International Journal of Trend in Scientific Research and Development (IJTSRD)
Volume 6 Issue 4, May-June 2022 Available Online: www.ijtsrd.com e-ISSN: 2456 – 6470

Energy Consumption Minimization of Squirrel Cage Induction Motor Using Classical Optimal Controller Techniques

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ABSTRACT

Energy insufficiency is one of the major problems in the world today due to the growing population. Induction motor is used in many industries due to its low cost, and low maintenance cost. The influence of these motors (in terms of energy consumption) in energy-intensive industries is significant in total input cost. For the industry to remain in the competition, its running cost and power consumption must be minimized. When an induction motor work close to its rated torque, and speed at a light load, there is usually no balance between the copper and iron losses resulting in a reduction in efficiency of the motor and high power consumption, leading to temperature rise and noise is generated. This article focuses on minimizing the energy consumptions of the induction motor using the classical optimal controller technique. This was achieved by minimizing the stator current to the least possible value by optimizing the stator current for a given torque. The stator voltage values of the induction motor were varied by varying the modulation index (Ma) using the principle of constant flux. The classical optimal control system which uses information on the torque of the motor was used to generate the appropriate voltage amplitude that minimize the induction motor stator current. The classical optimal current controller models were configured for a set of experimental data using the information generated for the approximate minimum stator current value according to fitness functions. The models were implemented using MATLAB/Simulink toolbox and were validated by simulation using a typical three-phase induction motor of 4000W, 400V at a nominal frequency of 50Hz. From the result, it was observed that at minimum load torque of 2Nm and phase voltage of 230.94V, the power consumed was 1290W when the open-loop method was used but it was reduced to 503.45W when the classical control method was used. Reducing the power consumed by 60.97%. Again, at a load torque of 10Nm, the power consumed was 1489W when the open-loop method was used and 1173.17W when the classical control method. Minimizing the power consumed at a load torque of 10Nm by 21.2%. It was also observed that at load torque of 20Nm to the maximum torque of 26.7Nm, the amount of current drawn and the power consumed were the same when the open-loop method and the classical control method were used. The results at different frequencies show that when implementing the classical optimal current control method, the stator current and power consumption were highly minimized when compared to the open-loop method.

KEYWORDS: *Torque, Frequency, Stator current, and Controller*

How to cite this paper: Asiwe, Uchechukwu M. | Uju, Isidore U. | Iloh John Paul "Energy Consumption Minimization of Squirrel Cage Induction Motor Using Classical Optimal Controller Techniques" Published in International Journal of Trend in Scientific Research and Development (ijtsrd), ISSN: 2456-6470, Volume-6 | Issue-4, June 2022, pp.409-418, URL: www.ijtsrd.com/papers/ijtsrd50056.pdf

IJTSRD50056

1. INTRODUCTION

Squirrel-cage induction motors are highly used in most industries in both developed and developing countries because of their ruggedness, low cost of maintenance, simplicity, cost, and function well independent of the environment (Bimal, 2007).

The speed control of a rotational or linear alternating current motor has become easier with the help of a variable frequency drive system which is done by varying the frequency of the electrical power supplied to the motor (Collins, 1990). This has also helped in increasing its usage in the industrial environment.

The demand for energy increases daily as a result of the ever-growing population, and every effort is required to utilize the insufficient energy. When an induction motor is switched on, at the point of starting, it draws an enormously high current for direct-on-line starting increasing power consumption and power losses.

Induction motor just like every other machine which includes: Blowers, compressors, conveyors, and pumps draw a large amount of current during starting due to their zero resistance at starting. As a result of the frequent use of induction motors for both domestic and industrial, it becomes necessary to minimize the energy consumption of the motor.

For the industry to compete effectively with others, it is necessary to minimize its running cost and power consumption. When an induction motor work close to its rated torque, and speed at light loads, there is usually no balance between the copper and iron losses resulting in a reduction in motors' efficiency and high power consumption, leading to an increase in temperature, noise is generated and more electrical stress on the motor winding. In the economy today, it is important to minimize induction motor losses.

In order to minimize the power consumption by an induction motor, it is important to minimize the starting current as well as the power consumption at light load. This can be achieved by designing a special controller that will help in reducing the starting current and the power consumption at light load which will in turn increases the efficiency of the motor.

The development of this optimal controller will help increase the power system which represents the most critical problem in the world due to the increasing high demand for energy resources.

The method adopted to achieve this, is called the classical optimal stator current control system (Boukhelifa et al, 2004).

This proposed classical optimal stator current controller will help reduce the current drawn by the induction motor at point of starting and when it is running at light load leading to smooth starting of the induction motor.

In this article, An AC open loop drive system was used. This drive system consists of three-phase squirrel cage induction motor, inverter and control signal generator.

The model of a three phase voltage source inverter is implemented using MATLAB/Simulink environment for effectiveness of this study.

2. Equivalent Circuit of an Induction Motor

The induction motor comprises of two main components namely, the stator and the rotor. The stator consists of a copper winding connected in series and attached to the motor housing. A magnetic field is developed in the windings when the voltage and current are applied to the stator winding terminals, and the magnetic field rotates electrically around within the housing of the motor (Sneha, et al, 2016).

