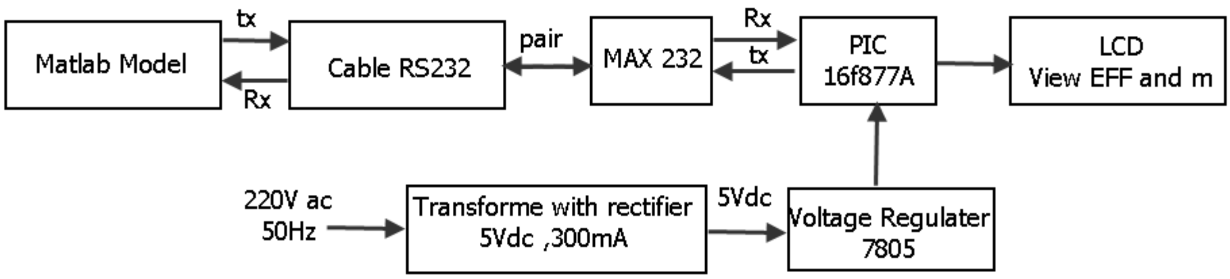

Figure 5. Block diagram of interface circuit between Matlab model and PIC microcontroller model.

III. Simulation Results

To show the effect of proposed efficiency optimization technique based on power factor optimization, a comparative analysis between original drive system and optimized one has been done. Investigation was provided under the same operating conditions: frequency (speed) and load torque. Figures (6-8) show the relationship between efficiency and load torque under constant frequency.

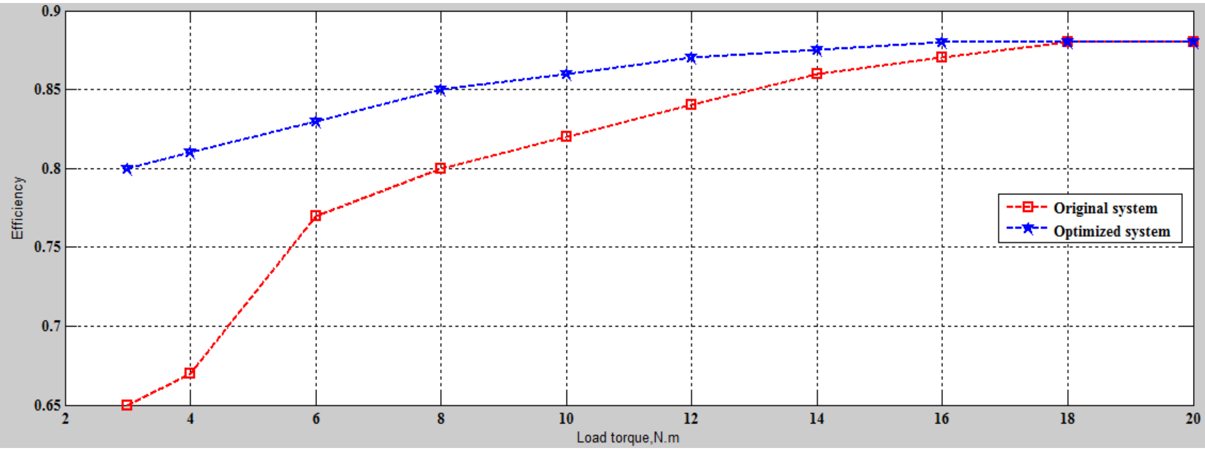

Figure 6. Relationship between efficiency and load torque at constant frequency $f = 50Hz$.

It is clear that the implemented efficiency optimization technique improves the efficiency of the drive system for the whole frequency range. Improvement is significant at light loads.

