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Voltage Control of Three-Phase Induction Motor for Energy Saving

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Abstract Energy saving is one of the most applications. In the industries, Induction motors are the mostly preferred due to their reliability, robustness, price and rugged construction. The largest percentage of consumed energy in industrial is consumed by induction motors. So, Energy conservation in induction motor drive results in the reduction in power consumption and the cost of electricity. This paper describes energy saving technique for squirrel cage induction motor. The energy saving is achieved through managing the voltage administered to the stator winding through the use of the three phase AC voltage controller. The simulation verifications are done in MATLAB/Simulink. The results show that the proposed scheme gives rise to the enormous energy-savings.

Keywords Induction motor drive; Energy saving; Reducing voltage; Motor losses

1. Introduction

Induction motors are used in different fields of industrial production systems and there is a strong demand for their reliable and safe operation. In industries induction motor drives are the power consuming tools and they are needed for applications of industry. Therefore, conservation of energy in results in reducing in cost of electricity in the industry.

Motor drive systems would use about half of all electricity of modern cities. So, such systems use over 75% of all electricity in industries. Also induction motor drives are used in air conditioning, fans, pumps, compressors, elevators and industrial drives. These motor drives contain induction motor drives, dc motor drives, synchronous motor drives, as well as other motor drives. Among these drives, induction motor drives are most prevalent with real applications [1]. Energy conservation techniques are used for induction motor drives they are divided into online and offline [2-3]. The online method includes voltage balance, proper cooling, flux optimization, automatic power factor correction (APFC) and Losses at switches, and the offline method includes suitable Hp rating selection, suitable capacitance rating selection, choosing good quality coils and choosing quality core. Many schemes of energy saving are subserved for induction motor [4]. Nowadays, Energy saving is necessary owing to the increasing demand for electrical power through over the whole world. A great interest for the consumption of energy and high energy efficiency has been given as they represent important factors in the development of the electrical energy consuming products. The decreasing of the efficiency and the power factor of the motors resulted of applications of the induction motors as these applications are variable-load [5,6]. In such applications the motor can have low-load operating periods where the efficiency and power factor are low [7]. Efficiency and power factor of the motors would greatly improve in the low load operating period, if the stator winding voltage is well regulated or reduced to proportional the varying of load torque [8].

The efficiency rate of an induction motor is high when it runs on under the full load. Generally, the efficiency rate is higher than 75%. Although, the efficiency of the induction motor drive systemis lower if an induction motor is operating at light loads or does not selected correctly. So, that the energy efficiency of induction motor drives and its improvementindicates huge energy saving [1].

2. Analysis of the Three Phase Induction Motor

These motors are modeled with the per-phase induction motor that is a circuit, shown in Fig 1. R_l and X_l are the stator impedance, R_2 and X_2 are the rotor impedance as referred to the stator, R_c models the core loss, and X_M represents the magnetizing reactance. The motor output power is displayed by R_{Load}:

$$R_{load} = \frac{R_2(1-S)}{S} \tag{1}$$

R_{Load} models random loss and mechanical loss besides the output power. The induction motor that is corresponding circuit is illustrated in many textbooks, such as [9]. The motor output power is

$$P_{out} = I_2{}^2 R_{load}. \tag{2}$$

Typically, slip s differs from no load to full load. At no load, s is zero, such that R_{Load} is very large, 1_2 is very tiny, and the power in R_{Load} refers to mechanical and random losses. At full load slip, R_{Load} lessens, I_2 raises, and the power in R_{Load} includes the rated output power in addition to losses. Full load slip values are in the range of 0. 03-0.05 p. u. [9], through using newer motors may have decreased full load slip.