An air gap separates the stator and rotor. This air gap allows the rotor to rotate freely and an EMF is induced in the rotor by the magnetic field generated in the stator. Another magnetic field is induced in the rotor which has an opposite polarity to that in the stator, then a current is produced in the rotor bars and shorting ring. Torque which will "pull" on the field in the rotor and establish rotor rotation is produced by the magnetic field developed (Jerry et al, 2012).

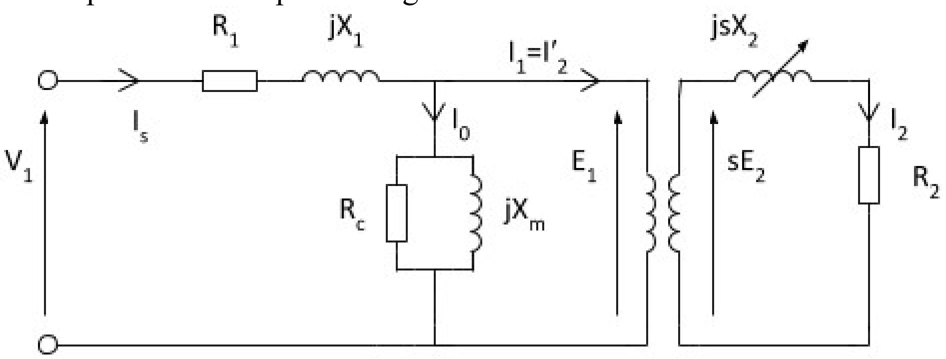

Figure 1.0: Equivalent Circuit of an Induction Motor

Where:
I_2 = Rotor Current
R_2 = Rotor Resistance
X_2 = Rotor Reactance
Z_2 = Rotor Impedance
$X_m = Z_m$ = Air Gap Impedance
I_m = Stator current.

The magnetization provided is greater at the starting than that is required by the load. This over magnetization produces heat in the motor. The solution to this is to determine what voltage the motor needs for proper operation at a given speed.

3. Methodology

The method adopted within the research is a classical optimal system, which uses information on the torque of the motor to get the acceptable optimal voltage that will give the induction motor optimal stator current. The classical optimal current control system consists of an open-loop AC drive system (Direct-on line system) and optimal current controller, which should be designed and modeled.

The stator voltages values of the three-phase induction motor at different load torques were obtained by varying the modulation index such that ($0 < m < 1$) using the principle of constant volt/hertz. (Krishnan, 2003 and Alfredo, 1998).

An embedded MATLAB model gives identical responses under equivalent operating conditions when used to analyze, model and simulate the open-loop AC drive system. (Rateb, 2006).

In this article, the open-loop AC drive system components were modeled using embedded MATLAB/ Simulink models. The complete equivalent circuit of the induction motor shown in figure 1.0 was used as the basis of the computation.

A 4.0KW, 400V, 50Hz, 1430rpm, three-phase induction motor was utilized in this study. The ratings and parameters of the motor are listed in table 1.0:

Table 1.0: Rating Parameters of the Three Phase Induction Motor

Parameter	Value
Rated power	5.4hp ,4000W
Rated Line to Line voltage	400[V]
Motor efficiency	0.95
Power factor	0.8
Rated frequency	50 [Hz]
Stator resistance R_1	1.47 [Ω]
Rotor resistance R_2	1.395[Ω]
Stator Leakage reactance X_s	0.005839[H]
Rotor Leakage reactance X_2	0.005839[H]
Air gap inductance	0.1722 [H]
Moment of Inertia	0.0131 [$Kg.m^2$]
Nominal speed	1430 [rpm]
Rated Torque	26.7N-m
Number of Poles	4

The power at frequency of 50Hz is 5.4Hp which is approximately 4000W.

The output torque at 50Hz is given as $T_n = \frac{P}{\omega}$ (1) (Sim Power Systems Version 4).

Power input $P_{in} = \frac{power\ output}{efficiency} = \frac{P_{output}}{\eta}$ (2)

Starting Current = $I_{start} = \frac{(Rated\ HP\ of\ the\ motor) x (code\ factor)}{\sqrt{3}(V_L)}$ (3)

Stator Phase Current $I_s = \frac{Power\ Input}{\sqrt{3}\ x V_L\ x\ pf}$ (4)

magnetizing current $I_m = I_0 \sin\Theta$ (5)

Power factor $\cos\Theta = \frac{R_2}{\sqrt{(R_2^2 + X_2^2)}}$ (6)

E_2 = Rotor EMF (generated by the air gap flux)

Rotor winding reactance / phase = $2\pi f' L_2 = 2\pi sfL_2 = s(2\pi fL_2) = sX_2$ (7)

Rotor winding impedance / phase $\sqrt{R_2^2 + (sX_2)^2}$ (8)

Rotor current / phase $I_2 = \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}}$ (9)

The power factor in the rotor circuit is $\cos \Phi_2 = \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}$ (10)

Where, $I_m = \frac{E_1}{X_m}$ (11)

Slip (S) = $\frac{N_s - N_r}{N_s}$ (12)

For a 400V nominal phase to phase voltage at the frequency of 50Hz, the DC voltage at the output of a rectifier circuit is $V_d = (400 \times 2^{0.5}) = 565.7$V.

