International Journal of Science and Research (IJSR)
ISSN (Online): 2319-7064
Index Copernicus Value (2015): 78.96 | Impact Factor (2015): 6.391

Simulation of the Impact of Soft Starter Controller on Induction Motor Transients

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Abstract: ***This research dwelt on the simulation of the impact of soft starter controller on induction motor transients. It was aimed at resolving the various challenges inherent in the dynamic operation of asynchronous motors, which included current and torque surges during motor start up. The method leading to solution include comprehensive mathematical model of asynchronous motor in both steady state and dynamic state conditions; as well as the development of soft starter control scheme and its application for the motor operational control and finally, the simulation of the impact of soft starter controllers on machines performance or behavior during transients from standstill to synchronous speed was carried out using MATLAB/SIMULINK software. The MATLAB/SIMULINK simulation was used to determine the variation of the starting inrush current and starting torque pulsation under different firing angle between α = (pi/12) rad., and α = (pi/3) rad. With the applied voltage of 220V, the starting current is between +205A and - 180A and the torque pulsation is between -85Nm and +250Nm when connected directly to the supply. It is seen that the starting inrush current is about 3 to 8 times of the motor no-load current. A control scheme is proposed for reducing the inrush current and torque pulsations. It was observed that the inrush current was about ±125A and the torque pulsation is between -150Nm and +130Nm. The inrush current is reduced to about 60.98%. At no-load condition, it is seen that the rotor accelerates from stall with zero load torque to synchronous speed but the time taken to achieve steady state is increased about 0.7sec. The application of load torque (10Nm) at 1sec results in a sharp drop in the motor speed from 186.3 rad/sec. to 185.2 rad/sec. and an increase in the electromechanical torque up to 10Nm with the applied load torque.***

Keywords: Steady state modeling, Dynamic modeling, Asynchronous motor, Mathematical modeling, Soft starter controllers, Torque pulsation, MATLAB/SIMULINK, THD

1. Introduction

The use of induction motors particularly the Squirrel cage rotor has increased tremendously since the day of its invention. The three phase induction motors are the workhorse of industry because of its robust construction, simplicity in design and cost effectiveness, reliability, high efficiency and good self-starting capability and easy maintenance [3-4],[6-7],[11]. These factors have promoted standardization and development of a manufacturing infrastructure that has led to a vast installed base of motors. It has been estimated that 70% to 80% of all electricity in the world is consumed by these motors. They are truly elegant machines in that there are no moving parts except the rotor, and there no brushes, commutators, or slip rings to wear out. It has become the most widely used machine ever invented by man as it now finds application in virtually all aspects of domestic and industrial operations. Single phase and three phase configurations abound all over the world. In homes, the motor is utilized in appliances such as washer, dryers, air conditioning unit, fans, grinding machines, blenders, video CD players, Video cassette recorders and audio tape players. Motor are found even in wristwatch drives, in computer mother boards to drive fans to cool the processor, while in the industries (oil and gas) they find applications in compressors, fans, pumps, blowers, conveyors. The electric motors utilized in all sorts of drives and also as a major component of industrial process, pumping water into a tank as well as pumping crude oil. The electric motor exist in ratings ranging from a few watts to hundreds of megawatts. Although recent research aims at using it for generator applications, but it is best used as motors [10].

In recent years the control of high performance induction motor for general industrial applications and area of production has received a lot of research interest, [2],[5],[12]. Induction motor modeling has continuously attracted the attentions of power system engineers and researchers not only because such motors are made and used in larger numbers but also due to their variant modes of operation both under steady state and transient state, [16]. Various models have been developed and the D-Q axis model for the study of transient behavior has been well tested and proven to be reliable and accurate, [1], [11].

Induction motor variable speed drives, soft starters are also essential components in every modern induction motor drives system. The squirrel cage induction motor is widely deployed in many applications. Whenever an induction motor is started, the electrical system experiences a current surge, and the mechanical system experiences a torque surge. With line voltage applied to the motor, the current can be anywhere between three to eight times the motor full-load current depending on the design characteristics [8-9], [13]. These current and torque surges can be reduced substantially by reducing the voltage supplied to the motor during starting. Soft starter controller offer many advantages over conventional starters such as

- Smooth starting.
- Soft starting and stopping.
- Current peaks are reduced.
- Line voltage fluctuations are avoided when starting
- The line supply is relieved.
- The mechanical stress on the drive is reduced.
- Simple to handle.
- Significant amount of space and wiring is saved when compared to conventional starters.

This paper focuses on development of a soft starter model to control or reduce the starting current and starting torque for a three phase Induction Motor drive. The soft starter uses two anti-parallel connected switches in each phase. Thyristors are used as the switches because of their higher power rating and high efficiency. Fig. 1.1 shows the block diagram of the entire system.

