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DESIGN OF ENERGY OPTIMIZATION CONTROL MODEL FOR THREE PHASE INDUCTION MOTOR

By

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Abstract

There is usually an imbalance between energy supplied and the amount of energy needed by the ever growing population of the world. Induction motors which is an energy consuming machines is highly used in many industries due to their low cost and low maintenance cost. The influence of these motors (in terms of energy consumption) in energy-intensive industries is significant with respect to total input cost. This work focused on designing an energy optimization control model for three phase induction motor using the classical optimal controller technique. This was achieved by minimizing the stator current to the least possible value by optimizing the energy drawn by the induction motor for a given torque. The stator voltage values of the induction motor were studied by varying the modulation index (M_a) 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 minimizes the induction motor energy consumption. 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, the energies drawn by the induction motor when using the optimal controller model were highly minimized when compared to the open-loop method. This work has showed that classical control system can be used to minimize the energy consumption of an induction motor to a least possible value for a given output torque.

Keywords:

Torgue, Energy, Optimization, Induction motor, Matlabsimlink.

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1.0 Introduction:

As the population of the world increases daily, the demand for energy has also increased. In order to increase the available energy in circulation, there is need to minimize the losses waste which is in form of losses in most machines used daily. One of this machines that is commonly used domestically and industrially are the induction motor. Induction motor is used as part of the components in fan blowers, cranes, mill run-out tables, and conveyors.

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.

Induction motor just like every other machine which includes: Blowers, compressors, conveyors, and pumps draw a large amount of current during starting resulting to high energy consumption of the machines. Because of the frequent use of induction motors for both domestic and industrial, it becomes necessary to minimize the energy consumption of the motor.

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.

The energy consumption of an induction motor is directly related to the power it draws, but also influenced by its efficiency and operating conditions (Collins, 1990). Higher power consumption generally leads to increased energy usage, especially when the motor operates at lower efficiencies or with a poor power factor. Optimizing the motor's load, power factor, and operating speed can significantly reduce energy consumption.
Induction motors draw a very high starting current, which can be a significant energy draw during startup. Reducing the starting current through techniques like soft starting can help reduce energy consumption(YakobLiklikwatil et al, 2021).

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

2.0: Starting of Squirrel Cage Induction Motor.

A three-phase induction motor when starting using direct-on-line (by applying the rated voltage directly to the motor) draws very high current about 5 to 7 times the rated current. To help reduce the high starting current, an appropriate voltage is applied to the stator with the help of energy optimal controller.

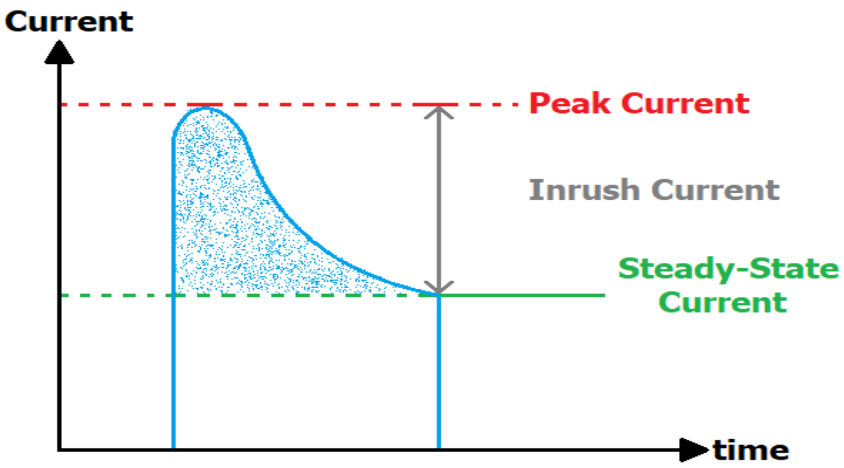

Figure 1.0: Diagram showing Starting Current (Cohen, 1995).

3.0: Constant Volts/Hertz (V/F) Principle

The speed of an induction motor depends primarily on the number of poles of the machine and the frequency of the supplied voltage. The amplitude of the voltage supplied and the load on the motor shaft also influences the motor speed, however not to the same degree (Zhenye. 1998).

Changing the frequency of the supply voltage is an ideal method for induction motor speed control. In order to ensure a correct motor magnetization, it is also necessary to change the amplitude of the voltage according to the following equation:

$$E = 4.44 \text{ x } \Phi_{max} \text{ x } f \text{ x } N \quad (1.0)$$

Where, 'E' is the electromotive force or the rotor induced voltage in Volts

'f' is the frequency of the voltage supplied in Hertz. ,'N' is the number of turns per phase, 'Φ' is the flux per pole.

