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The Impact of Three Phase Soft Starter Controller on Asynchronous Machine Response to Transients using MATLAB/Simulink

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ABSTRACT

This paper illustrates the impact of three phase soft starter controller during transients on an asynchronous machine in MATLAB/SIMULINK. It was intended by resolving the various challenges inherent in the dynamic operation of asynchronous motors during motor start up. Just as an advancement of three phase soft starter controller and its application for the motor operational control, the proposed strategy arrangement incorporate thorough numerical model of asynchronous motor and comparison was made with the impact of three phase soft starter controllers on machines performance in unfaltering state and dynamic state conditions. The effect of sudden variation of voltage at particular firing angle effects the speed, current and torque along with the starting inrush currents and starting torque pulsations are analyzed at different firing angles in simulation.

KEYWORDS:soft starter controller, asynchronous machine, dynamic state, inrush currents.

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1. INTRODUCTION

Now-a-days the three phase induction motors plays a wide range in industrial drives because of its robust construction, effective self-starting capability,designsimplicity, reliability, high efficiency, low cost and easy maintenance.Induction motors particularly the Squirrel cage rotor has increased tremendously since the day of its invention. 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 well-designed 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. The electric motor exists 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.

A research interest in the recent years is going on in industrial applications and in area of production among one is control of high-performanceasynchronous motor.Modeling ofasynchronous motor attracts power system engineers and researchers continuously and made attention because such motors are produced in bulk number and having variations in their operating mode during steady state and transient state operations.In the study of transient behavior D-Q axis model is a proven and tested model having accuracy and reliable.

The purpose of starter is not only to start the motor safely by optingsome special devices motor can accelerate,stop, reverse, and protect them. Whether it's a small fan, or piece of mining equipment, electric motors are often the driving force behind them.

Soft Starters are a combination of a controller and overload protection.

- **Controllers -** turns electric current to the motor on and off. A contactor is a controller that is controlled by an electromagnet.
- **Overload protection -**protects a motor from drawing too much current and "burning out" from overheating. The overload relay is the motor overload protection used in soft starters. It limits the time the overload current is drawn and protects the motor from overheating.

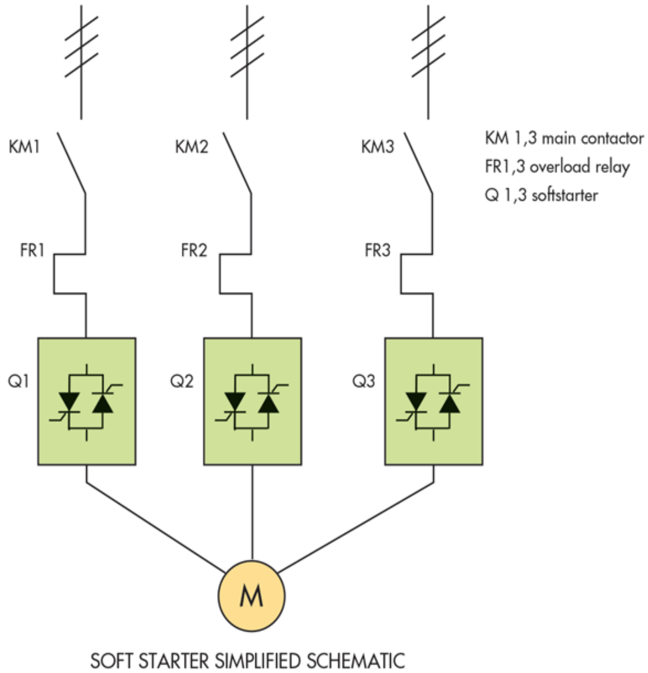

Figure1: Schematic diagram of Soft starter of Asynchronous Machine

2. BEHAVIOR OF ASYNCHRONOUS MACHINE

The electrical and mechanical parameters of an Asynchronous Machine be chooses in MATLAB dialog box either in pu or SI units.

The figure 2 indicates how to connect an Ideal Torque Source block from the Simscape library to the machine shaft to represent the machine in motor mode, or in generator mode, when the rotor speed is positive.