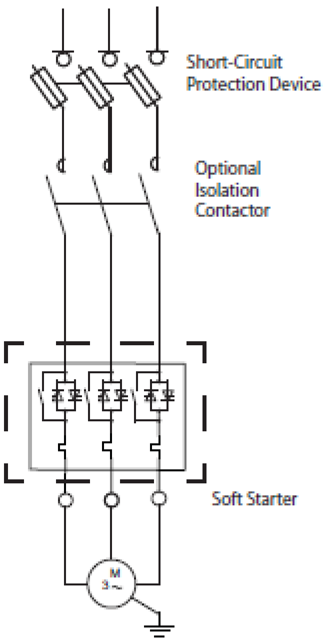

Figure 1.1: Block diagram of Solid-state soft-starter

In Fig. 1.1, the motor is connected to the soft starter at the starting and once the motor get its rated speed then the soft starter is disconnected and the motor drive system take the control over the motor. By using soft starter the controlled voltage is applied at the motor input, so the motor is protected and its life span extended.

2. Mathematical Model of Induction Motor

There are two commonly used dynamic models for the induction motor. These include:

(i) Derivation based on space vector theory and
(ii) Derivation from D-Q axis theory.

The space vector model features compact mathematical expressions and concise space vector diagram, whereas the D-Q axis model does not need the use of complex numbers or variables. Both models are equally valid for the analysis of transient and steady state performance of the induction motor. The motor models in the synchronous rotating reference frame and stationary reference frame are often employed [10].

It is assumed in the following analysis that the induction motor is a three phase symmetrical and its magnetic core is linear with a negligible core loss. The space vector model for induction motor is generally composed of three sets of equations.

i. The Voltage Equations

$$V_{ds} = R_s i_{ds} + \rho\lambda_{ds} - \omega\lambda_{qs} \quad (1)$$

$$V_{qs} = R_s i_{qs} + \rho\lambda_{qs} + \omega\lambda_{ds} \quad (2)$$

$$V_{dr} = R_r i_{dr} + \rho\lambda_{dr} - (\omega - \omega_r)\lambda_{qr} \quad (3)$$

$$V_{qr} = R_r i_{qr} + \rho\lambda_{qr} + (\omega - \omega_r)\lambda_{dr} \quad (4)$$

ii. The flux linkage Equations

$$\lambda_{ds} = L_{ls} i_{ds} + L_m(i_{ds} + i_{dr}) \quad (5)$$

$$\lambda_{qs} = L_{ls} i_{qs} + L_m(i_{qs} + i_{qr}) \quad (6)$$

$$\lambda_{dr} = L_{lr} i_{dr} + L_m(i_{ds} + i_{dr}) \quad (7)$$

$$\lambda_{qr} = L_{lr} i_{qr} + L_m(i_{qs} + i_{qr}) \quad (8)$$

iii. The motion Equations.

$$\frac{J}{P}\rho\omega_r = T_e - T_L \quad (9)$$

The electromagnetic torque is given by

$$T_e = \frac{3PL_m}{4}(i_{dr} i_{qs} - i_{ds} i_{qr}) \text{ Nm} \quad (10)$$

The D-axis and Q-axis equivalent circuit can be drawn using Equations 1, 2, 3 and 4. Fig. 1.2 shows the D-Q axis equivalent circuit.

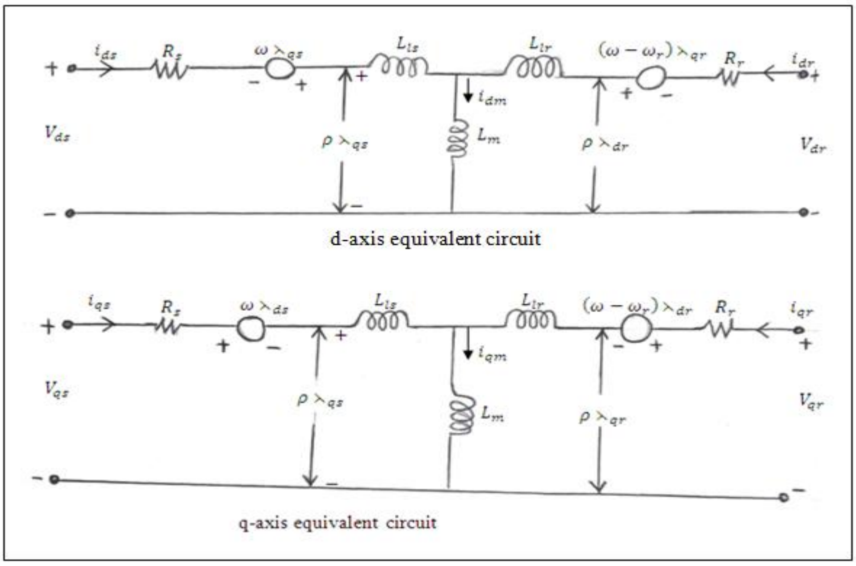

Figure 1.2: Equivalent Circuit Representation of Induction Motor In The Synchronous Rotating Reference Frame

