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Energy Saving of AC Voltage Controller Fed Induction Motor Drives Using Matlab/Simulink

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Abstract

This paper describes a MATLAB/Simulink realization of AC Voltage Controller Fed Induction Motor Drives. An attractive approach of RL model of induction motor is proposed. The proposed simulation model is checked by experimental work. Also energy saving is presented by controlling the voltage applied to the stator winding using the three phase AC voltage controller. An optimization model of the problem is presented and optimum SCR firing angle is identified. Computed results on induction motor show the effectiveness of the proposed algorithm.

Index Terms: Matlab/Simulink, induction motor drive, three phase AC voltage controller.

Introduction

There has been a growing global concern over energy consumption and high energy efficiency has become one of the most factor in the development of the products that consume electrical energy. Considering the fact that more than 50% of electrical energy produced is consumed by electric machines-mainly by induction machines- [1,2]. Three-phase, squirrel-cage induction motors are more than 90% of the electrical motors used in industry [3],

The average load factor of electric motors in the industrial sector is estimated to be in the of 60%to 25% according to the European Union. So a load alternates between near-full-load (e.g., more than 75% of full load) and very low load (e.g., less than 30% of full load) during their duty cycle. The reduction of both the efficiency and the power factor of the motors is the results of these situations. Conveyors, Escalators, Lifts, Mixers, Fans, Pumps, High-Inertia saws, Presses and etc. are variable-load applications, in this application the motor can have low-load operating periods in which the efficiency and power factor can be significantly low [4]. Both efficiency and power factor of the motors can be improved significantly in the low-load operating period, if the stator winding voltage is properly regulated.

On an average, 60–100 times is the ratio between the energy consumed by an induction motor during its life cycle to the initial cost of the motor. Fig. 1 shows the average main loss distribution in an induction motor [5].

In small-size induction motors , core losses generated constitute a significant part of total losses in such machines. Important factor in the case of energy saving motors is accurate determination of these losses[2].

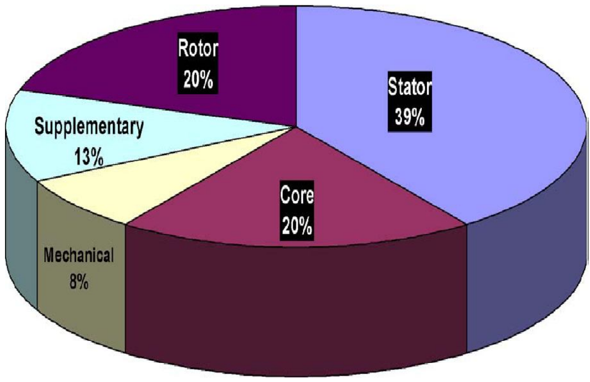


Fig. 1 The average main loss distribution in an induction motor

The stator voltage control of induction motor is achieved by using AC voltage controller, in between the motor terminals and power supply. The stator voltage is controlled between zero and full value by symmetrically controlling, SCR firing angle smoothly at line frequency[6].

Due to the recent developments achieved in the power electronics fields, such as control techniques and microprocessors have introduced such AC voltage controllers for the applications of power ranges from few watts up to fractions of megawatts[7].

In this paper, a simple but effective method for energy saving of ac motor is introduced. The proposed method is based on an optimal efficiency control which is operated by SCR firing angle as to maintain the maximum efficiency on the output characteristics of the motor. Initially an investigation has been carried out to find the effect of SCR firing angle, α on the profile of input voltage at different loads.

The author has found that this SCR firing angle is a function of motor parameters and motor slip hence varies largely with each motor load. This paper aims to bring a unified approach for identification of SCR firing angle which leads to least losses. As a first step towards this, an optimization framework for the problem at hand is developed and then optimum SCR firing angle is obtained by using Matlab/Simulink model of AC Voltage Controller Fed Induction Motor Drive.

I. ***Proposed Model of three Phase Induction Motor***

By using reference frame theory, a detailed analysis for induction machine has been carried out in [8]. So the variation of the torque and currents with the variation of input voltage can easily obtained. In this paper modeling of induction motor has been carried out by reducing its equivalent circuit to be *R-L* load. Then, MATLAB/ SIMULINK has been used to obtain all performance parameters in terms of its firing angle.

A. Core losses of Induction Motor:

The exact equivalent circuit of a three phase induction motor is shown in Fig.2.