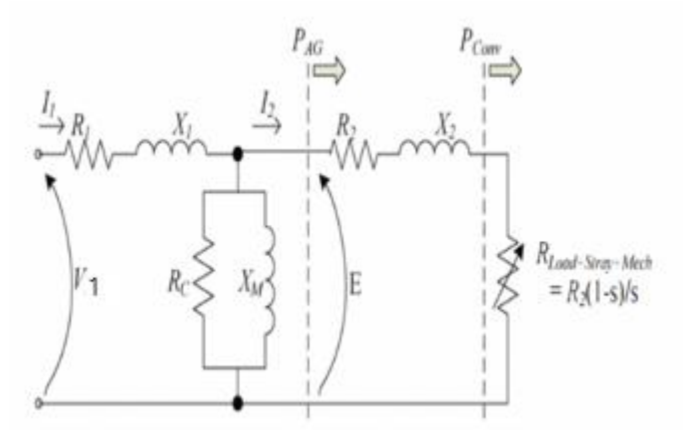

Figure 1: Corresponding Circuit Model for Induction Motor [9]

Fig 2 illustrates the power flow diagram of an induction motor. Each loss in the figure is represented by a specific resistance in the motor equivalent circuit; see Table 1. The stator and rotor resistive losses are modeled by R_l and R_2, Rc models core loss, whereas stray and mechanical losses are embedded in R_{Load}. The corresponding circuit of induction motor of the three phases can be lessened to the corresponding circuit by changing the lost resistance and magnetizing to the input terminals [8].

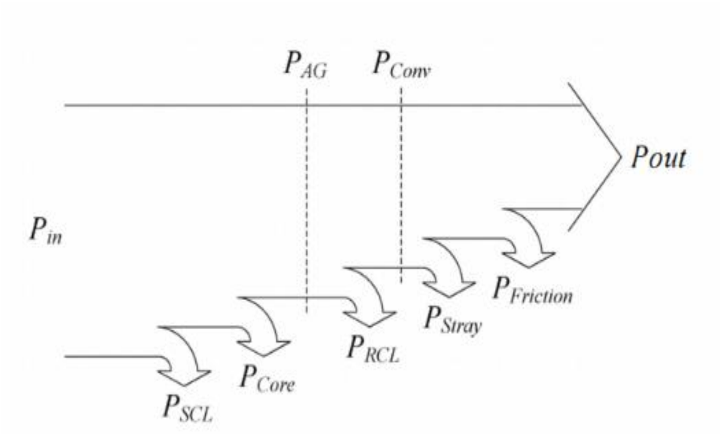

Figure 2: Power-flow Diagram of an Induction Motor [9]

Table 1: Induction Motor Loss Definition

Loss	Type	Circuit element
Stator winding	Resistive	R_1
Rotor winding	Resistive	R_2
Core	Magnetic	R_C
stray	Magnetic	R_{load}
Friction & windage	Mechanical	R_{load}

Stray and mechanical losses are accounted for in the load resistance [10].

3. Types of Losses in Three Phase Induction Motors

There are two types of losses happen in induction motors. The motor efficiency is decided by intrinsic losses which can be lessened through the changing in the design of the motor. These losses are divided into two kinds: constant losses, and variable losses [11].

The maximum efficiency condition is expressed as shown in (3). This equation can be decreased to be only motor parameters in terms of slip as shown in (4) and (5).

Pconstant losses=Pvariable losses (3)

$$3\frac{v_1^2}{R_c} = 3I_2^{\ 2}(R_1 + R_2) \tag{4}$$

$$\frac{3V_1^2}{R_C} = \frac{(3V_1^{\ 2}R_2 / S)}{[((R_1 + R_2 / S)) + (X_1 + X_2)^2)]} \tag{5}$$

Therefore, the slip that the maximum efficiency happens is illustrated as follow in (6)

$$S_{m\eta} = \frac{R_2}{\sqrt{(R_m(R_1 + R_2)) + (X_1 + X_2)^2 - R_1}} \tag{6}$$

It is obvious that the at most efficiency happens at slip value thatrelies on the parameters of the motor and equal 0.023 at speed 1758 rpm [8].