3. MATLAB/SIMULINK

The performance of the proposed system can be evaluated accurately by using proper simulation models. The models should be flexible and accurate to take into account the real time implementation issues as well. With the rapid development in computer software, new simulation packages which are much faster and user friendly are now available. This paper deployed the use of one such software, the MATLAB/SIMULINK. MATLAB (Matrix Laboratory), developed by Math works Inc., is a software package for high performance numerical computation and visualization. The combination of analysis capabilities, flexibility, and powerful graphics makes MATLAB the premier software package for electrical engineers [15].

MATLAB provides an interactive environment with hundreds of reliable and accurate built in mathematical functions. These functions provide solutions to a broad range of mathematical problems including matrix algebra, complex arithmetic, linear systems, differential equations, signal processing, optimization, non-linear systems, and many other types of scientific computations.

In Universities, Polytechnics and colleges of education, it is the standard instructional tool for introducing an advanced course in mathematics, science and engineering. In industry, MATLAB is the tool for high productivity research, development and analysis.

In this modern period, almost all the processes and techniques are first simulated before their actual real time implementation. This reduces a significant portion of effort and cost of real time implementation and loss of man hour [17]. Fig. 1.3 shows the SIMULINK model of three phase induction motor direct online starter.

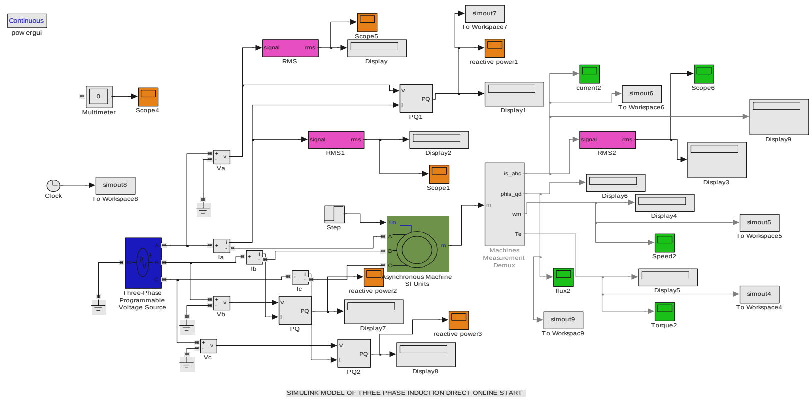

Figure 1.3: SIMULINK Model of Three Phase Induction Motor Direct On Line Starter

4. Simulation Model of Soft Starter Controller

In technical terms, a soft starter is an electronic device which reduces the starting current and starting torque applied to the electric motor by means of controlling the applied voltage by changing the firing angle every half cycle. The basic three-phase induction motor drive scheme is illustrated in Fig. 1.1, where the power switches are thyristors. In this test system, the supply to the induction motor is not direct but through thyristors. A soft starter consists of a number of anti-parallel thyristors, two in each phase. These thyristors are semi-conductor components which normally are isolating but by sending a firing signal, they can start to conduct, allowing the voltage and current to pass through. By allowing more and more of the voltage to pass through the thyristors, this is seen as a ramping up of the voltage from initial voltage to full voltage.

There is no exact rule that can be applied to define what time value should be set and which would be the best pedestal voltage value for the motor to guarantee the acceleration of the load. In a soft starter, voltage control must be done in both directions of the current. An anti-parallel configuration of two thyristors per phase must be used and are connected both in series and parallel to meet the high voltage and high current demands respectively. This method has the ability to regulate or control the supply voltage to the machine.

Three-phase sinusoidal voltages are generated using three independent voltage sources having phase difference of 120^0 and magnitude of 220V. The 220V sinusoidal voltage is generated using voltage source block from SIMULINK Library. The output of soft starter is connected to the input of a three-phase induction motor. Simulation is carried out and the various operating conditions, the No-load and on load, balanced voltages were analyzed and presented graphically. Also the total harmonic distortion (THD) in the output current and the resulting values were recorded. The controllable range of the firing angle of the Thyristor used was between α = (pi/12) rad. and α = (pi/3) rad. Fig. 1.4 shows the SIMULINK model of three phase soft starter connected to a three phase motor.