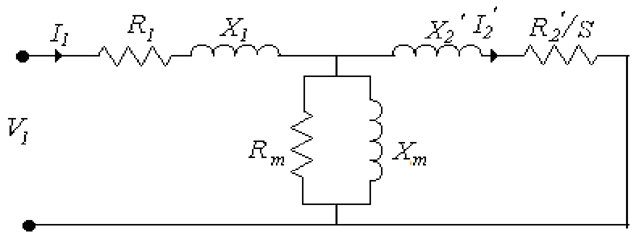


Fig. 2 Equivalent circuit of a three phase induction motor.

The simulation of three-phase induction motor has been carried out by using MATLAB 7.10.0 computer program. Intensive simulation has been carried out for different supply voltage to determine the core losses variation of this motor. The nameplate motor data used is shown below:

2 HP, Δ / Y, 380 / 660 V, 3.5 / 2 A, 50 Hz. 4 poles, 1500 rpm, R_1 = 23 Ω, R_2 = 7.37 Ω, X_1 = 44 Ω, X_2 = 44Ω, X_m = 377 Ω and R_m= 1432 Ω.

The variation of core losses with motor speed for different values of supply voltage is shown in Fig.3. It is clear that the core losses is approximately linear and directly proportional to the motor speed. Also the core losses is proportional to the square of the supply voltage.

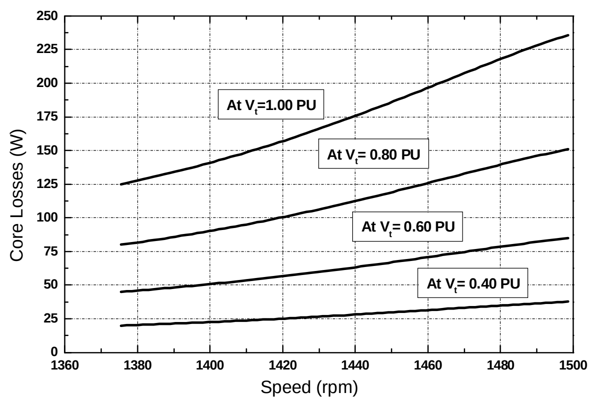


Fig. 3 The variation of core losses with motor speed for different values of supply voltage

So the core losses can be expressed as follow;

$$P_C = \left(\frac{V_a}{V_r}\right)^2 (69966 - 144.7\,N + 0.1\,N^2 - 0.000023\,N^3) \tag{1}$$

Where; V_a : is the applied line voltage in volt

V_r : is the rated line voltage which equal 660 V

N : is the motor speed in rpm

The modeling of the core losses expression is done by simulation in Matlab Simulink environment as shown in Fig. 4

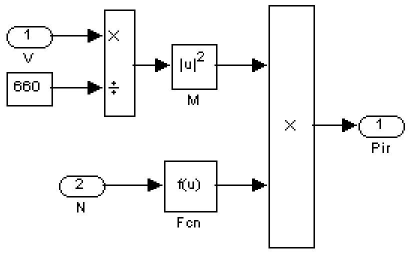


Fig. 4 The block diagram of core losses expression

B. R-L Model of Induction Motor:

The exact equivalent circuit of a three phase induction motor can be reduced to the IEEE-recommended equivalent circuit by ommiting core losses resistance.

The total impedance can be express as shown in (2). This equation can be reduced to be just R and L elements in terms of slip as shown in (3) and (4) respectively.

$$Z_t = Z_1 + \frac{JX_m * Z_2}{JX_m + Z_2} \tag{2}$$

$$R_t = R_1 + \frac{{X_m}^2\, R_2/S}{(R_2/S)^2 + (X_m + X_2)^2} \tag{3}$$

$$X_t = X_1 + \frac{X_m (R_2/S)^2 + X_m X_2 (X_m + X_2)}{(R_2/S)^2 + (X_m + X_2)^2} \tag{4}$$

As the total impedance of the motor are found, it could be represented by MATLAB/ SIMULINK as shown in Fig.5,

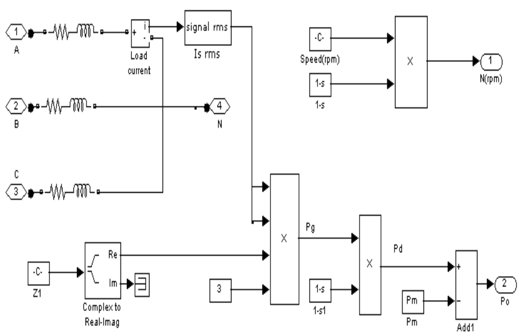


Fig. 5 The block diagram of RL model.