3.1. Constant Losses

Fixed losses that are separated from the motor load includes friction and magnetic core failure and windage failure. Magnetic core losses that is the unity of current and hysteresis losses in the stator. Friction and windage failure are the result of friction in the bearings of the motor and aerodynamic failure attached with the ventilation fan and other rotating parts [11]. In small induction motors, core failure produced form a part of total failure in these machines [8].

3.2. Variable Losses

Variable failure relies on load including resistance failure in the stator and in the rotor and multifold stray losses. Stray losses originate from a variety of sources and are difficult to measure directly or calculate, but are in general proportional to the square of the rotor current [11]. To improve motor efficiency is to reduce motor losses.

Where:

3.1.1. Core loss

Core loss refers to the energy needed to get the core material magnetized (hysteresis) and includes losses owing to generation of eddy currents that flow in the core. Core losses are those found in the stator-rotor magnetic steel and are a result of hysteresis effect and eddy present effect during magnetization of the core material [11].The variety of core losses with motor speed for various values of supply voltage is illustrated in Fig.3. It is obvious that the core losses is to extent linear and equivalent to the motor speed. In addition, the core losses is equal to the square of the supply voltage.

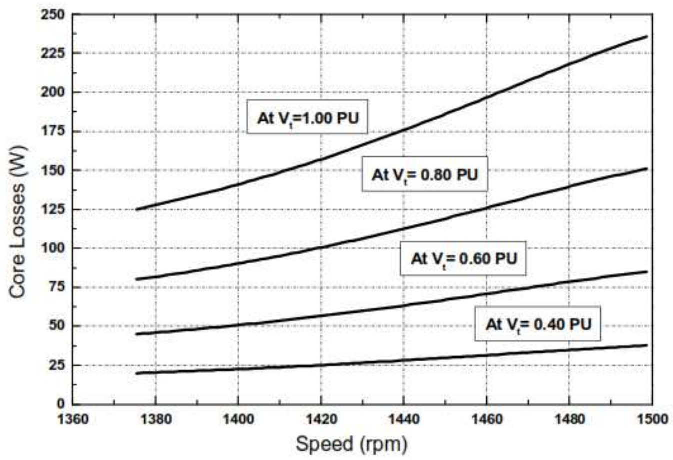

Figure 3: The variation of core losses with motor speed for different values of supply voltage [8].

So the core losses can be expressed as follow;

$$P_C = \left(\frac{V_a}{V_r}\right)^2 (69966 - 144.7N + 0.1N^2 - 0.000023N^3) \quad (7)$$

Where:

V_a: is line voltage in volt.

V_r: is the line voltage that equals 460 Volt.

N: is the speed of the motor in rpm.

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

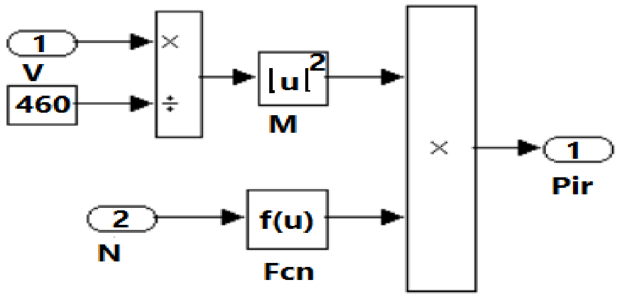

Figure 4: The block diagram of core losses expression [8]

3.1.2. Windage and friction

Windage and friction losses happen owing to bearing friction and air resistance. Both core losses and windage and friction losses are separated from motor load. Friction and windage losses result from bearing friction, windage and revolving air through the motor and account for 8–12% of total losses. The reduction in heat allows the use of smaller fan [11].

3.2.1. Stator losses

Stator losses seem as heating as a result of current flow (I) through the resistance (R) of the stator winding. This is known as an I^2R loss. These are main losses and account for 55–60% of the total losses. I^2R losses are heating losses resulting from current passing through stator and rotor conductors [11].