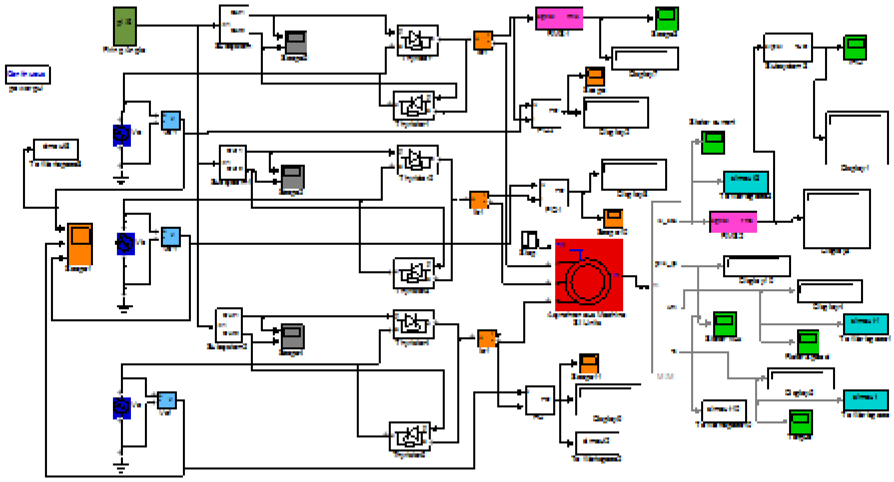

Figure 1.4: SIMULINK Model of three phase soft starter connected to a three phase motor

5. Simulation Results

In this paper, we will examine the starting performance (Torque, Speed and Current) of some of these methods on a 10HP, 4 pole, 220V, three phase, 60Hz, squirrel-cage induction motor with the following parameters;

Table 1.1: Three Phase Induction Motor Parameters

Stator Resistance (R_s)	0.531 Ω
Rotor resistance (R_r)	0.408Ω
Stator leakage inductance (L_{ls})	0.0025H
Rotor leakage inductance (L_{lr})	0.0025H
Magnetizing inductance (L_m)	0.085H
Moment of inertia (J)	0.1Kgm^2

The effect of varying parameters such as motor current, torque and speed of the three phase induction motor are investigated and results are analyzed. To illustrate the transient operations of the induction motor, a simulation study of direct on line starting and soft starting is demonstrated, the motor, was de-energized and at standstill, is connected to a 220V, 60Hz, three phase balanced supply through a cable. The load Torque 'T_L' applied to the motor shaft is variable and set to any value between 0 to 10Nm.

Effect of the Soft Starter on the Motor Current

The best way to observe the effect or the impact of a soft starter controller on the induction motor is to compare the motor inrush current when a soft starter is used to the inrush current when a Direct on Line starter is used.

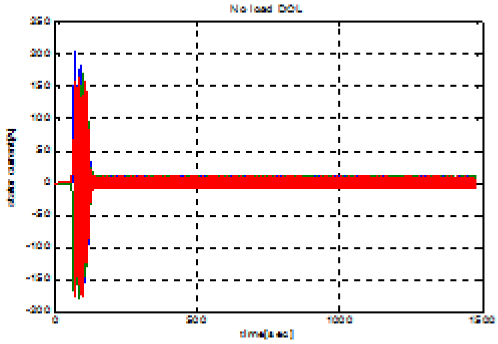

Figure 1.5: Stator current on No-load (DOL)

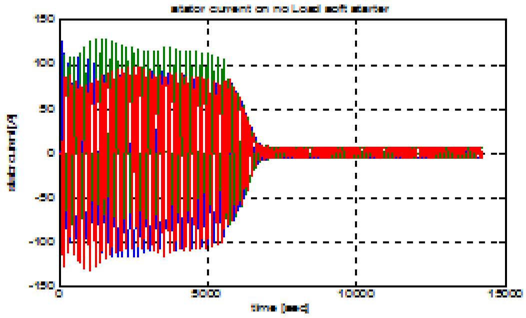

Figure 1.6: Stator current on No-load (SOFT START)

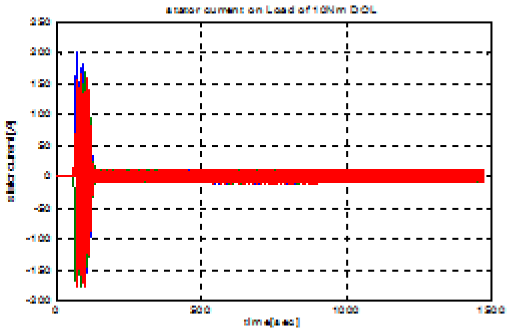

Figure 1.7: Stator current on 10Nm-load (DOL)