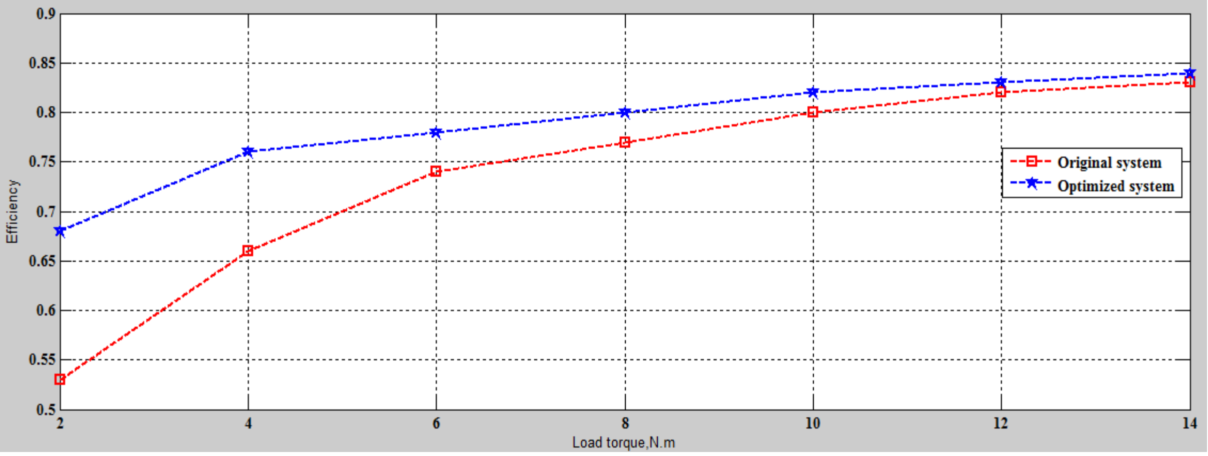

Figure 7. Relationship between efficiency and load torque at constant frequency $f = 35Hz$.

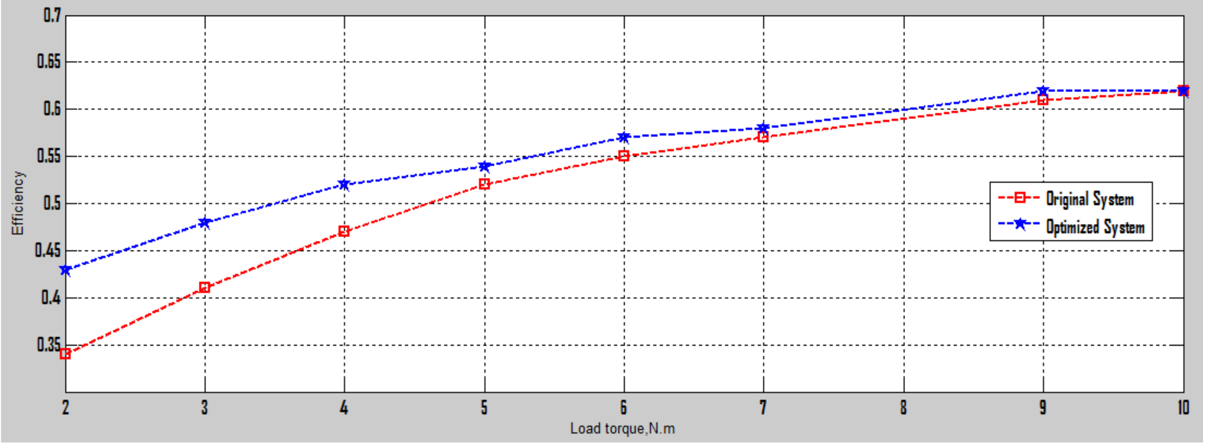

Figure 8. Relationship between efficiency and load torque at constant frequency $f = 15Hz$.

The relationship between efficiency and frequency at constant load torque is presented in Figures (9-10). At light load torques the efficiency improvement is very significant for the whole frequency range.