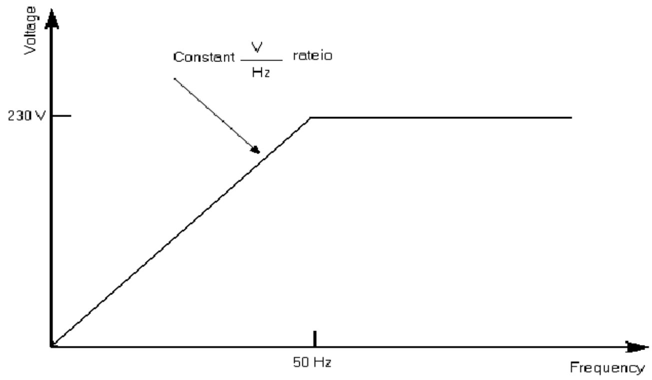

Figure 2.0: Voltage vs Frequency under the Constant Volt/Hertz principle

The motor's stator's coil inductive reactance (X_L) is given as 2πfL and it is directly proportional to the frequency.

4.0: Induction Motor Torque

The torque developed in the induction motor is done by inducing current to the rotor, which is proportional to the differential speed of the rotor and the rotating magnetic field in the stator

To calculate the internal electromagnetic torque produced as it relates to the internal power (P_g), recall that the mechanical power is equal to the torque (T) times the angular velocity, or

$$P = \omega_s T. \qquad (2.0)$$

Where: ω_s = the synchronous angular velocity of the rotor; p is the power

5.0: Ac Drive System

(i) Open Loop AC drive System:

Example of open-loop drive system is direct-on-line starter of an induction motor.

The basic parts of the AC drive system are shown in figure 3.0 below.

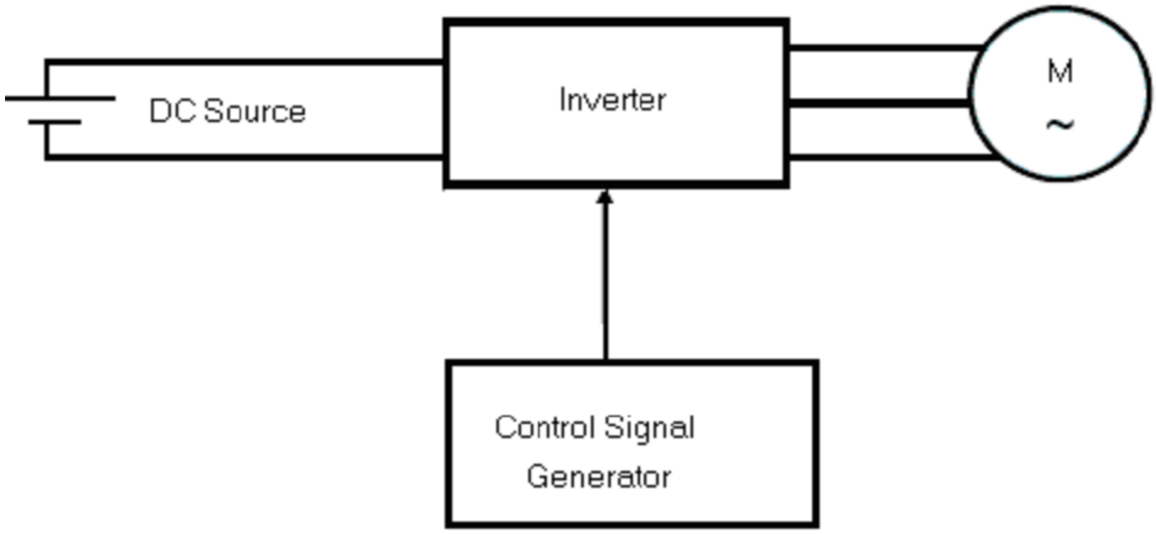

Figure 3.0: Basic parts of Open-loop AC drive system

(ii) Closed-Loop Ac Drive Systems

In a closed Loop drive system, a controller is introduce which help to monitor the optimal current needed and also helps to control the energy drawn by the motor in order to improve the system performance.

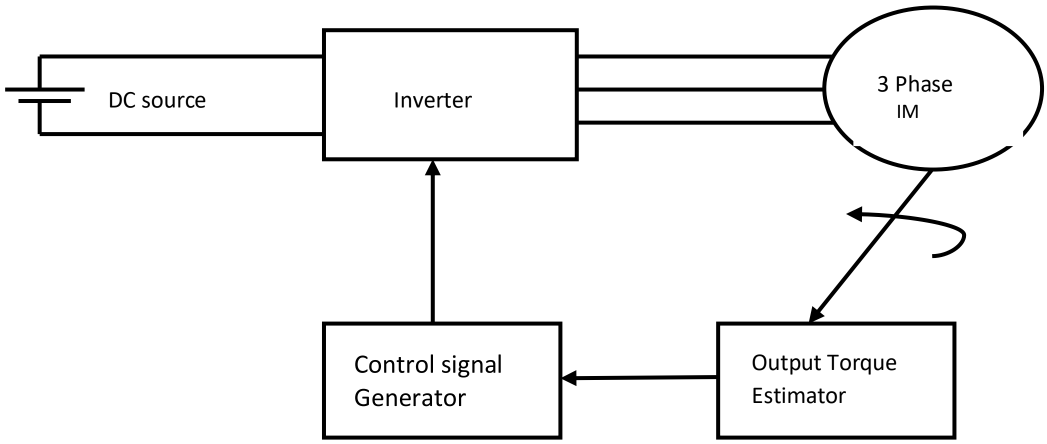

Figure 4.0: Basic components of a Closed-loop AC drive system

6.0 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 power developed. The classical energy control system consists of an open-loop

AC drive system (Direct-on line system) and optimal energy consumption 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.