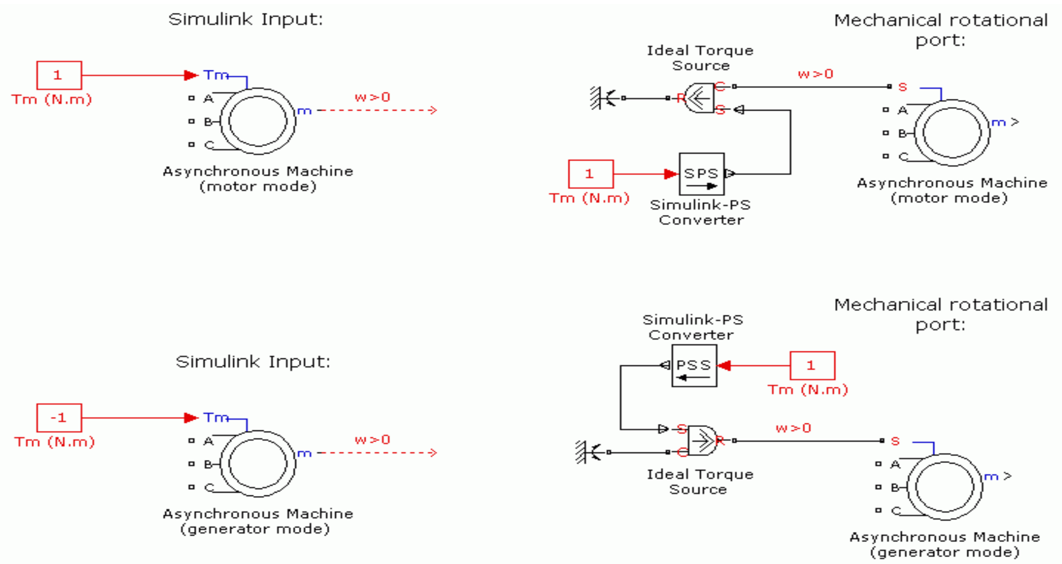

Figure2:Indicates how to connect an ideal torque source block from the Simscape library to the Machine Shaft

The following relationships describe the abc-to-dq reference frame transformations applied to the Asynchronous Machine phase-to-phase voltages.

$$\begin{bmatrix} V_{qs} \\ V_{ds} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2cos\theta & cos\theta + \sqrt{3}sin\theta \\ 2sin\theta & sin\theta - \sqrt{3}cos\theta \end{bmatrix}\begin{bmatrix} V_{abs} \\ V_{bcs} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} V_{qs} \\ V_{ds} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2cos\theta & cos\theta + \sqrt{3}sin\theta \\ 2sin\theta & sin\theta - \sqrt{3}cos\theta \end{bmatrix}\begin{bmatrix} V_{abs} \\ V_{bcs} \end{bmatrix} \quad (2)$$

In the preceding equations, θ is the angular position of the reference frame, while $\beta = \theta - \theta_r$ is the difference between the position of the reference frame and the position (electrical) of the rotor. Because the machine windings are connected in a three-wire Y configuration, there is no homopolar (0) component. This configuration also justifies that two line-to-line input voltages are used inside the model instead of three line-to-neutral voltages. The following relationships describe the dq-to-abc reference frame transformations applied to the Asynchronous Machine phase currents.

$$\begin{bmatrix} i_{as} \\ i_{bs} \end{bmatrix} = \begin{bmatrix} cos\theta & sin\theta \\ \frac{-\cos\theta + \sqrt{3}sin\theta}{2} & \frac{-\sqrt{3}\cos\theta - sin\theta}{2} \end{bmatrix}\begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} i'_{ar} \\ i'_{br} \end{bmatrix} = \begin{bmatrix} cos\beta & sin\beta \\ \frac{-\cos\beta + \sqrt{3}sin\beta}{2} & \frac{-\sqrt{3}\cos\beta - sin\beta}{2} \end{bmatrix}\begin{bmatrix} i'_{qr} \\ i'_{dr} \end{bmatrix} \quad (4)$$

$$i_{cs} = -i_{as} - i_{bs} \quad (5)$$

$$i'_{cr} = -i'_{ar} - i'_{br} \quad (6)$$

The following table shows the values taken by θ and β in each reference frame (θ_e is the position of the synchronously rotating reference frame).

Table1: The values of θ and β in each reference frame

Reference Frame	θ	β
Rotor	θ	0
Stationary	0	− θ
Synchronous	θ	$\theta - \theta_r$

The choice of reference frame affects the waveforms of all dq variables. It also affects the simulation speed and in certain cases the accuracy of the results.

3.MATHEMATICAL MODELLING OF INDUCTION MOTOR

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

(i) space vector theory and

(ii) D-Q axis theory.

Both models are valid to study the transient and steady state performance of an induction motor but the only difference is space vector model uses mathematical expressions and concise space vector diagram, whereas D-Q axis model no need to use complex numbers or variables. The motor models in the synchronous rotating reference frame and stationary reference frame are often employed.