C. Proposed Model of Induction Motor:

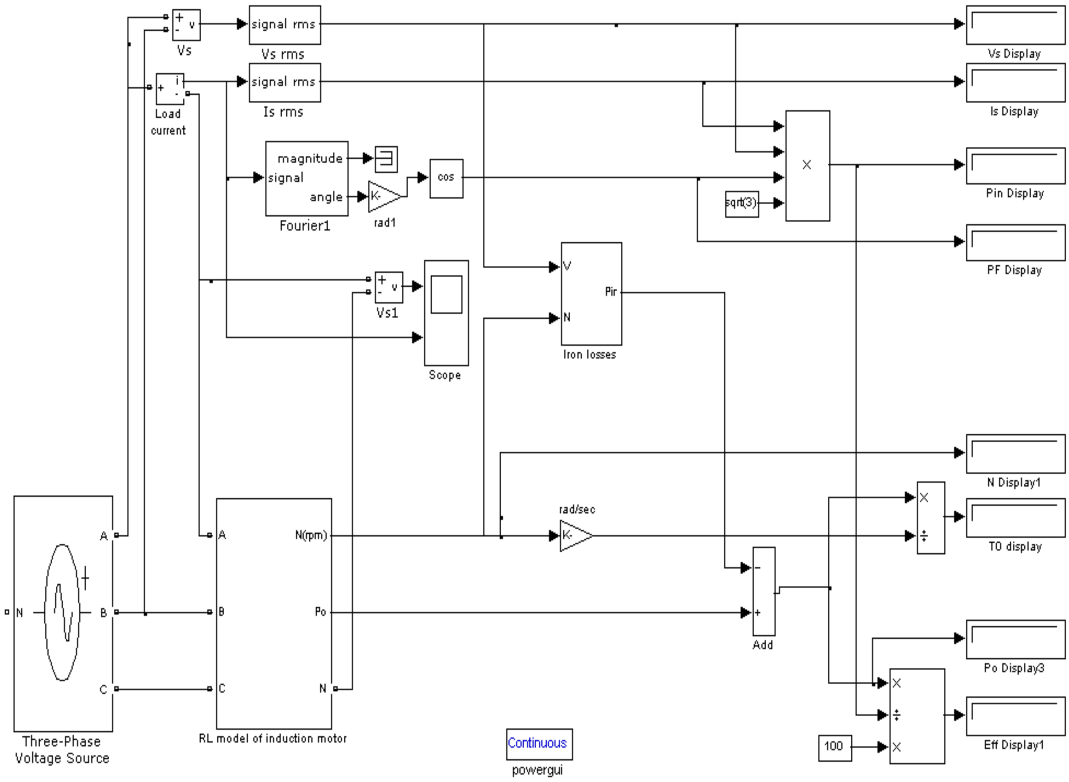


Fig. 6 The block diagram of the Induction Motor Model.

As the total impedance of the motor and core losses expression are found, it could be represented by MATLAB/ SIMULINK as shown in Fig.6, which is investigated by comparing the simulation result with experimental work as shown in Fig.7, Fig.8 and Fig. 9.

Fig. 7 shows the variation of motor speed with load torque, also Fig. 8 shows the variation of stator phase current with load torque. And Fig. 9 shows the variation of efficiency with load torque.

These figures clearly illustrate the great acceptance of our proposed model results .

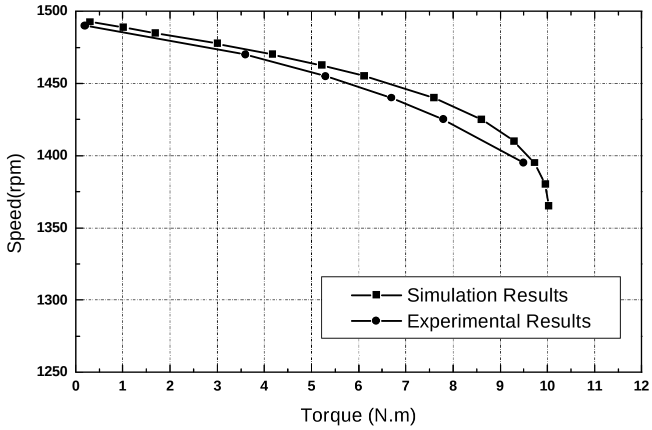


Fig. 7 The variation of motor speed with load torque with the experimental results