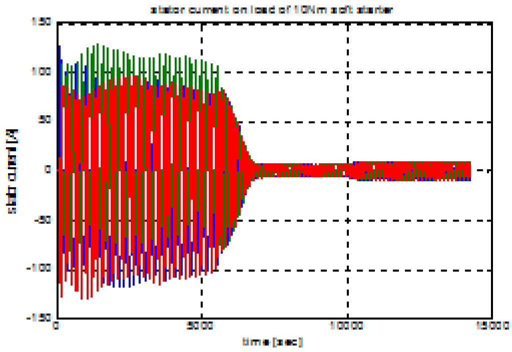

Figure 1.8: Stator current on 10Nm-load (SOFT START)

With a DOL starter, the motor current is maximal at the instant the starter applies power to the motor winding and decreases gradually as the motor gains speed. As the motor approaches full speed, the current decreases more rapidly until it stabilizes at a steady state value when the motor reaches full speed. The value at which the current stabilizes depends on the torque opposing rotation (mainly due to friction). The higher the inertia of the mechanical load coupled to the motor, the longer the current stays high since the motor takes more time to reach full speed. If the current stays high for too long, the motor windings are at risk of overheating and the over load protection trips or the motor burns if it has no functional over load protection.

By contrast, soft starter does not apply the full voltage to the motor windings at start up. Instead, the voltage is gently ramped up to full voltage. This reduces the current that the motor draws and keeps it significantly lower than when a DOL starter is used. As the motor speed increases, the current increases slightly but remains much lower than when a DOL starter is used. The motor current decreases rapidly as the motor approaches full speed in somewhat the same way as when the DOL starter is used. Finally, the current stabilizes at a steady state value as when a DOL starter is used. furthermore, the lower maximum current drawn at start up when using a soft starter helps reduce the undesired effects of voltage sags or dip.

Effect of the Soft Starter on the Motor Torque

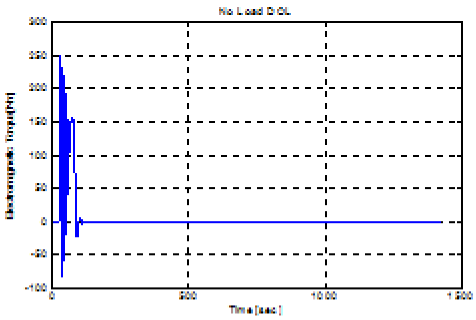

Figure 1.9: Electromagnetic Torque on No-load (DOL)

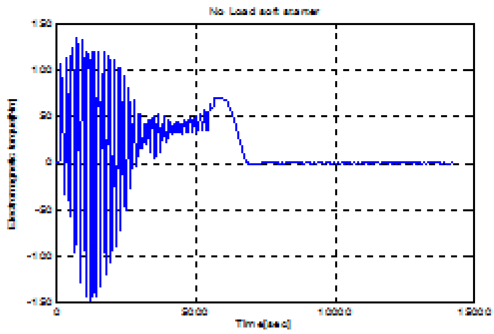

Figure 1.10: Electromagnetic. Torque on No-load (SOFT START)

Paper ID: 11031707 DOI: 10.21275/11031707

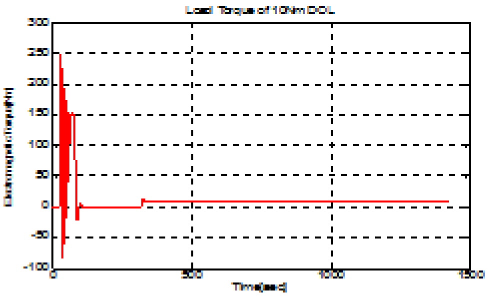

Figure 1.11: Electromagnetic Torque on A-load torque of torque of 10Nm (DOL)

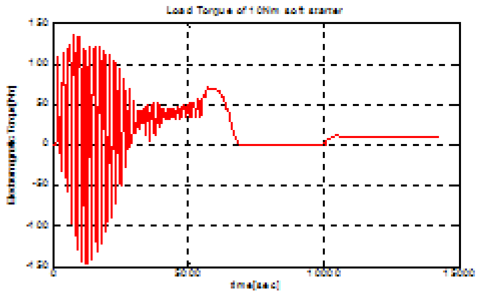

Figure 1.12: Electromagnetic Torque on A-load 10Nm (SOFT START)

With a DOL starter, the full voltage of the power source is applied to the motor at start up and a large torque is exerted on the rotor. This torque is transmitted to the mechanical components connected to the rotor with the aforementioned consequences. Therefore, starting the motor at a reduced voltage using a soft starter also reduces the torque because the torque of induction motor is directly proportional to the square of the voltage applied to the stator windings. Reducing the motor torque at start up is one of the most useful features of soft starters since it reduces the frequency of the mechanical break downs and consequently, the down time and maintenance cost of the equipment.