The inverter output voltage (RMS) is calculated by $V_{rms} = \frac{(m \times Vd)}{\sqrt{2}}$, (13)

Where: m is the modulation index.

The power device within the three-phase voltage source inverter circuit is that the modeled metal oxide field-effect transistor (MOSFET) in Simulink. And therefore the MOSFET has the subsequent parameter:

1. The MOSFET has an ON-state resistance of $1 \times 10^{-3}\Omega$
2. For a 5.4Hp, 400V, 50Hz mechanical output power during a discretized model in Simulink, the snubber capacitance of the MOSFET is

$Cs = \frac{4000}{(1000 \times 2\pi \times 50 \times 400)} = 32 \times 10^{-6}$ farad (Sim Power Systems Version 4)

3. The snubber resistance of the MOSFET is given by $R_s = \frac{2 X Ts}{Cs}$ (14)

Where: Discrete time step = $T_s = 2 \times 10^{-6}$ (Sim Power Systems Version 4)

The discrete SV PWM block is an inbuilt three-phase generator in Simulink that generates three-phase pulses to the three-phase inverter consistent with the constant volt/hertz principle, using space vector pulse width modulation technique (Bimal, 2007):

Where:

- The $\frac{voltage}{frequency}$ = constant (15)
- The stator voltages values of the three-phase induction motor at different load torques were obtained by varying the modulation index such that ($0 < m < 1$) using the principle of constant volt/hertz. The results obtained were presented in table 2.0

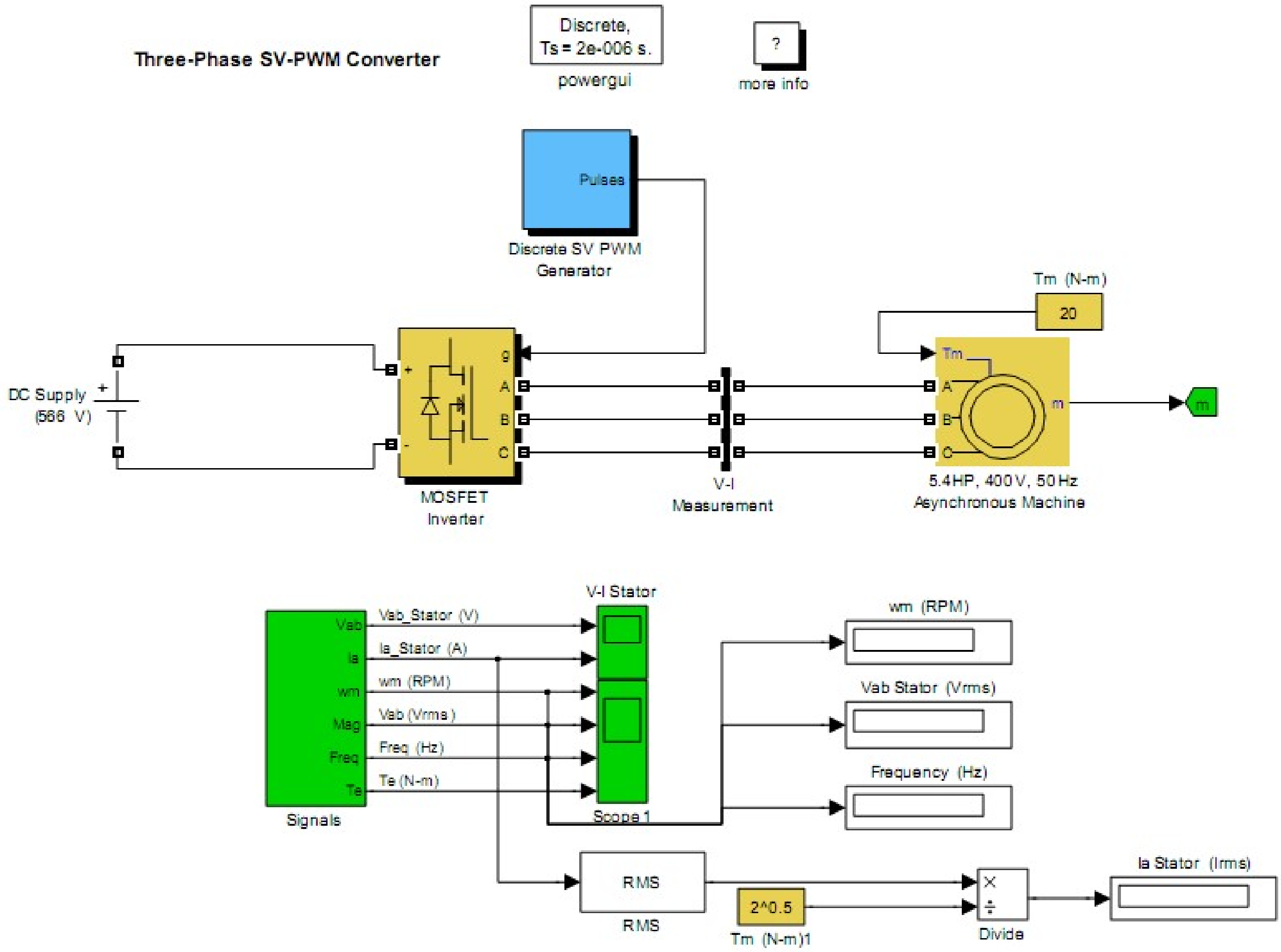

Figure 2.0: Direct on line (Open-loop) control model of an induction motor using constant V/Hz principle and a space vector (SV) PWM technique in MATLAB/Simulink