It is assumed in the following simulation analysis that the asynchronous 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. Voltage Equations: -

$$V_{ds} = R_s i_{ds} + \frac{d}{dt}\varphi_{ds} - \omega\varphi_{qs} \quad (7)$$

$$V_{qs} = R_s i_{qs} + \frac{d}{dt}\varphi_{qs} + \omega\varphi_{ds} \quad (8)$$

$$V_{dr} = R_r i_{dr} + \frac{d}{dt}\varphi_{dr} - (\omega - \omega_r)\varphi_{qr} \quad (9)$$

$$V_{qr} = R_r i_{qr} + \frac{d}{dt}\varphi_{qr} + (\omega - \omega_r)\varphi_{dr} \quad (10)$$

ii. The flux linkage equations: -

$$\varphi_{ds} = L_{ls} i_{ds} + L_m(i_{ds} + i_{dr}) \quad (11)$$

$$\varphi_{qs} = L_{ls} i_{qs} + L_m(i_{qs} + i_{qr}) \quad (12)$$

$$\varphi_{dr} = L_{lr} i_{dr} + L_m(i_{ds} + i_{dr}) \quad (13)$$

$$\varphi_{qr} = L_{lr} i_{qr} + L_m(i_{qs} + i_{qr}) \quad (14)$$

iii. The Motion Equations

$$\frac{J}{P} * \frac{d}{dt}\omega_r = T_e - T_l \quad (15)$$

The electromagnetic torque is given by

$$T_e = \frac{3PL_m}{4}(i_{dr} i_{qs} - i_{ds} i_r)\text{Nm} \quad (16)$$

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

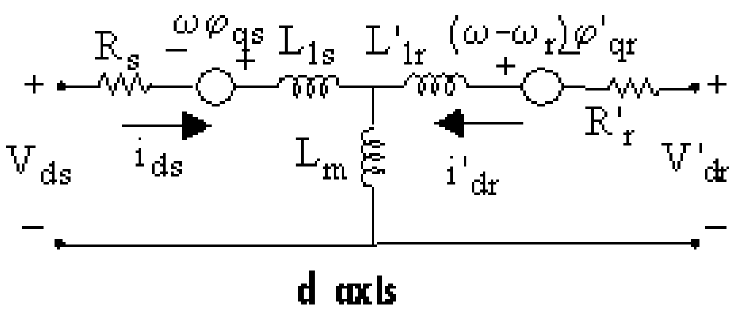

Figure3:d-axis Equivalent circuit of Induction motor

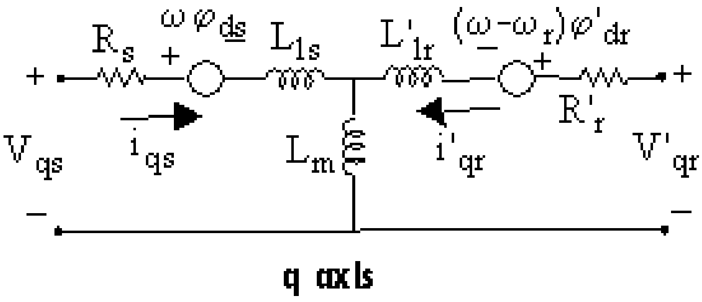

Figure4: q-axis Equivalent circuit of Induction motor

4. SIMULINK MODEL OF INCORPORATING DOL STARTER IN THREE PHASE INDUCTION MOTOR

In this modern period, almost all the processes and techniques are first simulated before their actual real time implementation, thus reduces a significant portion of effort and cost of real time implementation as well as loss of man hour. Figure 5 shows the SIMULINK model of three phase induction motor direct online starter.