3.2.2. Rotor loss

Rotor loss is shown as I2R heating in the rotor winding. Rotor losses is lessened through the rise in the quantity of the conductive bars and end rings to get low rotor losses [11].

3.2.3. Stray load losses

Stray load losses are caused by leakage fluxes (I) through the resistance (R) of the stator winding. Such losses differ according to square of the load current and are resulted from leakage flux induced by load currents in the laminations and account for 4–5% of total losses [11].

4. Modelling of Induction Motor.

In this Section, the simulation model administered in Matlab environment for induction motor will be analyzed through using electrical and three phase voltage control models, that interact as diagrammed in Fig. (5). the block diagram of the electrical model for the induction motor is schematically shown. the voltage" V" In the electrical model, and the torque "N.m" decide the stator and rotor current. The total of all forces on the motor cylinder include the mechanical model. Here, the driving force produced by the motor is resisted by the load force and the moment of inertia of all the rotating elements. The thermal model relies on the equation for heat rise as a result of current flowing in a conductor decided by the feedback control, and the rotor slip.

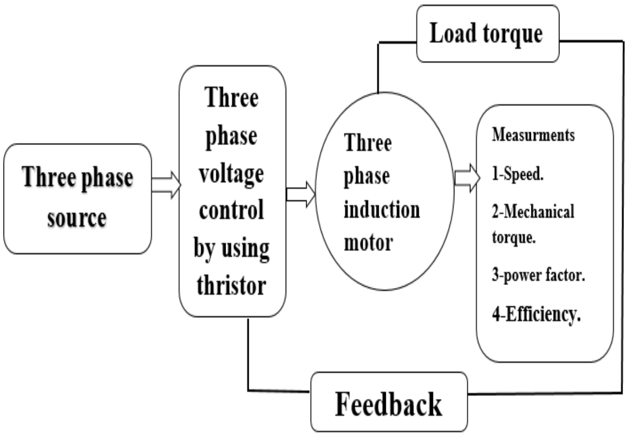

Figure 5: Block diagram of the model

5. Estimation Load Torque of the Motor

For estimating load and efficiency three steps are used. First, use input power, line slip measurements to decide the load forced on the motor. Second, get a motor part-load efficiency value. Finally, build a modified load using the power measurement at the motor finals and the part load efficiency value [13].

A-Input Power Measurements

You can quantify the motors part-load the comparison of the measured input power under load to the power needed when the motor runs at rated capacity. The following equation shows this relationship:

Load =Pi /Pir *100% (8)

With load the output power as a % of rated power, Pi, the measured three phase power in KW, and Pir, the input power at full rated load in KW.

B-Line Current Measurements

The current load estimation method is preferred when amperage measurements are valid. In the low load region, current measurements are no longer a useful indicator of load.

C-The Slip Method

It is advised to use the slip method when motor speed measurements are valid. The motor load can be assessed with slip measurements as shown in equation (9):

Load = (I/Ir) *(V/Vr) *100% (9)

With load, as output power as a % of rated power, I is the RMS current (mean of 3 phases), Ir the nameplate rated current, V the RMS voltage, and Vr the nameplate rated voltage.

6. Block Diagram of Energy Saving Device in Induction Motor

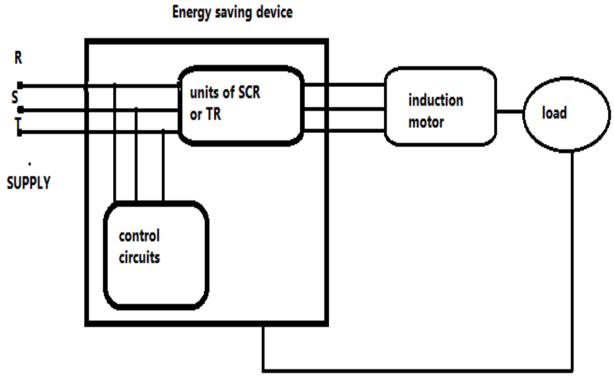

Figure 6: Block diagram of energy saving device

Fig. 6 shows the device of energy saving which connect between the source and the motor where the device contains on units group such as TR or SCR to reduce the voltage and control circuits to ignition this units, as it should be influenced the ignition with the current and voltage of the load. The device also includes on microprocessor for programming pulse ignition according to need load.