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 research, 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 2.22 was used as the basis of the computation.

A 5.4hp, 400V, 50Hz, 1430rpm, three-phase induction motor was utilized in this study.

The amount of electrical energy consumed over time is directly related to the power the motor draws and the duration of operation.

$$\text{Power} = \frac{\text{Energy consumed}}{\text{time}}$$

This implies that Energy consumed = Power x Time

$$\text{Energy consumed} = \text{iv}\, dt \qquad (3.0)$$

If the time taken (dt) is 1second

Then

$$\text{Energy consumed} = \text{Power drawn x time} = \text{iv}\, dt = iv \qquad (4.0)$$

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

The output torque at 50Hz is given as

$$T_n = \frac{p}{\omega}$$

$$T_n = \frac{60P}{2\pi N} = \frac{60 \text{ x } 4000}{2 \text{ x } 3.142 \text{ x}1430} = 26.7\text{N-m}$$ (Sim Power Systems Version 4).

For a 400V nominal phase to phase voltage at the frequency of 50Hz, the DC voltage at the output of a rectifier circuit is

$V_d = (400 \times 2^{0.5}) = 565.7V$.

The inverter output voltage (RMS) is calculated by

$$V_{rms} = \frac{(m \times Vd)}{\sqrt{2}}, \quad (5.0)$$

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:

i. The MOSFET has an ON-state resistance of $1 \times 10^{-3}\Omega$

ii. For a 5.4Hp, 400V, 50Hz mechanical output power during a discretized model in Simulink, the snubber capacitance of the MOSFET is

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

i. The snubber resistance of the MOSFET

$$R_s = \frac{2 \text{ X } Ts}{Cs} \quad (6.0)$$

$$= \frac{2 \times 10^{-6}}{32 \times 10^{-6}} = 309.84 \text{ ohms},$$

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

  And it is $\frac{400}{50}$ = 8 volts/hertz

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 1.0

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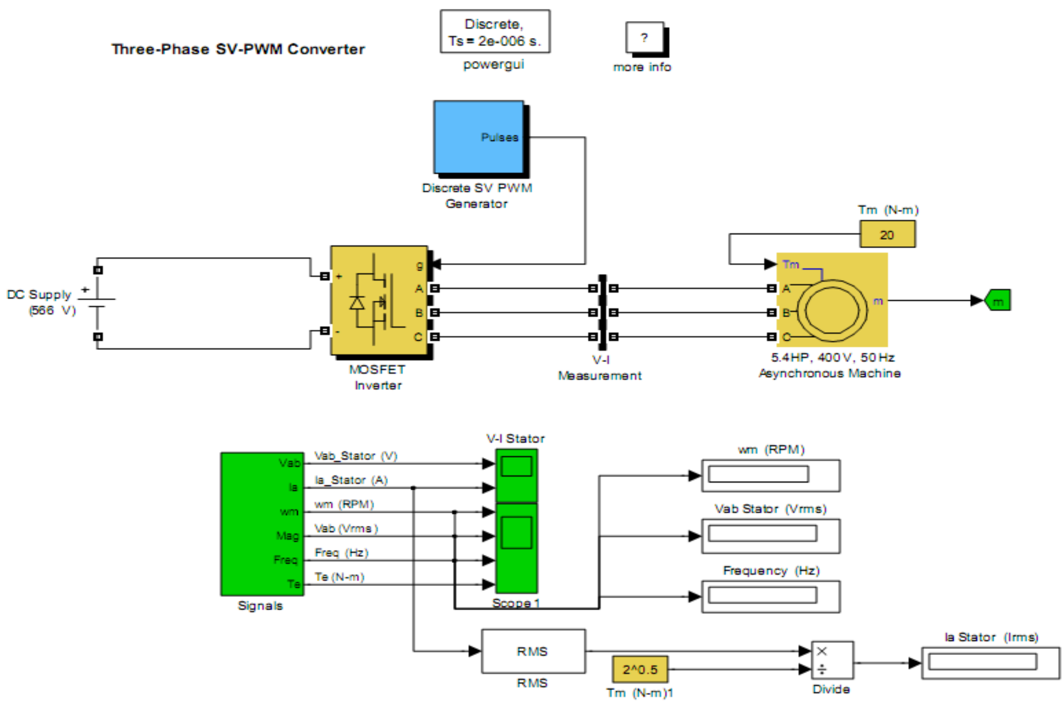

Figure 5.0: Direct on line (Open-loop) control model of an induction motor using constant V/Hz principle and a space vector (SV) PWM technique in MATLAB/Simulink