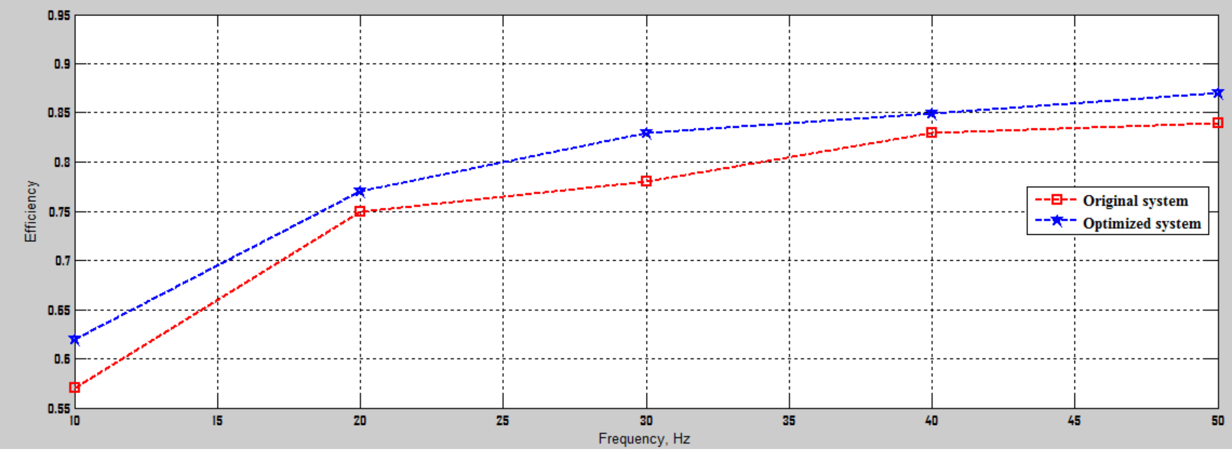

Figure 9. Relationship between efficiency and frequency at constant load torque $T = 12N.m$

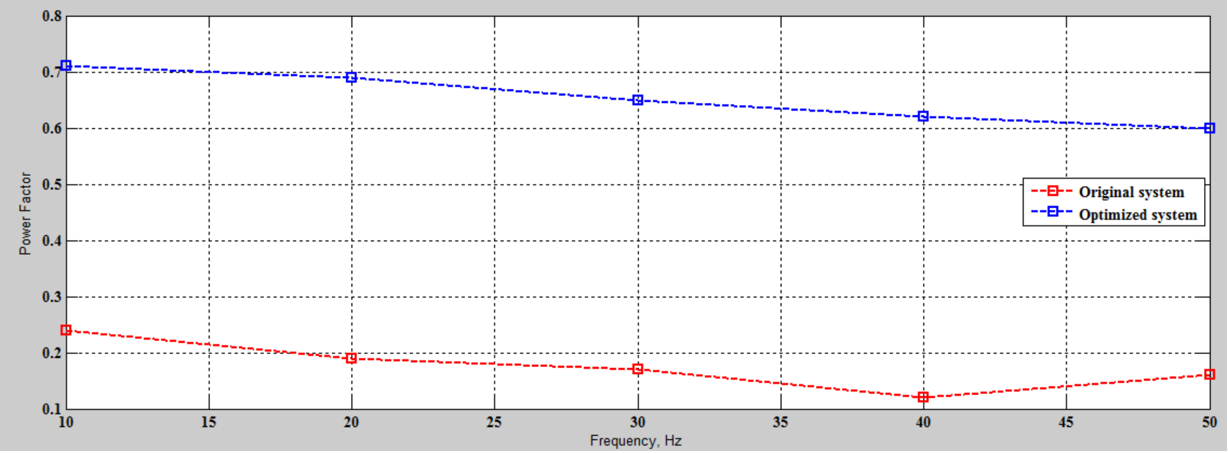

Figure 10. Relationship between power factor and frequency at constant load torque $T = 2N.m$

Figure (11) is an example of the relationship between power factor and frequency at constant load. It is clear that the optimized system has better power factor for all frequencies.