7. Simulation Results

The induction motor used in simulation model has the following parameters: F= 60, P= 3730w, V=460v, N=1800rpm, R_s=1.115 ohm, R_r =1.083 ohm, poles=4, J=0.02 [Kg.m^2]. MATLAB/SIMULINK software is used to perform the simulation using power system block sets with a simulation time of 5seconds.

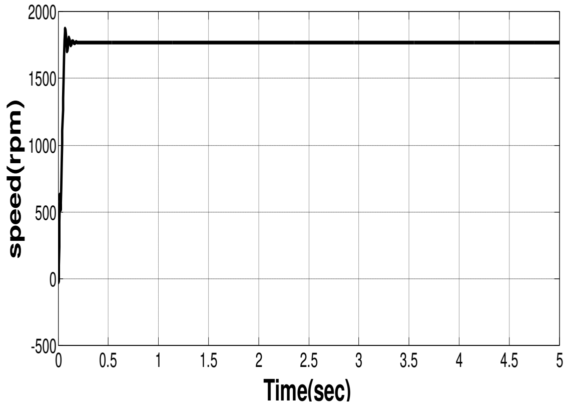

Figure 7: The relation between Speed and Time

Fig 7 shows the speed of motor. From this figure it can be noted that the speed is constant after transient period, approximately at 0.3 sec the speed is constant at 1800 rpm.

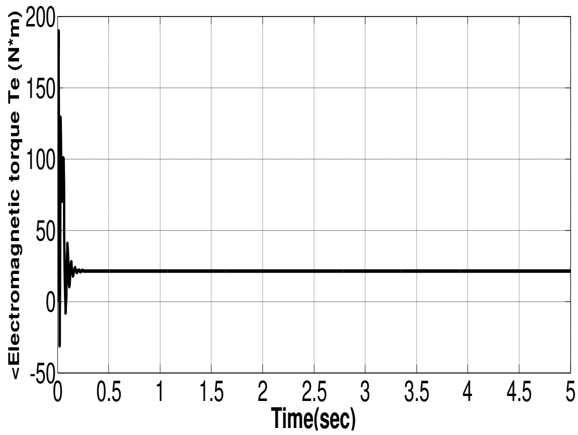

Figure 8: The relation between load torque and Time

Fig 8 indicates the electromagnetic torque of motor with time. From this figure it can be noted the electromagnetic torque values are changeable at 0.3 sec this period of time is called starting period. Afterwards the electromagnetic torque becomes stable at 20.3 N-m.

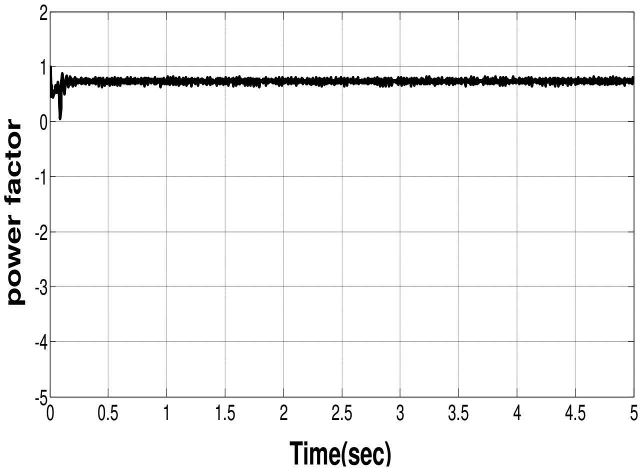

Figure 9: The relation between P.F. and Time

Fig 9 shows the power factor of motor. It indicates that the power factor values are changeable from 0 to 0.2 sec. Afterwards power factor becomes still at 0.9.