From table 1.0

Line voltage = 400V and Phase voltage = $\frac{400}{\sqrt{3}}$ = 230.94V

Table 1.0 : Starting energy consumed per second and voltages from open loop at different load torques at 50Hz

	Voltage (V)		Torque (Nm)									
M	Line	phase	T=2	T=3	T=4	T=6	T=8	T=10	T=12	T=13,	T=16	T=20,
M	V_{l-l} (V)	V_p(V)	E (J)	E (J)	E (J)	E (J)	E (J)	E (J)	E (J)	E (J)	E (J)	E (J)
0.10	40	23.09	-	-	-	-	-	-	-	-	-	-
0.15	60	34.64	38.45	-	-	-	-	-	-	-	-	-

0.20	80	46.18	51.26	52.64	54.03	55.42	57.26	-	-	-	-	-
0.25	100	57.73	80.82	82.55	83.71	88.36	89.48	-	-	-	-	-
0.30	120	69.28	117.08	119.85	121.24	126.78	130.93	-	-	-	-	-
0.35	140	80.83	158.43	162.46	165.70	172.17	177.02	-	-	-	-	-
0.40	160	92.37	205.99	212.45	217.07	225.38	231.85	237.30	242.93	-	-	-
0.45	180	103.92	262.92	268.11	275.39	285.78	294.09	301.37	307.60	-	-	-
0.50	200	115.47	325.62	333.71	338.33	353.34	363.73	371.81	379.89	383.36	-	-
0.55	220	127.02	392.49	402.65	411.54	425.52	449.65	458.54	463.62	471.24	-	-
0.60	240	138.56	468.33	479.42	490.50	507.13	522.37	534.84	547.31	551.47	-	-
0.65	260	150.11	549.40	564.41	576.42	589.93	613.95	628.96	642.47	648.47	658.98	-
0.70	280	161.65	638.17	654.68	669.23	691.86	704.79	730.66	746.82	75329	762.99	-
0.75	300	173.21	730.95	750.00	767.32	793.30	815.82	836.60	855.66	862.59	876.44	-
0.80	320	184.75	8.33.22	855.39	873.86	903.42	929.29	944.07	973.581	920.06	934.84	-
0.85	340	196.30	940.28	965.80	985.43	1020.7	1050.2	1075.7	1087.50	1109.09	1126.76	1177.80
0.90	360	207.84	1003.9	1082.8	1105.7	1145.2	1178.5	1207.5	1234.56	1242.88	1263.67	1321.86
0.95	380	219.39	1167.1	1197.8	1222.0	1263.6	1298.7	1331.7	1360.22	1371.18	1408.48	1452.36
1.00	400	230.94	1297.9	1330.2	1357.9	1424.9	1443.3	1478.0	1508.03	1524.20	1561.15	1611.96

- $V_{l\text{-}l}$ 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)
- T is the output torque in Newton-metre (Nm)
- E is the energy drawn by the motor at a given load torgue in Joule (J)

3.2. Design of Classical Optimal Energy consumption Controller

The optimal energy consumed 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 energy consumed by the motor at different load torques were determined using the parameters of the induction motor.

The tables 2.0below shows the average minimum points obtained by fitting curve of the optimal voltages (V_{opt}) and the optimal energy consumption values for different selected load torques at the specified frequencies, and satisfy the best performance for motor operation.

Table 2.0: Optimal stator voltages value, starting current and Energy consumed value within the first two second at starting of different load torques at 50Hz

T [N.m]	**V_{opt}[V]**	**I_s(A)**	**E(J)**
2	92.37	2.23	205.99
3	103.92	2.58	268.11
4	115.47	2.93	338.33
6	150.11	3.94	589.93
8	161.65	4.36	704.79
10	184.75	5.11	944.07
12	196.30	5.54	1087.50
13	207.84	5.92	1242.88
16	219.39	6.42	1408.48
20	230.94	6.98	1613.72
T [N.m]	**V_{opt}[V]**	**I_s(A)**	**E(J)**
2	92.37	2.23	205.99
3	103.92	2.58	268.11
4	115.47	2.93	338.33
6	150.11	3.94	589.93
8	161.65	4.36	704.79
10	184.75	5.11	944.07
12	196.30	5.54	1087.50

13	207.84	5.92	1242.88
16	219.39	6.42	1408.48
20	230.94	6.98	1613.72

The MATLAB Curve Fitting Toolbox was used to derived the relationship between the stator voltage and the energy drawn at different load torques at the same frequency . And the data table 3.4 are shown in figure 6.0 and figure 7.0.