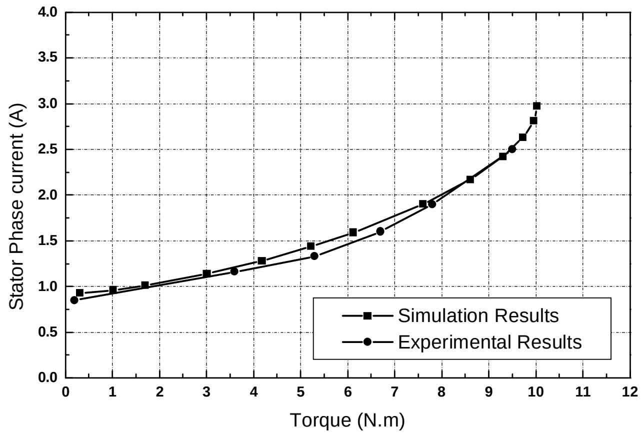


Fig. 8 The variation of stator current with load torque

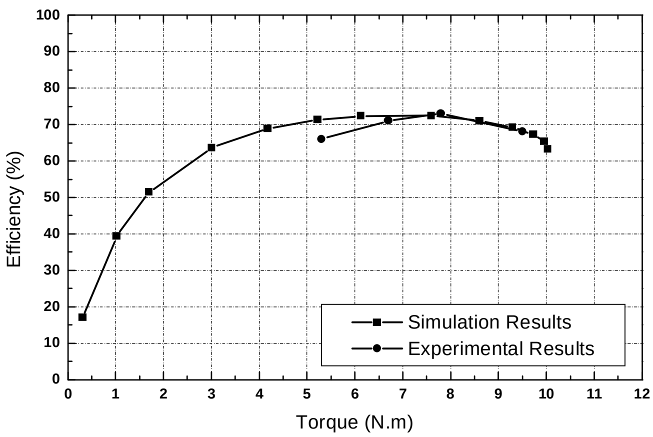


Fig. 9 The variation of efficiency with load torque

II. ***Simulation of Ac Voltage Controller – Fed Induction Motor Drive***

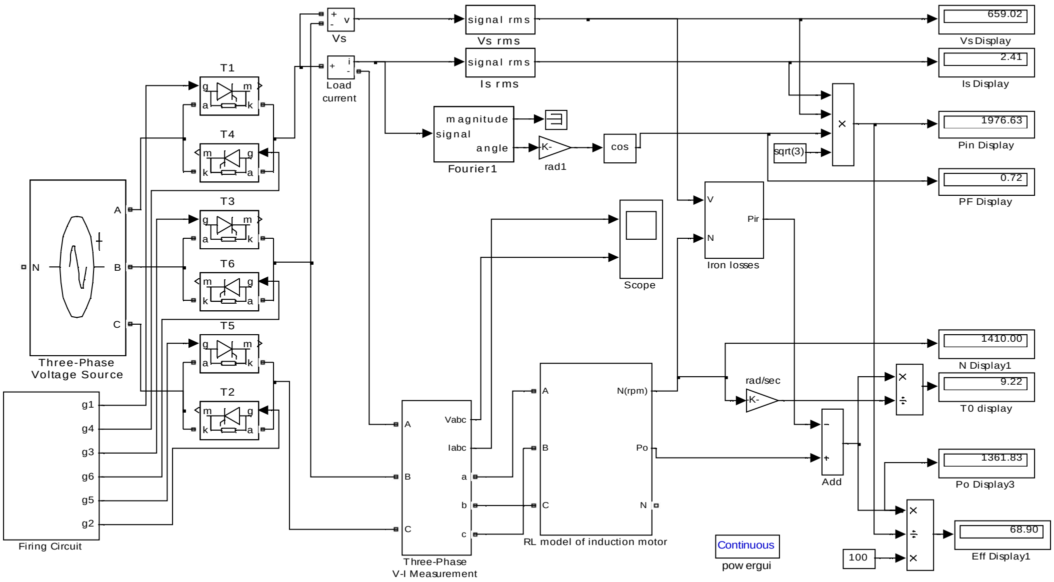


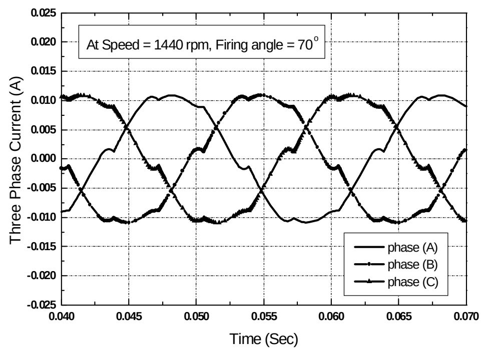
Fig. 10 The block diagram of the AC Voltage Controller Fed Induction Motor Drives