Table 2.0: Stator current value and voltages from open loop at different load torques

M	V_{l-l} (V)	V_p (V)	I_m (A)	T=2, I_s(A)	T=3 I_s(A)	T=4 I_s(A)	T=6, I_s(A)	T=8 I_s(A)	T=10 I_s(A)	T=12, I_s(A)	T=13 I_s(A)	T=16 I_s(A)	T=20 I_s(A)
0.10	40	23.09	-	-		-	-	-	-	-	-		-
0.15	60	34.64	0.59	-	-	-	-	-	-	-	-		-
0.20	80	46.18	0.78	1.11	1.14	1.17	1.20	1.24	-	-	-		-
0.25	100	57.73	0.98	1.40	1.43	1.45	1.53	1.55	-	-	-		-
0.30	120	69.28	1.18	1.69	1.73	1.75	1.83	1.89	-	-	-		-
0.35	140	80.83	1.37	1.96	2.01	2.05	2.13	2.19	-	-	-		-
0.40	160	92.37	1.57	2.23	2.30	2.35	2.44	2.51	2.57	2.63	2.65	-	-
0.45	180	103.92	1.77	2.53	2.58	2.65	2.75	2.83	2.90	2.96	2.99	-	-
0.50	200	115.47	1.97	2.82	2.89	2.93	3.06	3.15	3.22	3.29	3.32	-	-
0.55	220	127.02	2.16	3.09	3.17	3.24	3.35	3.45	3.54	3.61	3.65	3.71	3.87
0.60	240	138.56	2.36	3.38	3.46	3.54	3.66	3.77	3.86	3.95	3.98	4.05	4.23
0.65	260	150.11	2.56	3.66	3.76	3.84	3.93	4.09	4.19	4.28	4.32	4.39	4.59
0.70	280	161.65	2.76	3.95	4.05	4.14	4.28	4.36	4.52	4.62	4.66	4.72	4.94
0.75	300	173.21	2.95	4.22	4.33	4.43	4.58	4.71	4.83	4.95	4.98	5.06	5.29
0.80	320	184.75	3.15	4.51	4.63	4.73	4.89	5.03	5.11	5.27	5.32	5.41	5.60
0.85	340	196.30	3.35	4.79	4.92	5.02	5.20	5.35	5.48	5.54	5.65	5.74	6.00
0.90	360	207.84	3.55	4.83	5.21	5.32	5.51	5.67	5.81	5.94	5.92	6.08	6.36
0.95	380	219.39	3.74	5.32	5.46	5.57	5.76	5.92	6.07	6.20	6.25	6.42	6.62
1.00	400	230.94	3.94	5.62	5.76	5.88	6.17	6.25	6.40	6.53	6.60	6.76	6.98

- m is the modulation index
- $V_{l\text{-}l}$ is the line to line (Root mean square) value of stator voltage in volts (V)
- V_p is the per phase (Root mean square) value of stator voltage in volts (V)
- I_s is the per phase (Root mean square) value stator current in Ampere (A)
- T is the output torque in Newton-metre (Nm)
- I_m is the magnetizing current in Ampere (A)

4. Design of Classical Optimal Stator Current Controller

The optimal stator current value and corresponding stator voltage value of the three-phase induction motor at different load torques can be obtained by varying the stator voltage throughout the modulation index variation. The stator current points for different load torques were determined using the parameters of the induction motor given in table 3.0.

Table 3.0: Optimal stator voltages value and optimal stator current value of different load torques

T [N.m]	V_{opt} [V]	I_s[A]
2	92.37	2.23
3	103.92	2.58
4	115.47	2.93
6	150.11	3.94
8	161.65	4.36
10	184.75	5.11
12	196.30	5.54
13	207.84	5.92
16	219.39	6.42
20	230.94	6.98

The MATLAB Curve Fitting Toolbox was used to derived the relationship between the stator voltage and the stator current at different load torques at each frequency . And the data table 3.0 are shown in figure 3.0 and figure 4.0.