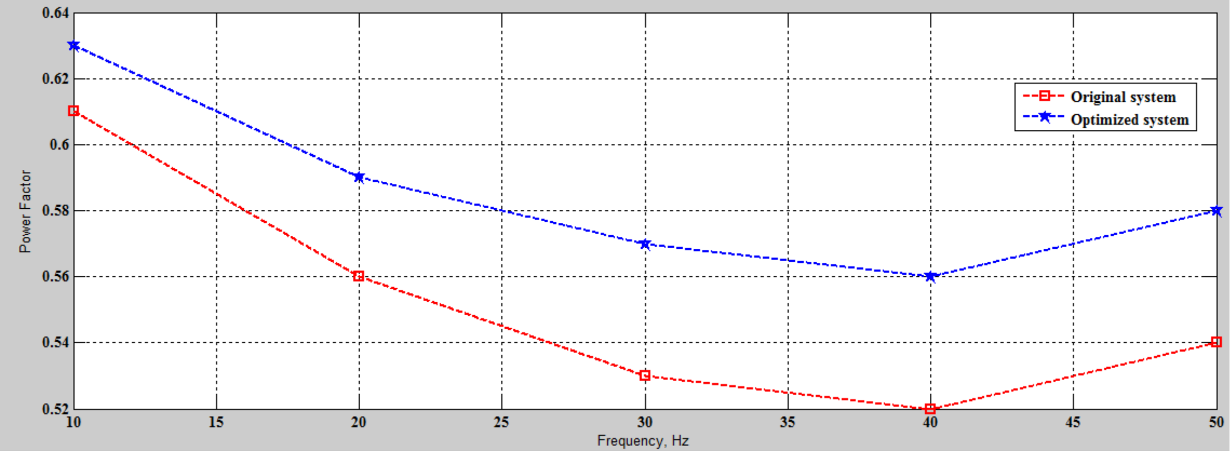

Figure 11. Relationship between power factor and frequency at constant load torque $T = 10N.m$

It was noticed that the dynamic response of the optimized system has been improved. The oscillations in electromagnetic torque and angular speed disappeared and the response becomes faster. Examples of dynamic response at load torque $T = 5\text{N.m}$ and frequency $f = 30\text{Hz}$ are shown in Figures (12, 13).