Many papers analyzed and simulated the 3-phase AC controller under induction motor load to obtain mathematical and programmable form for the variation of torque, speed and line currents along with firing angle.

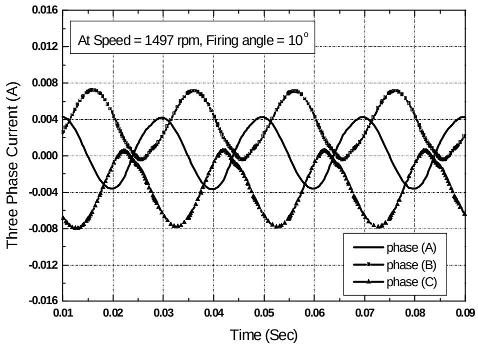
In this paper, the modeling of the whole drive system is done by simulation in Matlab/Simulink environment. The block diagram of the whole drive is as shown in Fig. 10

A. Different Modes of Drive Operations:

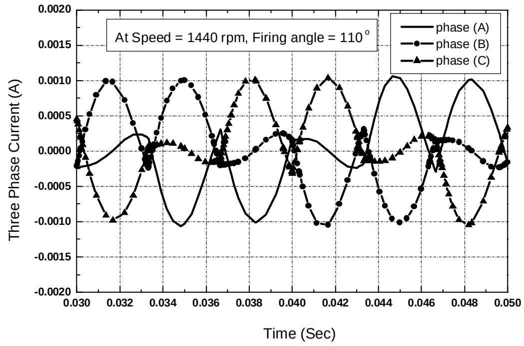
The operation analysis of the AC voltage controller fed induction motor drives depend on the relative values of firing and phase angles. Different modes of operations, namely, mode 2/3, mode 0/2/3 or mode 0/2 will appear in the system works due to different relative values of firing and phase angles [9]. Fig.11 shows the simulation results of the three phase supply current for different modes of operations.



(a) Three-phase currents for 0/2/3 mode.



(b) Three-phase currents for 2/3 mode.



(c) Three-phase currents for 0/2 mode.

Fig.11 Three-phase currents for different modes of operations.

From the simulation results, different modes of operations can be obtained for firing angle ranges which are summarized as shown in Table(1)[10]. It is clear that the mode 2/3 has near sinusoidal current waveform , also for the same speed ;as the firing angle increases the operation mode will be changed form 2/3 to 0/2.

Table(1) Firing angle ranges for operation modes.

Firing angle range	Operation mode
$0 \le \alpha \le \Phi - \pi/3$	0/2
$\Phi - \pi/3 \le \alpha \le \Phi_1$	0/2/3
$\Phi_1 \le \alpha \le \Phi + \pi/3$	2/3
$\Phi + \pi/3 \le \alpha \le 2\pi/3$	0/3/2
$2\pi/3 \le \alpha \le 7\pi/6$	0/2

Where:

α : The firing angle.

Φ : The overall motor power factor angle

Φ_1 : The fundamental motor power factor angle

B. Drive Performance Characteristics:

The performance characteristics of the drive is investigated by carrying out the simulation under that constant firing angle variable speed. Three different values of firing angle have been used. These values are 90^o,70^o and 50^o respectively. The speed has been used as independent variable and changed from 0.7 pu to 1 pu (as the stability region until 0.085 pu) . The variation of line voltage with speed for different values of firing angle is shown in Fig.12. It is clear that the line voltage is inversely proportional to speed at low speed and is directly proportional to speed near to synchronous speed. Line voltage is high for low firing angle and vice versa.