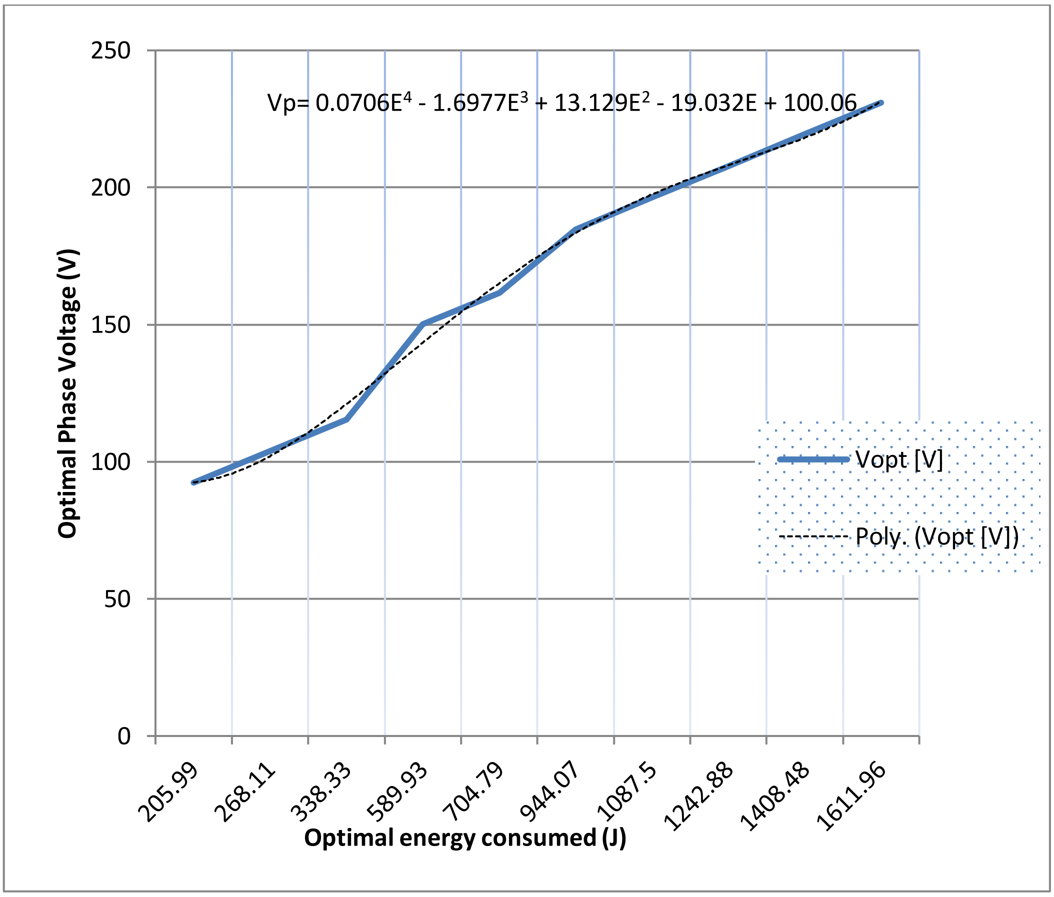

Figure 6.0: Stator Voltage against Energy consumption fitting curve at 50Hz

The optimal energy consumption controller's equation at frequency of 50Hz in figure6.0 from the fitted curve equation is given by