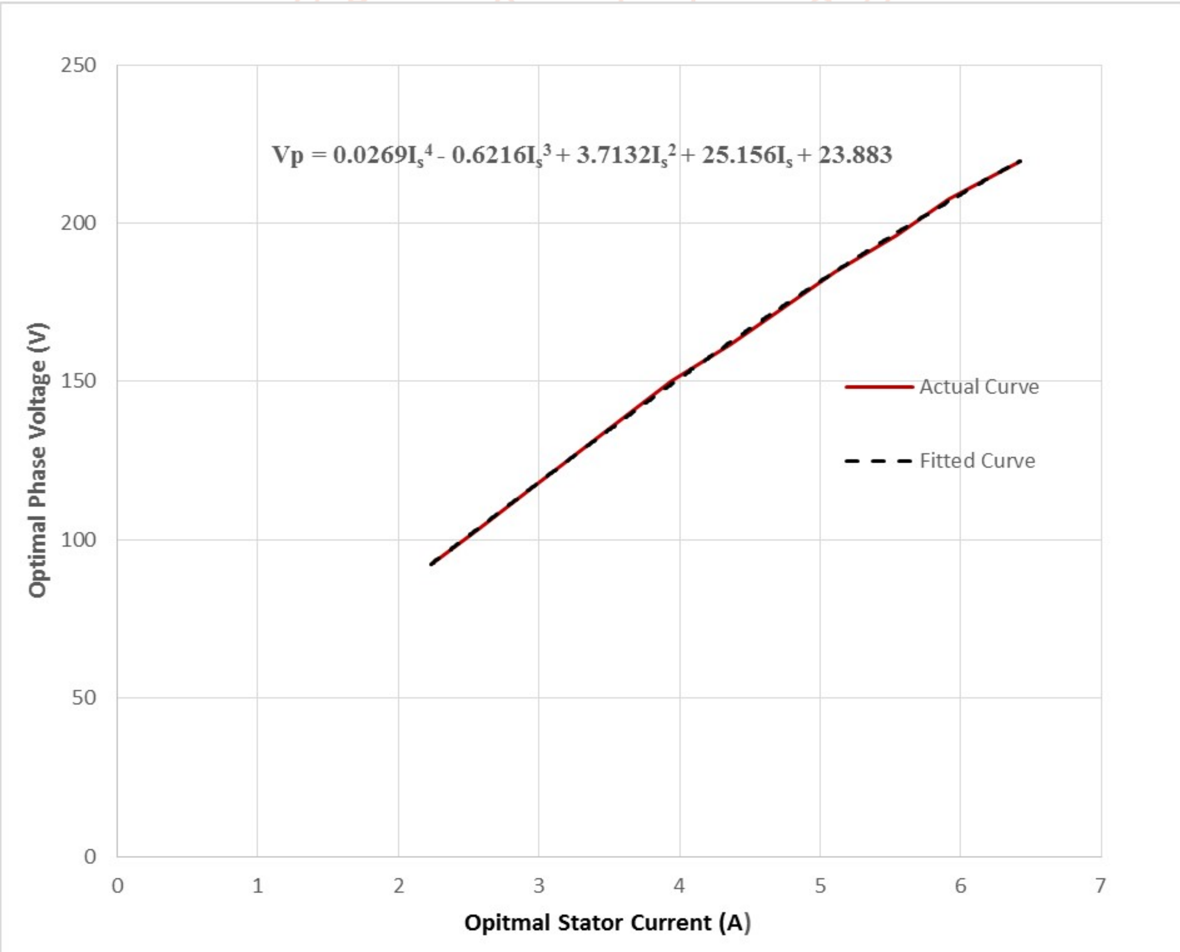

Figure 3.0: Optimal Stator Voltage against Stator Current fitting curve

The optimal current controller's equation at frequency of 50Hz in figure 3.0 from the fitted curve equation is given by

$V_p = 0.0269I_s^4 - 0.6216I_s^3 + 3.71321I_s^2 + 25.156I_s + 23.883$ (16)