The variation of torque with speed for different values of firing angle is shown in Fig.13. The motor torque is directly proportional to speed at low speed and inversely proportional to speed near to synchronous speed. It is clear that the maximum torque increases with decreasing the firing angle values

The variation of power factor with speed for different values of firing angle is shown in Fig.14. The power factor is directly proportional to speed at low speeds and inversely proportional to speeds near to synchronous speed. It is clear that the maximum power factor increases with decreasing the firing angle values.

The variation of stator current with speed for different values of firing angle is shown in Fig.15. The stator current is inversely proportional to speed at low speed and near to synchronous speed. It is clear that the stator current increases with decreasing the firing angle values.

The variation of efficiency with speed for different values of firing angle is shown in Fig.16. It is clear that the efficiency is approximately same in each motor speed for low firing angle and decreases for high firing angle due to the drive is forced to work in 0/2 mode which is characterized by low efficiency and higher S_{max}. Also it is clear that the efficiency increases with decreasing the firing angle values.

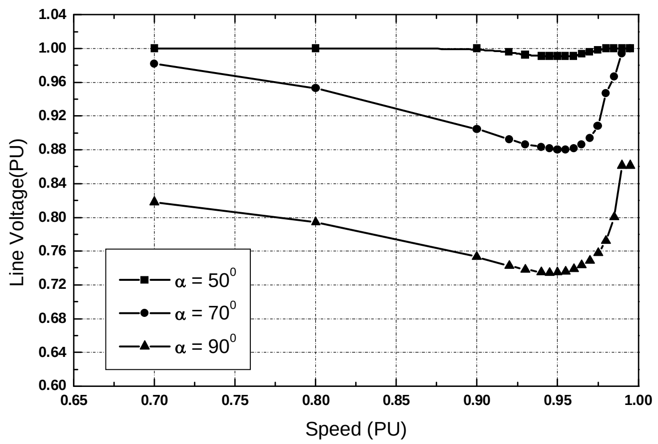


Fig.12 The variation of line voltage with motor speed for different values of firing angle.

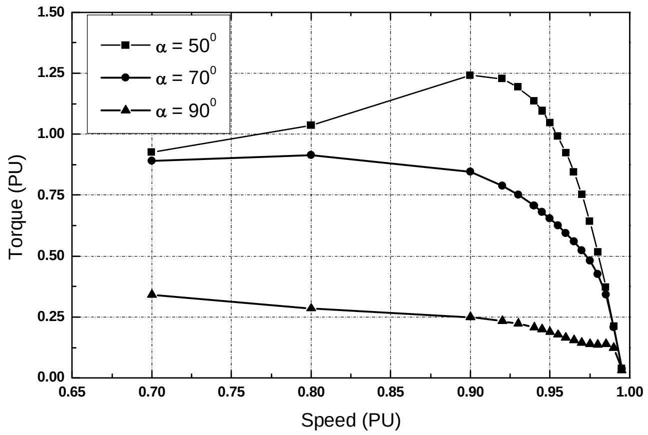


Fig.13 The variation of motor torque with motor speed for different values of firing angle.

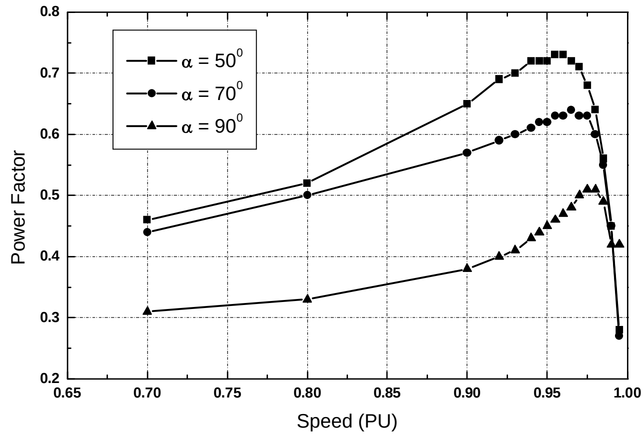


Fig.14 The variation of motor power factor with motor speed for different values of firing angle.

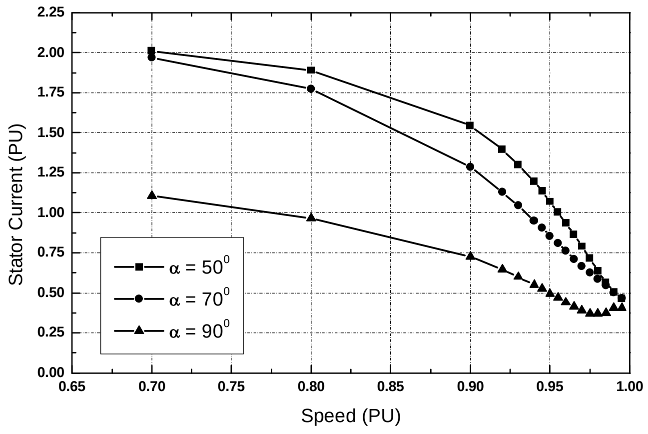


Fig.15 The variation of stator current with motor speed for different values of firing angle.