It is observed that the induction motor exhibits large torque ripple due to transient and settles down to zero in less than 0.7seconds. A step load torque of 10Nm is applied at t=1s, the electromagnetic torque rises and settles to 10Nm and the simulation results are shown in Fig. 1.9 and 1.11. With soft starter, the simulation of the electromagnetic torque characteristics are shown in Fig. 1.10 and 1.12 under various loading conditions and it is observed that the starting torque is reduced compare to the DOL starter.

Effect of the Soft Starter on the Motor Speed

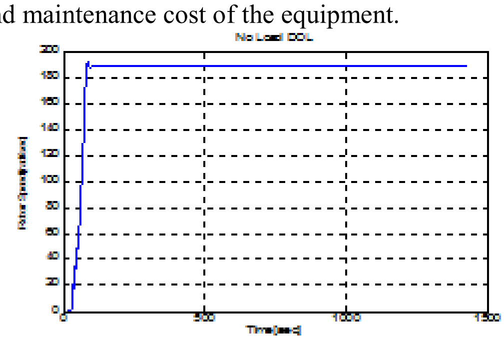

Figure 1.13: Rotor speed on NO load (DOL)

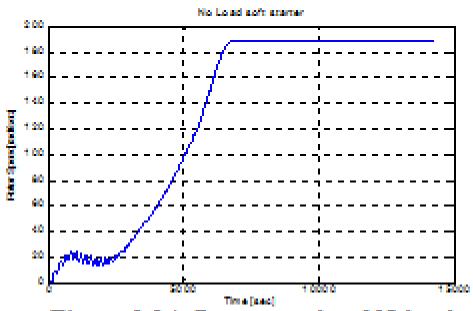

Figure 1.14: Rotor speed on NO load

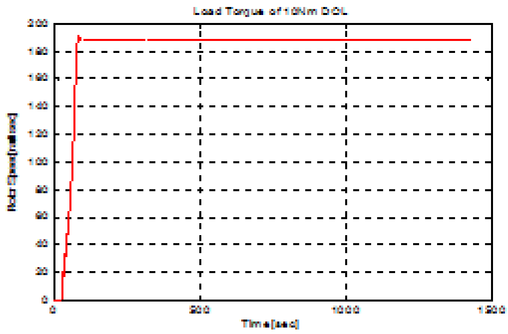

Figure 1.15: Rotor speed on A-load of 10Nm (DOL)

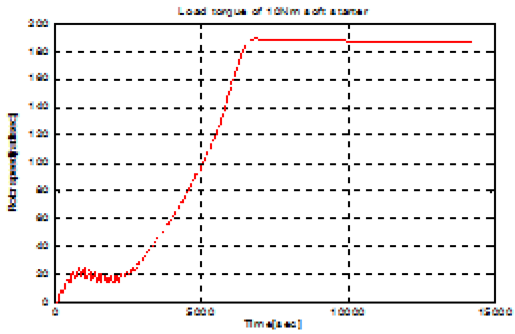

Figure 1.16: Rotor speed on A-load of 10Nm SOFT START)

Starting a motor at reduced voltage using a soft starter has another interesting effect. The induction motor starts with a small ripple due to transient and settles at the final speed of 188.5 rad/sec as shown in Fig. 1.13 on no load and Fig. 1.15 settled at the final speed of 185.2 rad/sec when a load of 10Nm was applied to the motor shaft. But with soft starter controller, the speed settled at 188.5 rad/sec at no load as shown in Fig. 1.14 and when a load torque of 10Nm was applied to the machine, the simulation shows that the rotor speed settled at 186.3 rad/sec. as shown in Fig. 1.16. Less voltage applied to the stator windings means the motor produces less torque to accelerate the rotor. Hence, it takes more time for the motor to reach full speed when a soft starter is used.