$$V_P = 0.0706E^4 - 1.6977E^3 + 13.129E^2 - 19.032E + 100.06 \qquad (7.0)$$

Let $V_p = a_1 E^4 + a_2 P^3 + a_3 P^2 + a_4 P + a_5$

Where; $a_1 = 0.0706$,

$a_2 = -1.6977$,

$a_3 =$ 13.129

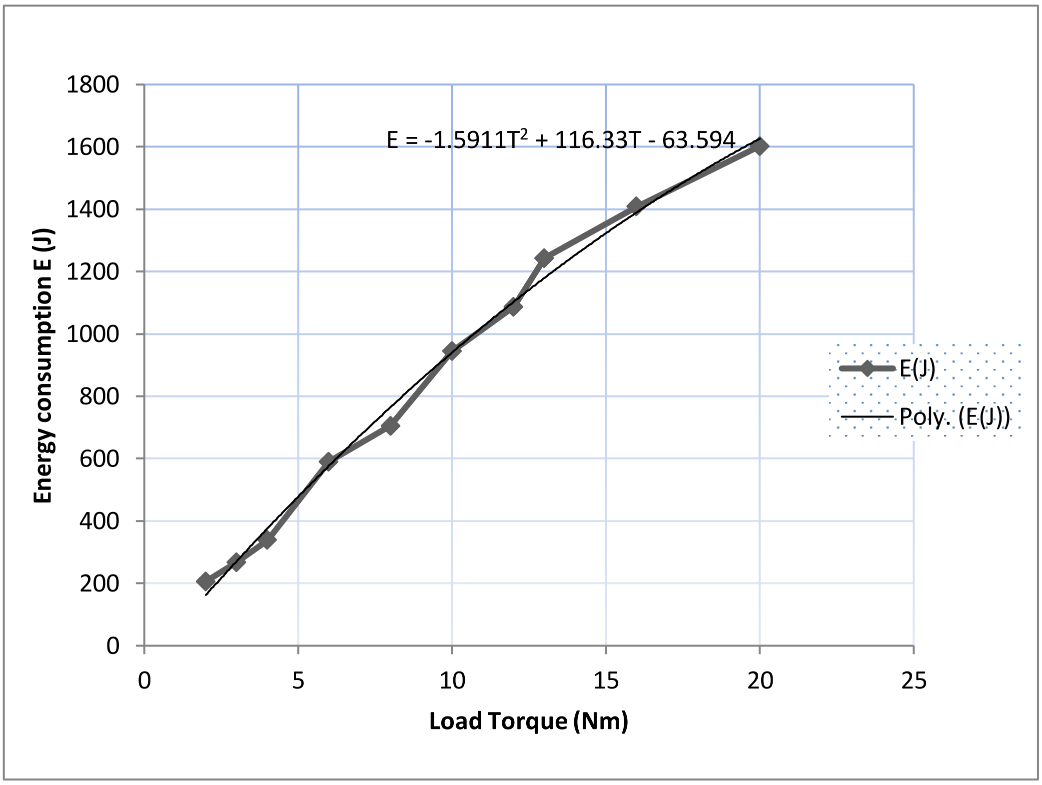

Figure 7.0: Optimal Energy Consumption Value against load torque fitting curve at 50Hz

The equation relating optimal energy consumption and load torque at 50Hz in figure 7.0 from the fitted curve equation is given by

$$E = -1.5911T^2 + 116.33T - 63.594 \quad (8.0)$$

Let $(E) = b_1T^2 + b_2T + b_3$

Where; $b_1 = -1.5911$

$b_2 = 116.33$

$b_3 = -63.594$

3.3. Modeling of Classical Optimal Energy Consumption Controller

Figures 3.4 shows the models of optimal energy consumption controller using equations (7.0) and (8.0) at frequency of 50Hz, The MATLAB/Simulink toolbox was used to build the models.

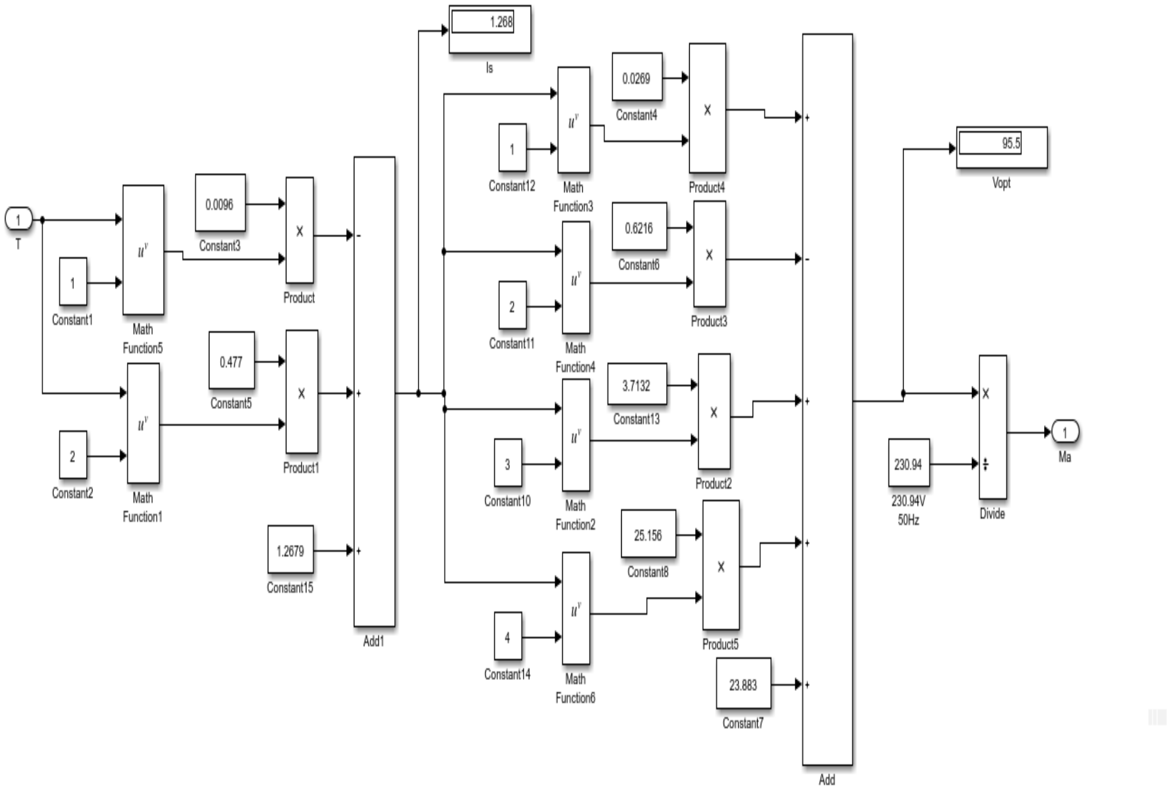

Figure 8.0: Optimal Energy Consumption Controller Model at frequency of 50Hz Using Matlab Simulink

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.