Let $V_p = a_1I_s^4 + a_2I_s^3 + a_3I_s^2 + a_4I_s + a_5$

Where; $a_1 = 0.0269$,

$a_2 = -0.6216$,

$a_3 = 3.7132$

$a_4 = 25.156$,

$a_5 = 23.883$

V_p is the per phase stator voltage and I_m is the stator current

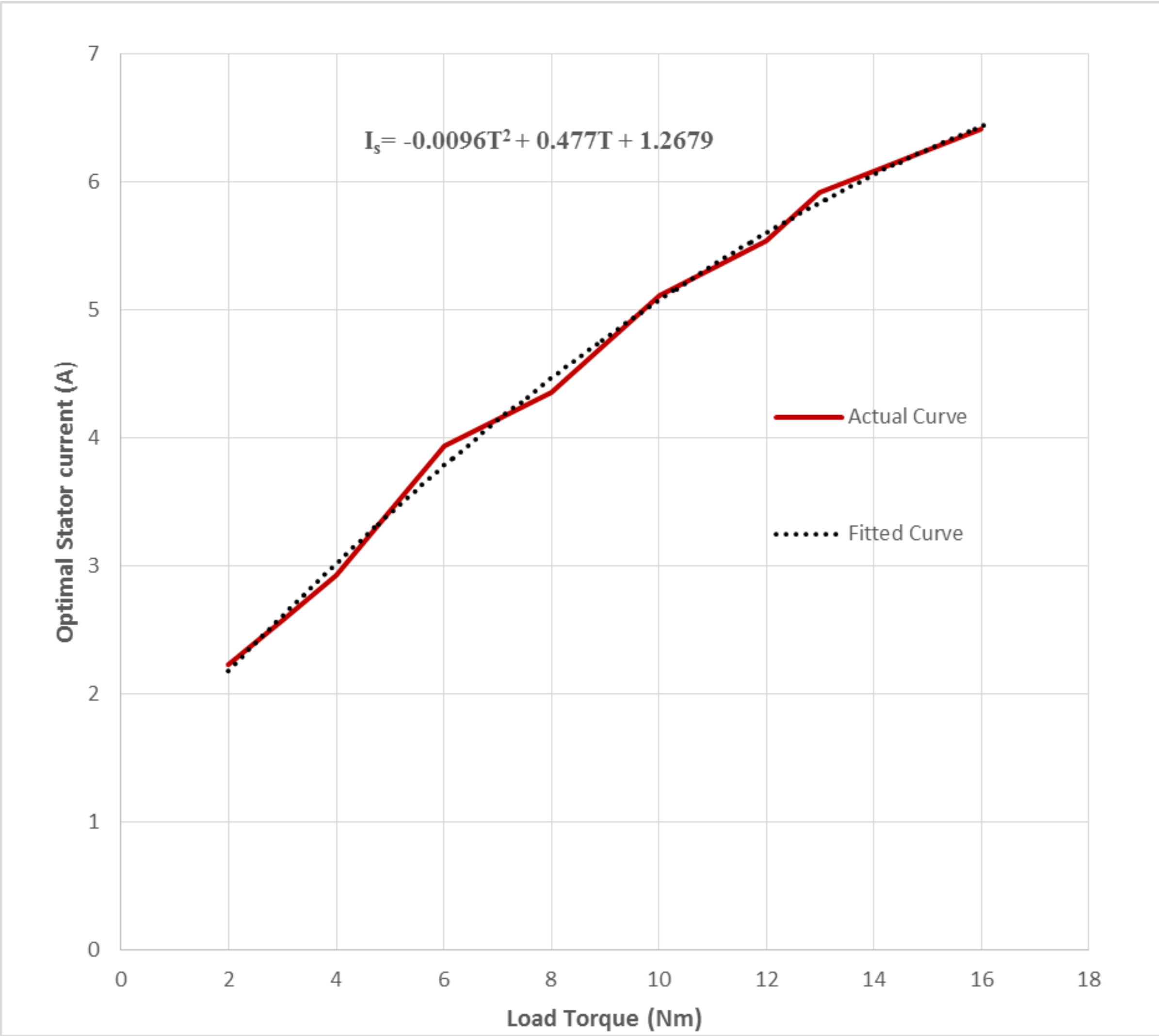

Figure 4.0: Optimal Stator current Value against load torque fitting curve

The equation relating optimal stator current and load torque at 50Hz in figure 4.0 from the fitted curve equation is given by

$(I_s) = -0.0096T^2 + 0.477T + 1.2679$ (17)

$(I_s) = b_1T^2 + b_2T + b_3$

Where; $b_1 = -0.0096$, $b_2 = 0.477$ and $b_3 = 1.268$

5. Modeling of Classical Optimal Current Controller

The MATLAB/Simulink toolbox was used to build the models using equations (16) and (17).

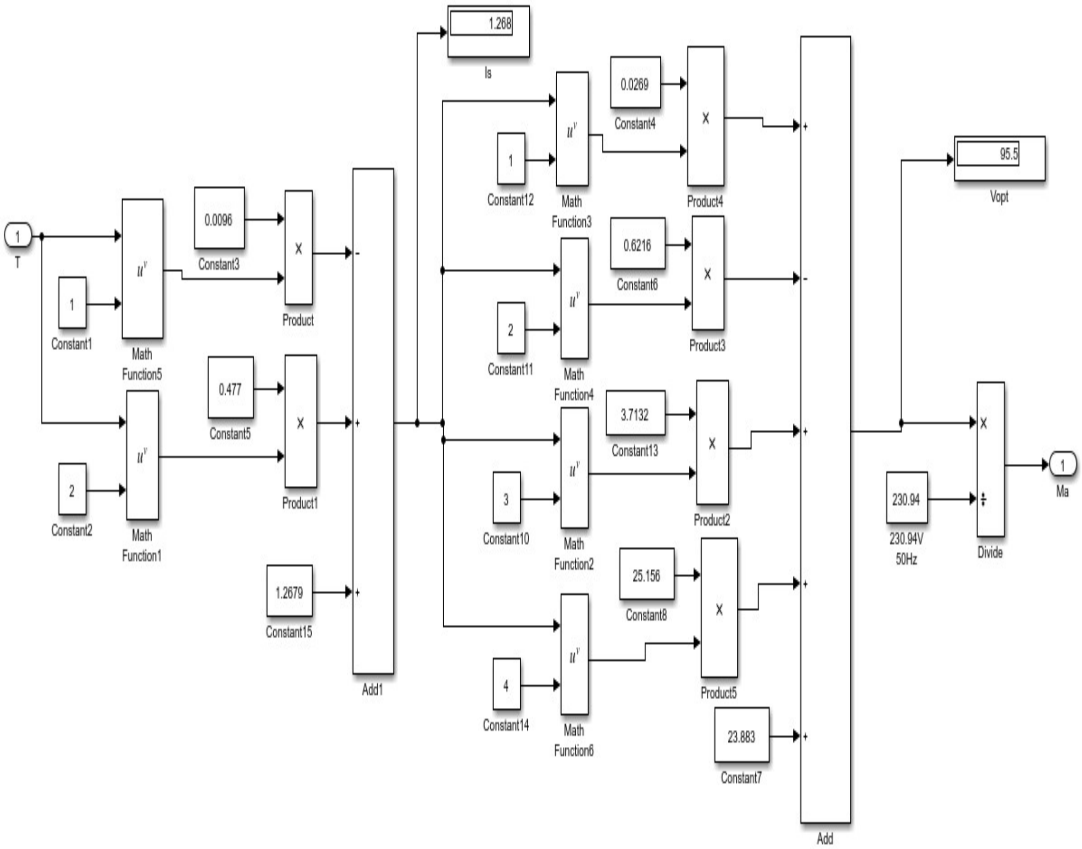

Figure 5.0: Optimal Current Controller Model at frequency of 50Hz Using Matlab Simulink

According to frequency applied, an automatic switch can select proper controller, which applies the suitable modulation index (M_a) as a control signal to control the value of applied voltage on the stator.