Table 1.2: Direct Online power consumption and Current with applied load at t = 1s

T (Nm)	Currents (A)			Machine Active and Reactive Power					
	A	B	C	A		B		C	
				Watt	Var	Watt	Var	Watt	Var
0	7.308	7.298	7.182	92.88	1739	-41.02	1739	32.2	1739
10	7.841	7.851	7.527	862.7	1728	538.7	1728	585	1728

Table 1.3: Soft starter power consumption and Current with applied load at t=1s

T (Nm)	Currents (A)			Machine Active and Reactive Power					
	A	B	C	A		B		C	
				Watt	Var	Watt	Var	Watt	Var
0	4.728	4.699	4.716	13.97	735.3	14.01	730.7	17.7	733.4
10	6.36	6.36	6.36	654.7	741.8	654.6	741.9	654.6	741.8

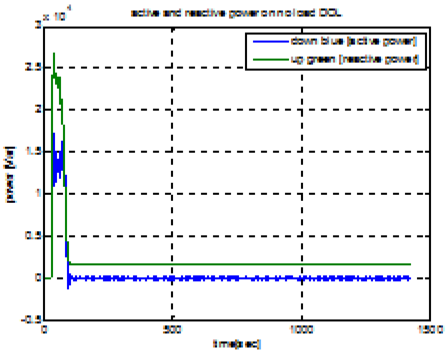

Figure 1.17: Phase A Active and Reactive Power Consumption on No-load (DOL)

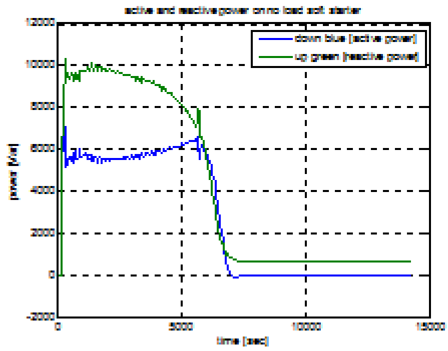

Figure 1.18: Phase A Active and Reactive Power Consumption on No-load (SOFT START)

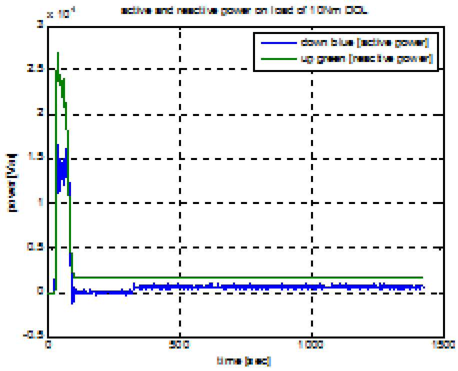

Figure 1.19: Phase A Active and Reactive Power Consumption on a -load of 10Nm (DOL)

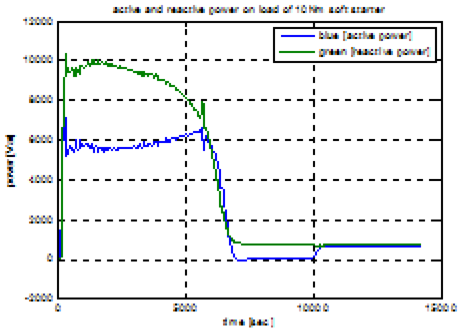

Figure 1.20: Phase A Active and Reactive Power Consumption on a -load of 10Nm (SOFT START)

As observed in the Tables and Figs. above, the starting inrush current under DOL test system is found to be 205A on no load condition and the steady state current was approximately 7.3A. The power consumption was found not to be balanced under no-load condition in the three phases. When a load of 10Nm was applied at the shaft, the power consumption was 862.7W and 1728Var in phase A while phases B and C were (538.7W and 1728Var) and (585W and 1728Var) respectively, while for the soft starter at firing angle of (pi/6) rad., it shows that the starting inrush current was 125A and the steady state current was approximately 4.7A. The power consumption was found not to be balanced under no-load condition in the three phases. When a load of 10Nm was applied at the shaft of the induction motor, the power consumption was 654.7W and 741.8Var in phase A while phases B and C were (654.6W and 741.9Var) and (654.6W and 741.8Var) respectively. The power consumption was balanced under loading condition unlike the DOL test results. At higher firing angle greater than 30^0 the power consumption and the stator current of the machine increases.

Total Harmonic Distortion (THD) for Thyristor Firing Angle

Total Harmonic Distortion (THD) is a widely used notion in defining the level of harmonic content in alternating signals. This value is defined as the ratio of the sum of the powers of all harmonic components to the power of the fundamental frequency. The THD of the currents signal at various firing angle under light and heavy loading conditions are presented in table 1.4 through 1.6. The range of firing angle investigated was between α = ***(pi/12)*** rad. and α = ***(pi/4) rad***. During the simulation, the various loadings were applied at t=1s and the THD records were taken at t=1s

Table 1.4: THDs of Current for Soft Start with applied load at t= 1s, α = (pi/12) rad

T (Nm)	Total Harmonics Distortion (THD)		
	A	B	C
0	0.6352	0.6127	0.6414
10	8.914	12.39	10.88

Table 1.5: THDs of Current for Soft Start with applied load at t=1s, α = (pi/6) rad

T (Nm)	Total Harmonics Distortion (THD)		
	A	B	C
0	0.6902	0.6101	0.7021
10	8.483	8.836	8.38