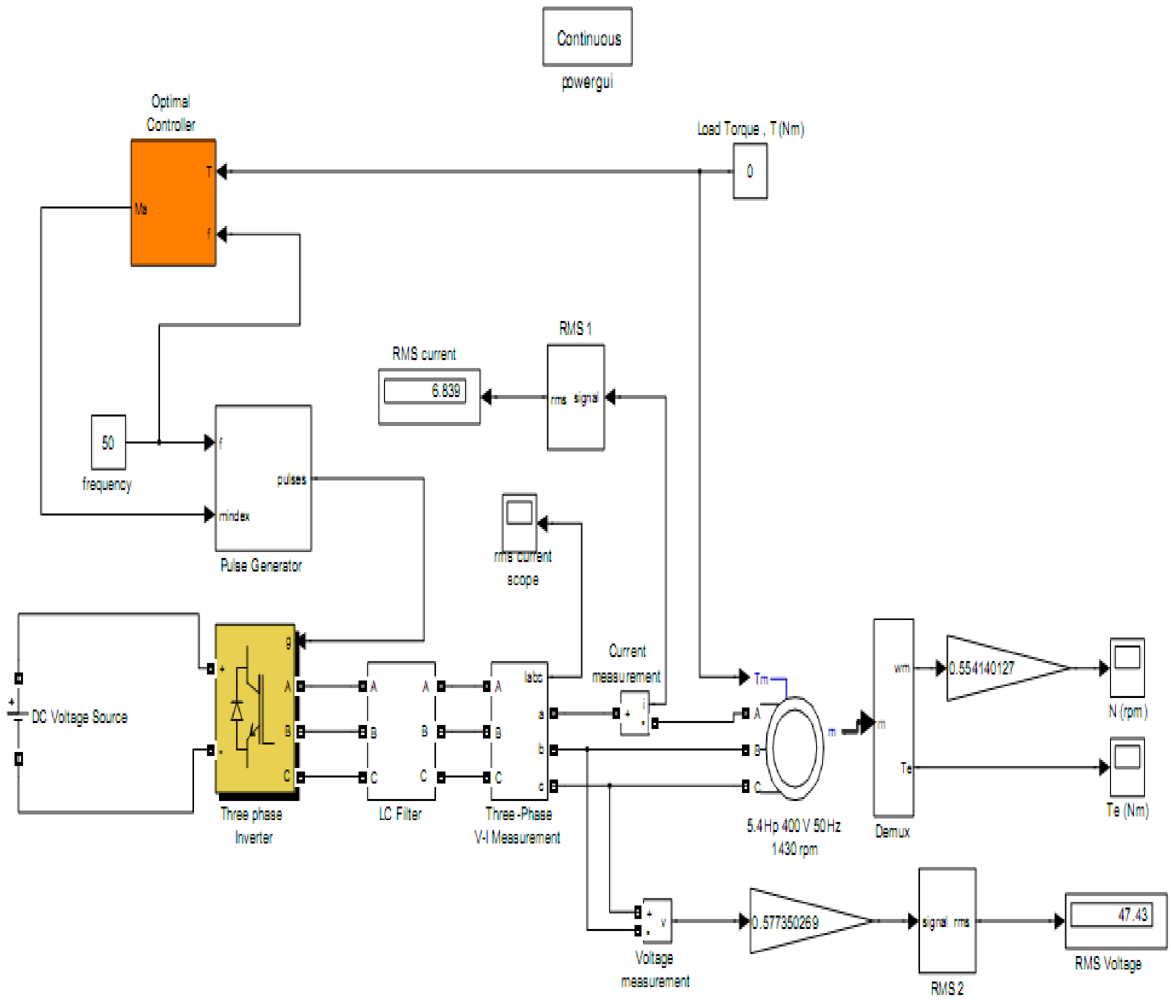

Figure 9.0: Classical Optimal Energy consumption Control System Model Using Matlab Simulink.

7.0: Comparison energy consumed by the induction motor using the Open-loop AC Drive System, and Classical Optimal Control System

The results presented were for open-loop AC drive system, (Direct on line System) and classical optimal control system. All these results are supported by figures that compare the open-loop system and the classical optimal control system.

The comparison of the energy consumed by the induction motor when using open-loop AC drive system and the classical optimal control system at frequency of 50Hz is represented graphical formshown figure 10.0. respectively.