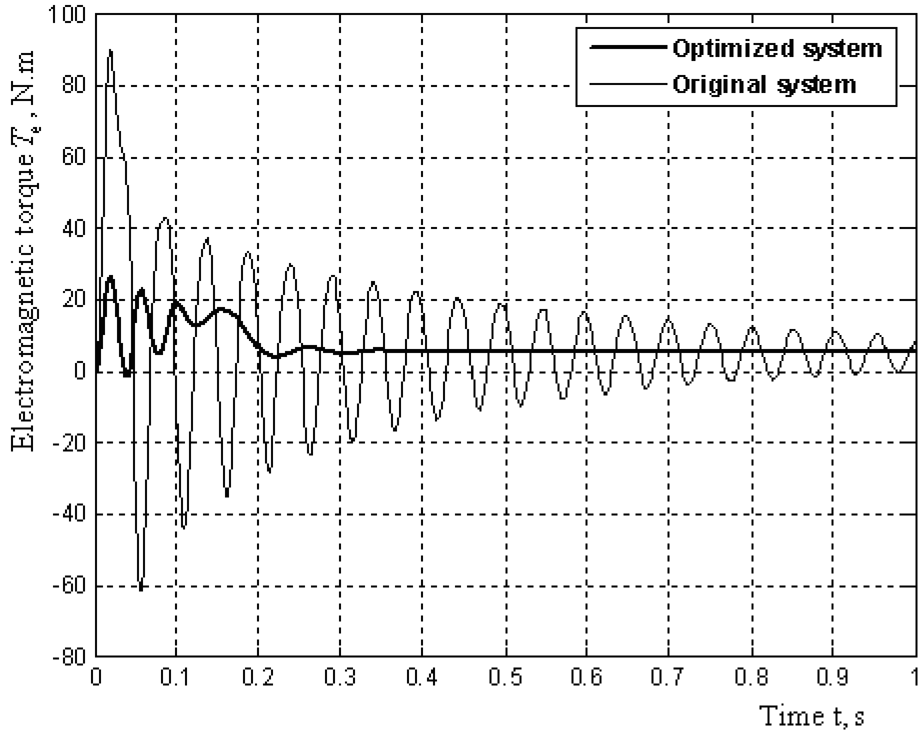

Figure 12. Dynamic response of electromagnetic torque at load torque $T = 5\text{N.m}$ and frequency $f = 30\text{Hz}$.

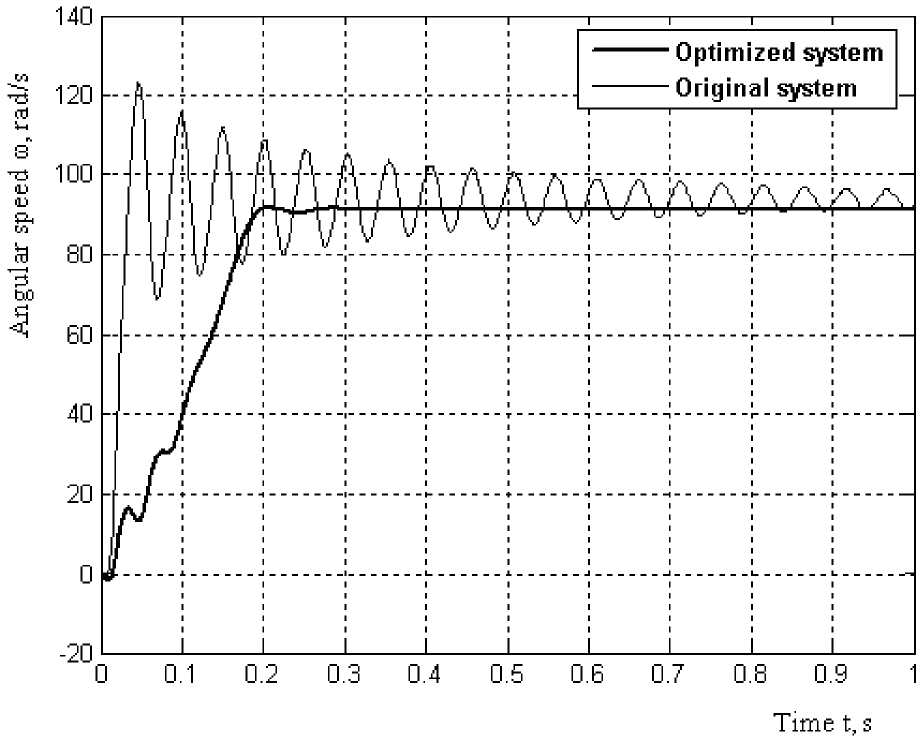

Figure 13. Dynamic response of angular speed at load torque $T = 5\text{N.m}$ and frequency $f = 30\text{Hz}$.

IV. CONCLUSIONS

An online efficiency optimization control technique based on detecting optimal power factor, which minimizes the total operational power losses in vector-controlled induction motor drive is proposed in this paper. The power factor is used as the main control variable and manipulates the stator current in order for the motor to operate at its minimum-loss point. Simulation results show that the implemented method significantly improves the efficiency and dynamic performance of the drive system, especially when the system operates at light loads and low frequencies.

V. FUTURE WORK

The obtained simulation (theoretical) results should be experimentally tested and validated for industrial drive systems, operating at variable speeds with different load types. Also, the results should be compared with that, for scalar-controlled drive system to insure that vector control approach gives better results and ease to implement.

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