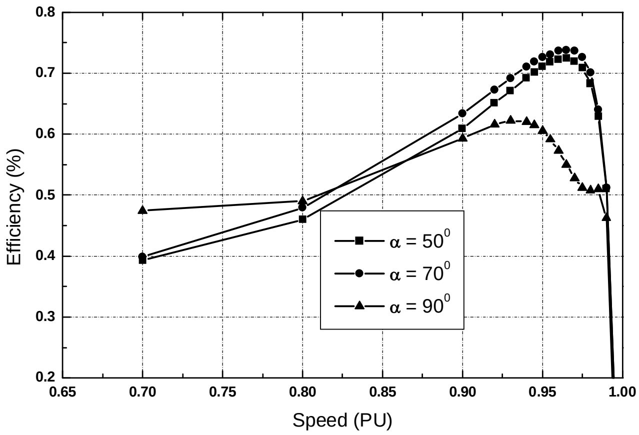


Fig.16 The variation of motor efficiency with motor speed for different values of firing angle.

III. Energy Saving Operation

A. Maximum Efficiency Conditions:

The exact equivalent circuit of a three phase induction motor can be reduced to the approximate equivalent circuit by shifting the core losses resistance and magnetizing to the input terminals.

The condition of maximum efficiency can be express as shown in (5). This equation can be reduced to be just motor parameters in terms of slip as shown in (6) and (7) respectively.

$$P_{constant\ losses} = P_{Variable\ losses} \tag{5}$$

$$3\,V_1{}^2 /\ R_m = 3I_2^{`\,2}(R_1 + R_2^{`}) \tag{6}$$

$$\frac{3\,V_1{}^2}{R_m} = \frac{3\,V_1{}^2\,R_2/S}{(R_1+(R_2/S))^2+(X_1+X_2)^2} \tag{7}$$

So, the slip that the maximum efficiency occurs is expressed as follow in (8);

$$\therefore\ S_{m\eta} = \frac{R_2^{`}}{\sqrt{(R_m(R_1+R_2^{`}))+(X_1+X_2^{`})^2} - R_1} \tag{8}$$

From the previous equation, it is clear that the maximum efficiency occurs at slip value which depends on the motor parameters and equal 0.036 at speed 1446 rpm.

B. Drive Performance Characteristics at optimum speed:

The performance characteristics of the drive at energy saving operation is investigated by carrying out the simulation under the optimum speed (around 1446 rpm). Different values of firing angle have been used.

The variation of firing angle with motor torque, speed and efficiency for energy saving operation are shown in Fig.17. It is clear that to achieve energy saving operation, the speed is fixed (1446 rpm) for low firing angle (until 75 ^{o}) and decreases for high firing angle due to the drive is forced to work in 0/2 mode which is

characterized by low efficiency , so it is better to decrease speed to work in 2/3 mode. Also, It is clear that to achieve energy saving operation, the firing angle increases as the load torque decreases.
The efficiency is approximately constant for low firing angle and decreases for high firing angle due to optimum speed decreasing to work in 2/3 mode instead of 0/2 mode.
From Fig.17 a feedback controller is constructed to feed the drive with optimum firing angle according to load torque.