Table 1.6: THDs of Current for Soft Start with applied load at t= 1s, α = (pi/4) rad

T (Nm)	Total Harmonics Distortion (THD)		
	A	B	C
0	1.242	0.9849	1.355
10	1.277	1.056	1.358

Table 1.7: THDs of Current for Soft Start at different firing angle

T_L (Nm)	Firing angle (α)	Total Harmonics Distortion (THD)		
		A	B	C
0 No - Load	$Pi/12$	0.6352	0.6127	0.6414
	$Pi/6$	0.6902	0.6101	0.7021
	$Pi/4$	1.242	0.9849	1.355
	$Pi/3$	1.894	1.051	1.579
10	$Pi/12$	8.914	12.39	10.88
	$Pi/6$	8.483	8.836	8.38
	$Pi/4$	1.277	1.056	1.358
	$Pi/3$	1.698	0.9225	1.366

The results of the harmonic analysis show that the Total Harmonic Distortion (THD) increases for higher values of firing angle (α) when the motor is running on no-load, which indicates the increased harmonics in the line current while the THD decreases for higher values of α when a load of 10Nm is applied to the shaft of the motor which indicates a decreased harmonics in the line current. It is to be noted that THD is significantly lower for motor load during light loading and higher for heavy loading. It is observed that the response is faster for small firing angle and the response becomes slower for bigger firing angle. This is due to lower average output voltage of the Thyristor. At (pi/6) rad. firing angle, the stator current and torque settles to their steady state values once the motor attains the steady speed. On the other hand it is observed that the speed response contains ripples, the firing angle increases, and the power consumption of the motor also increases.

CONCLUSION

This paper presents a comprehensive models using MATLAB/SIMULINK in the simulation of the impact of soft starter controller on induction motor transients. The model is based on; the D-Q transformation covers the steady state operations and dynamic behaviors as well as the control scheme of the induction motor. The model is quite versatile and capable of simulating the induction motor during a sudden change in load torque.

The proposed scheme proved effective for the transients' behavior of the machine. It is observed that the motor performs satisfactorily at the firing angle of (pi/6) rad., but when the magnitude of the firing angle is increased beyond the value of (pi/5.6) rad., the motor become unstable. For a steady state operations of the drive system, the safe firing angle of the thyristor should ≤ (pi/6) rad. It is also observed that for a larger values of firing angle (α), the (THDs) decreases when a torque load of 10Nm is applied to the shaft of the motor and also the THD increases for higher values of firing angle (α) when a the motor is operating on no-load, the rotor speed of the motor changes, the stator current and the active and reactive power of each phase becomes unbalanced and the machine may fail to start in critical situation or conditions.

The simulation models of this research work can be integrated into electrical machines courses in electrical/Electronic engineering department in the Universities and polytechnics. This will help students to understand the principles of operation of the induction motor, dc motors and other types of electrical motors. In order to incorporate the simulation model of the induction motor into the courses, the laboratory practice section should be divided into two parts, the software laboratory and the hardware laboratory sections, where students can carry out the simulation aspect of the study of machines.

Also in the industries, this control scheme work can be integrated into the manufacturing line of electrical motors which will enhance the production of more efficient and rugged motors.

Nomenclature

d	Direct Axis
Q	Quadrature Axis
S	Stator variable
R	Rotor variable
X_m	Magnetizing reactance
X_{ls}, X_{lr}	Stator and rotor leakage reactance
f	Frequency
P	Number of poles
J	Total moment of inertia of the rotor and load.
T_L	Load torque
T_e	Electromagnetic output torque
L_s, L_r	Stator and rotor self inductance.
L_m	Magnetizing inductance
L_{ls}, L_{lr}	Stator and rotor leakage inductance.
R_s, R_r	Stator and rotor winding resistance.
ω_r	Rotor angular speed (Electrical)
$\omega,$	Rotating speed of an arbitrary reference frame
ρ	Derivative operator = d/dt
V_{ds}, V_{qs}	d-axis and q-axis stator voltage.
V_{dr}, V_{qr}	d-axis and q-axis rotor voltage.
I_{ds}, I_{qs}	d-axis and q-axis stator current.
I_{dr}, I_{qr}	d-axis and q-axis rotor current.
$\hat{I}_s, \hat{I}_r$	Stator and rotor current vectors.

$\hat{V}_s, \hat{V}_r$	Stator and rotor voltage vectors.
$\hat{\lambda}_s, \hat{\lambda}_r$	Stator and rotor flux leakage vectors.
$J\omega\hat{\lambda}_s$, $J(\omega - \omega_r)\hat{\lambda}_s$	Speed voltages

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