Table 2: Optimal voltages and currents of variant load torques at nominal frequency

T(N-m)	20.3	15	10	8	6	3	2	1
I_{opt}[A]	6.6	6.1	4.8	4.2	3.8	3.4	3.2	2.4
V_{opt}[V]	440	360	320	290	240	150	120	110

Table 3: The efficiency, power factor and losses without saving at voltage=460 volt

Load%	**100%**	**75%**	**50%**	**40%**	**30%**	**15%**	**10%**	**5%**	**0%**
T_L(N-m)	20.3	15	10	8	6	3	2	1	0
Eff(η)	0.87	0.81	0.74	0.70	0.96	0.48	0.4	0.3	0
PF	0.82	0.79	0.69	0.64	0.54	0.4	0.3	0.2	0.1
P_{input}	4277	3397	2517	2122	1623	1161	894.4	501.8	281.3
P_{output}	3738	2779	1863	1494	1123	563	376	188	0
Losses	539	618	654	628	500	598	518	314	281.3

Table 4: Comparison the values of efficiency, power factor and losses with saving

Load%	**100%**	**75%**	**50%**	**405**	**30%**	**15%**	**10%**	**5%**	**0%**
T_L(N-m)	20.3	15	10	8	6	3	2	1	0
voltage	440	360	320	290	240	150	120	110	100
E_{FF}(η)	0.88	0.85	0.83	0.81	0.78	0.67	0.58	0.4	0
PF	0.84	0.87	0.85	0.85	0.86	0.89	0.9	0.9	0.75
P_{input}	4252	3212	2209	1815	1408	801	614.4	624.3	223.1
P_{output}	3730	2746	1838	1471	1099	541	357.2	181	0
Losses	522	466	371	344	309	260	257.2	243	223.1

Table 2 show the relationship between the stator current and stator voltage at different load torques can be obtained by using mat lab where, the value of current and voltage decreased when reduce the value of torque. The maximum efficiency of induction motor can be achieved when operates at full load. But when reduce the load torque without reduce stator voltage the efficiency, stator current, power factor, input power and output power are decreased but losses increase this is meaning the motor operate without energy saving this is show in table 3.

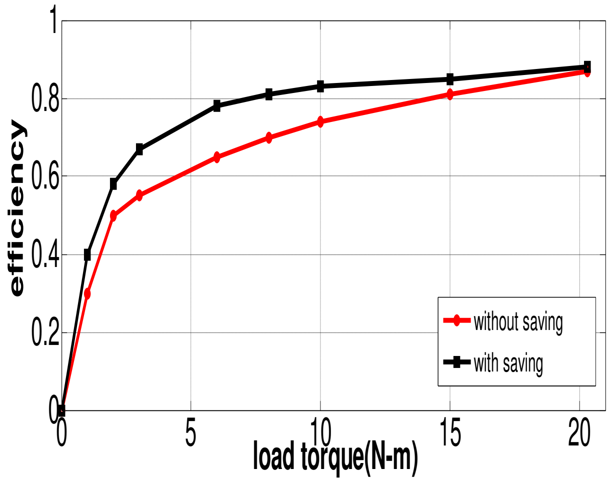

Figure 10: The relation between load and efficiency

Fig.10 shows the relation between efficiency and load torque with and without energy saving. From this figure it can be noted the efficiency with energy saving is more than the efficiency without energy saving at the same load value as shown at value 5 N-m. As the load approach to full load the difference in value of efficiency between energy saving and without saving is minimized, at full load both values of efficiency become equal.