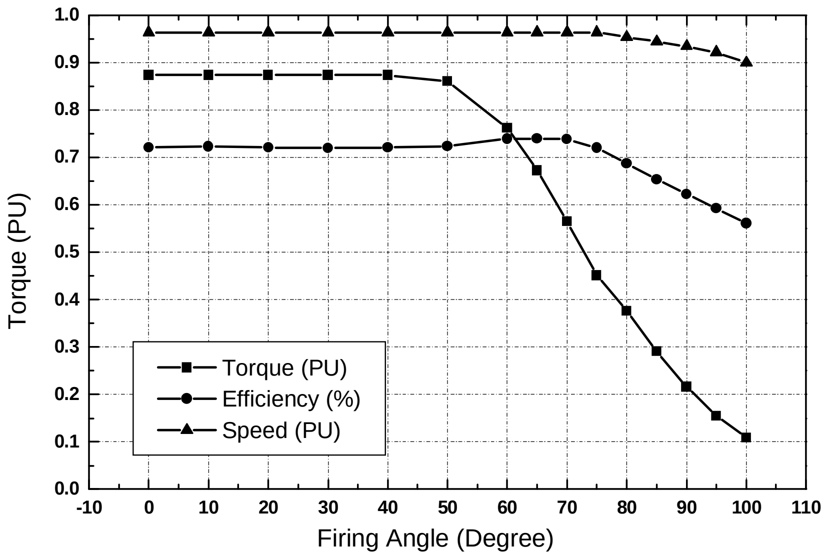


Fig.17 The variation of firing angle with motor torque, speed and efficiency for energy saving operation.

The validity of the proposed drive can be checked by carrying out the simulation when the load torque change from 0.875 pu (7 N.m) to 0.45 pu (3.6 N.m) (around 1446 rpm).
Fig.18 shows the comparison between open loop operation and closed loop operation of the drive. The motor is operating with a load torque of 7 N-m (0.875 pu), speed of 1441 rpm (0.964 pu), efficiency of 72.1 % and with an optimum firing angle of α = 40 ^{o}. At t = 2.5 sec., the load torque is decreased to 3.6 N-m (.45 pu); for open loop operation the speed will be increased to1473.5 rpm (0.982 pu),while the efficiency will be decreased to 66.8 % and the firing angle will be the same (α = 40 ^{o}) as it is. For closed loop operation the new optimum value of firing angle, α = 40 ^{o} is estimated as 75 ^{o}(from feed -back controller) and the SCR firing angle is changed accordingly resulting the energy efficient operation of the drive as the efficiency will be decreased to 71.98 %, while the speed will be the same of1446 rpm (0.964) pu,

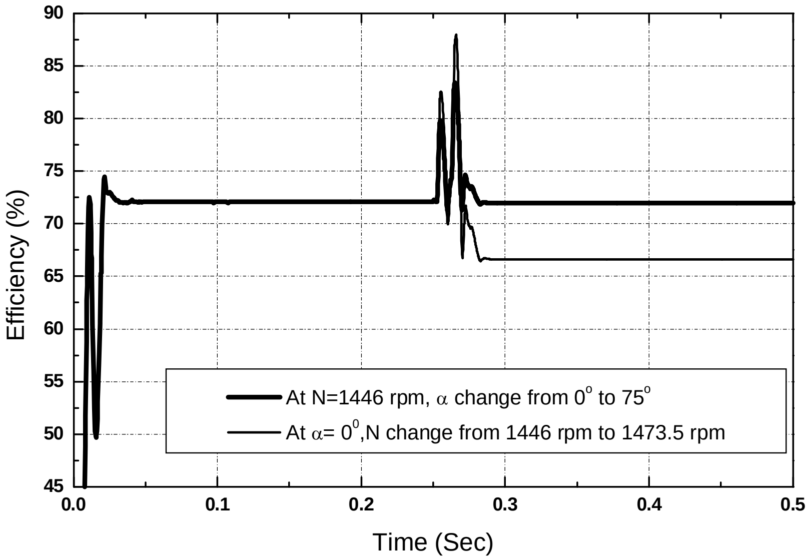


Fig.18 The comparison between open loop operation and closed loop operation of the drive during load change

Conclusion

A Simulink model of energy saving operation which is realized using a three phase AC voltage controller fed induction motor drive is presented. Proposed model of induction motor is presented and investigated by experimental work comparison. New model of a three phase AC voltage controller fed induction motor drive is obtained for a wide-range of operation modes. The relation between the speed of the motor and the firing angle depends on the mode of operation. So, the energy saving operation has to identify the mode of operation to send a correct value of firing angle to switches otherwise the system will get out of control.

Efficiency of the drive depends on the mode of operation where their values are good around mode 2/3. So, it is recommended to force the motor to work in this mode of operation and avoid other modes.

The energy saving operation is approximately occurs at definite speed for low firing angle, but for high firing angle the optimum speed decreases to work in 2/3 mode instead of 0/2 mode .

The comparison between open loop operation and proposed closed loop operation of the drive during load change gives good results, which demonstrate the validity of the proposed drive.

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