The classical optimal stator current controller model is shown in figure 6.0.

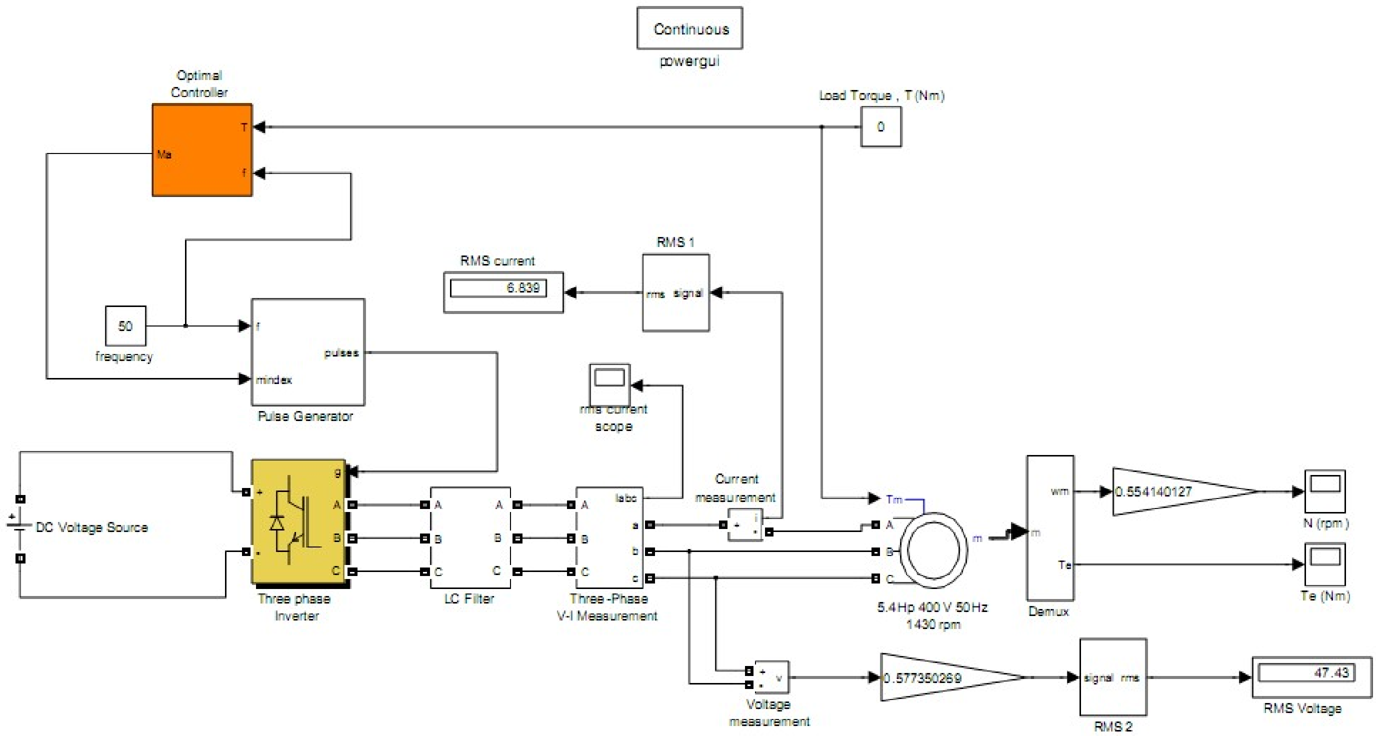

Figure 6.0: Classical Optimal Current Control System Model Using Matlab Simulink

6. Results Analysis

The results presented were for open-loop AC drive system, (Direct on line System) and classical optimal control system.

Table 4.0: Stator Current and Power Consumed Comparison between the Open-loop AC Drive System, and Classical Optimal Control System at a nominal frequency (50Hz)

T [Nm]	Open Loop system I_s (A)	Classical control system I_s (A)	Power consumed using Open-loop system (W)	Power consumed using Classical Control method system (W)
2	5.62	2.18	1297.88	503.45
3	5.76	2.61	1330.21	602.75
4	5.88	3.02	1357.92	697.44
6	6.17	3.78	1424.89	872.95
8	6.25	4.47	1478.01	1032.30
10	6.40	5.08	1478.01	1173.17
12	6.53	5.61	1508.03	1295.57
13	6.60	5.85	1524.20	1351.00
16	6.76	6.44	1561.15	1487.25
20	6.93	6.93	1600.41	1600.41