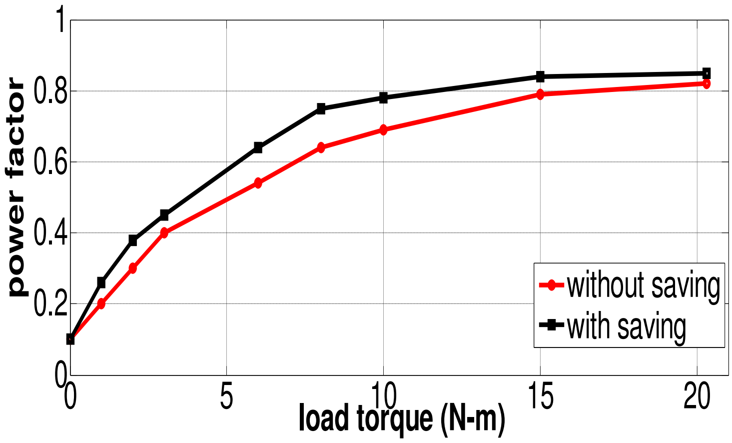

Figure 11: The relation between power factor and load torque

Fig 11shows the relation between power factor and load torque with and without energy saving. From this figure it can be noted the power factor with energy saving is more than the power factor without energy saving at the same load value as shown at value 5 N-m. As the load approach to full load the difference in value of power factor between energy saving and without saving is minimized, at full load both values of power factor become the same.

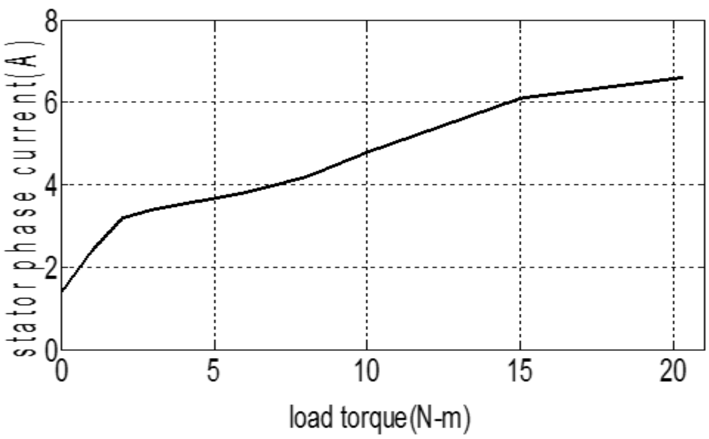

Figure 12: The relation between load torque and current

Fig 12 shows the relation between stator phase current and load torque. This figure indicates that with increase the load torque value the stator phase current increase.

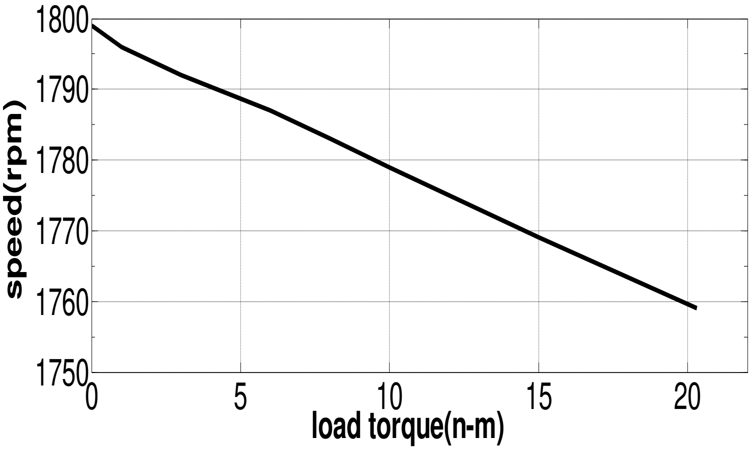

Figure 13: The relation between load torque and speed

Fig 13 shows the relation between speed and load torque. It reveals the speed values decreased with increase the load torque values.

8. Conclusion

Obtained results indicate the various ways of energy conservation in inducting motor drive. Hence, higher energy conservation can be produced using methods such as choosing cores and coils of good quality, automatic power factor correction, flux optimization, choosing proper condenser for reactive power compensation, voltage balance and choosing proper rating of motor corresponding to load. Less energy preservation is done including reducing losses at power electronic switches and suitables cooling. This paper presents information about electrical energy conservation field.

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