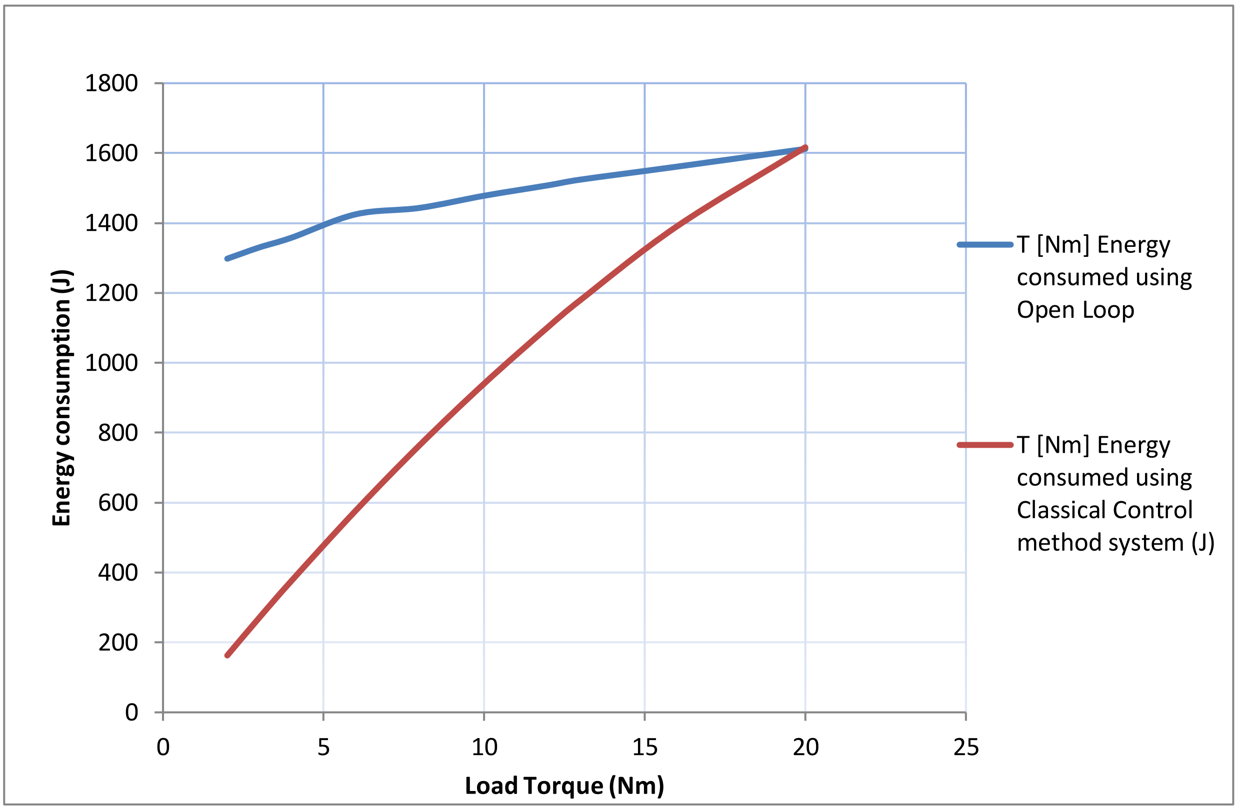

Figure 10.0: Stator Current comparisons at nominal frequency of 50Hz

The open-loop (Direct-on-line) speed control system of an induction motor was set up using the given parameters of the induction motor. The optimal values of the voltage and the optimal values of the energy consumed were computed in line with the following equations (7.0) and equation (8.0) Thestator voltage of the three-phase induction motor was varied by varying the modulation index using the principle of voltage /frequency to take the approximate constant flux. The values of the stator current at load torques for frequency of 50Hz, was recorded in table 1.0,

The information of the induction motor was used to generate the optimal stator energy consumed according to the fitness function for a given frequency value as shown in figure 7.0. The relationships between the optimal energy consumed and the load torque at 50Hz was generated and shown in figures 6.0, and 7.0. The stator voltage and optimal energy consumption a relationship was shown in figure 6.0.

The optimal energy controller models at the frequency of 50Hz shown in figure 8.0 were built using the MatLab program. The models were built using the equations 7.0 and 8.0.

The optimal energy controller models was validated by simulation using a typical induction motor model drive as shown in the circuit diagram in figure 9.0.

A classical energy controller was installed in the open-loop (direct-on-line) system as shown in figure 9.0. And simulation was carried out. The value of energy consumed using the open-loop system was compared to the value of the energy consumed when using the classical current controller system. The optimal controller helped in minimizing the stator current which in turn reduced the energy consumed.

From figure 10.0, it shows at minimum load torque of 2Nm and phase voltage of 230.94V, the starting current of 5.62A drawing energy of 1297.88J when using the open loop method. While using the classical control system, the minimum current was reduced to 2.18A and the energy drawn was reduced to 162.70J. At a torque of 10Nm, the current drawn using the open-loop system was 6.40A consuming 1478.01W of energy while using the classical control system, the starting current was reduce to 5.08A , consuming only 940.60W of energy. At a torque of 16Nm, the starting current drawn using the open-loop system was 6.76A consuming 1478.01W of energy, but when using the optimal controller method, the starting current was reduce to 6.76A, consuming only 1390.36W of energy.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 starting current and energy consumption. The results in figure 4.1 show that when the classical optimal control system if implemented, the stator starting current and energy consumption by the induction motor will be highly minimized when compared to the open-loop AC system.

9.0 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 systemprovides 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.

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