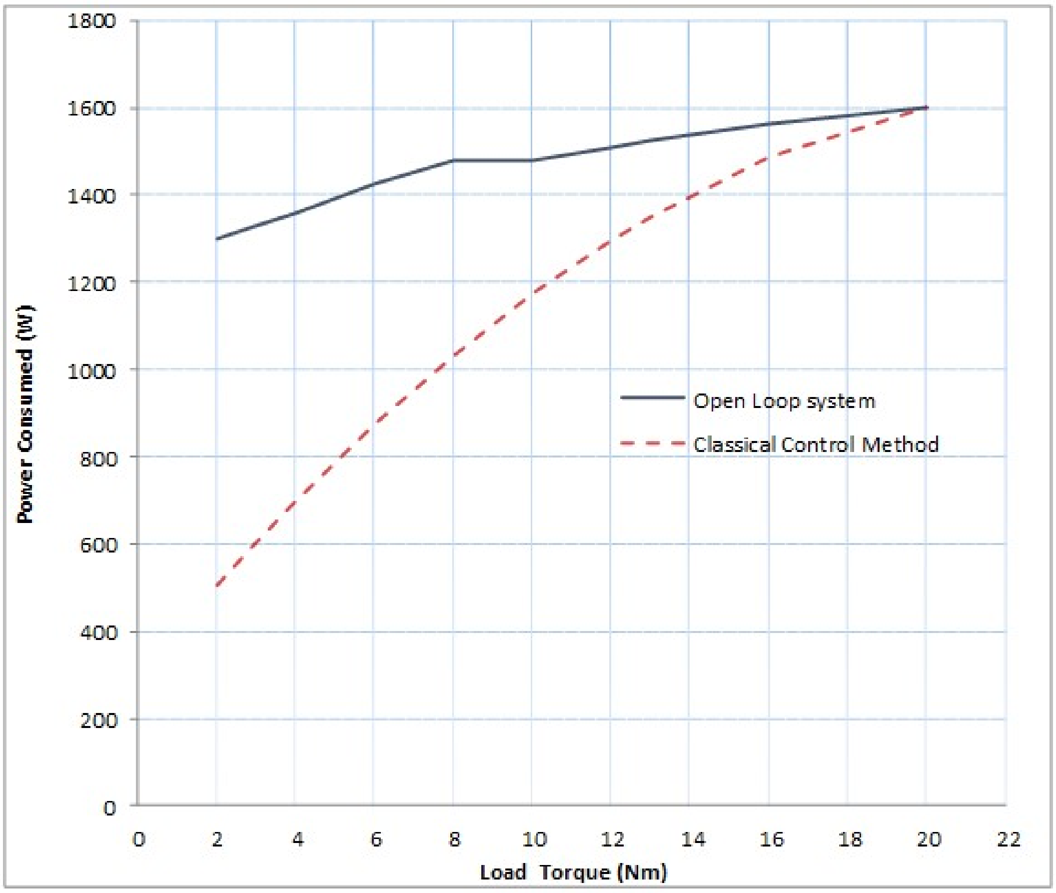

Figure 7.0: Power Consumed comparisons at nominal frequency of 50Hz

Table 4.0 and figure 7.0 shows at minimum load torque of 2Nm and phase voltage of 230.94V, the initial current needed to operate the induction motor at a nominal frequency of 50Hz using the open-loop system was 5.63A. While using the classical control system, the minimum current was reduced to 2.18A. The power consumed was 1297.88W using the open-loop system which was reduced to 503.45W using the classical control system. Power saved was 794.4W. At a torque of 10Nm, the current drawn using the open-loop system was 6.40A while using the classical control system, 5.08A was drawn. The power consumed was 1478.01W using the open-loop system and was reduced to 1173.17W using the classical control system. Power saved was 305W. At a torque of 20Nm to the maximum torque of 26.7Nm, both the open-loop system and the classical control system have the value for current and power consumed. The results in figure 4.1 show that when the classical optimal control system was implemented, the stator starting current is highly minimized when compared to the open-loop AC system.

The results from table 4.1 to table 4.4 and figure 4.1 to figure 4.4 show that when implementing a classical optimal control system, the stator current and power consumption were highly minimized when compared to the open-loop system (DOL).

7. Conclusion

A new method of quantifying and minimizing the energy consumption of an induction motor is proposed. This new method called the classical optimal current controller technique will help to improve the general performance of the induction motor by minimizing the stator current which is usually high when using the direct-on-line (Open-loop) system.

It is obvious that the classical optimal controller system provides a very good opportunity to save energy, reduce operating costs and increase profit and as well increase the life of the induction machine. It has also helped to improve the efficiency of the induction motor when compared to direct on line system. And finally, operating the induction motor at the minimized stator current will increase the input power to the rotor and also will help prolong the life span of the induction motor by reducing the vibration, heat, and noise generated.

Induction motors are one of the most used electric motors in the industry. So, every design in minimizing energy consumption is important.

Recommendations

This work shows that if the classical current control system is installed in every induction motor manufactured by the manufacturer, a reasonable power consumed by the induction motors before it reaches its maximum load torque will be minimized, energy will be saved, operation cost, and the machine efficiency will be increase.

It is hereby recommended to implement the classical optimal control system for application in industrial drives. The current controller should be installed in every induction motor by the manufacturer at the point of construction.

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