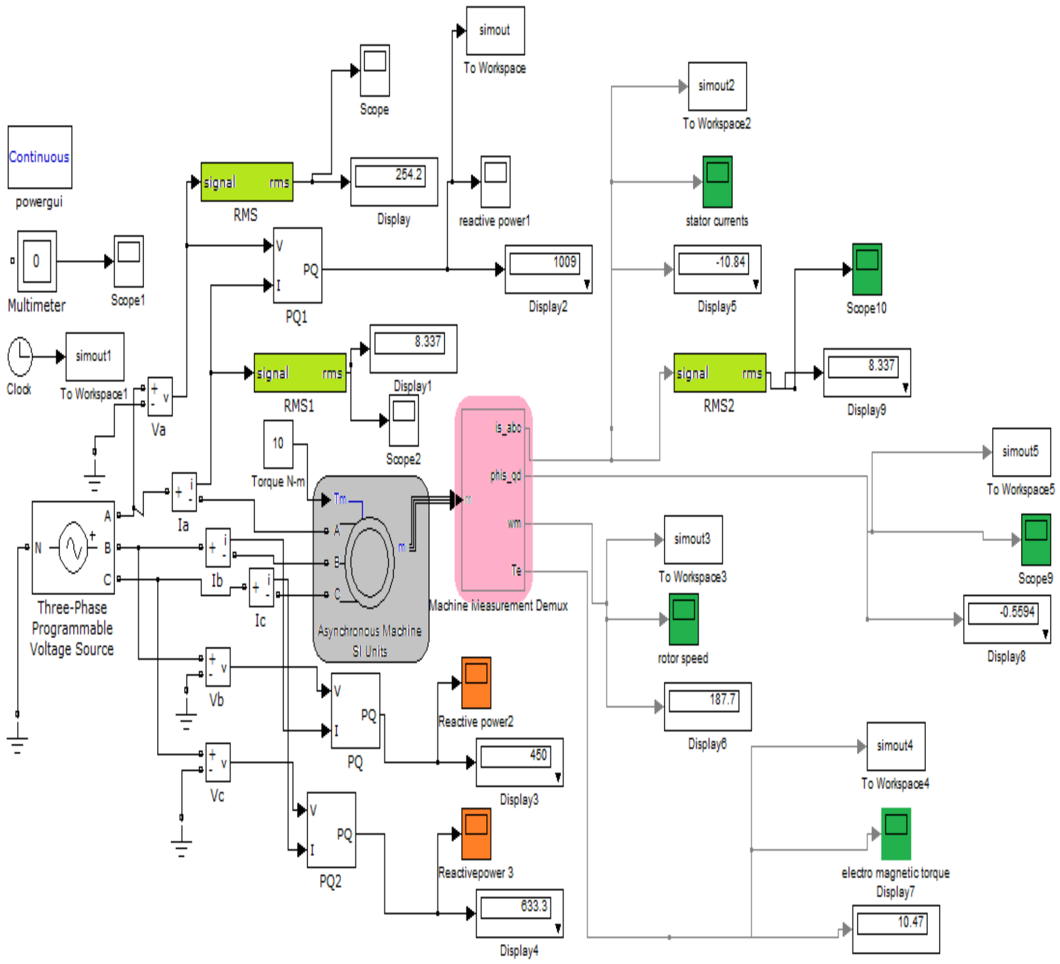

Figure5:Simulink Model ofThree Phase Induction Motor with incorporating DOL Starter and 10N-m loading

5. SIMULINK MODEL OF THREE PHASE INDUCTION MOTOR WITH INCORPORATING SOFT STARTER CONTROLLER

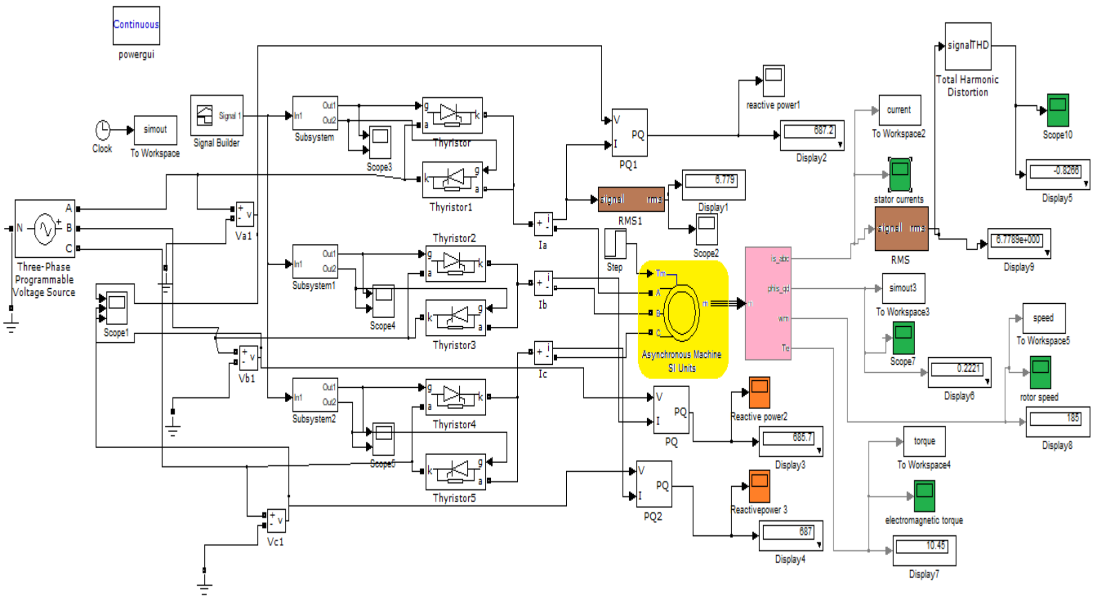

Figure6:Simulink Model of Three Phase Induction Motor with incorporating Soft starter Controller and 10N-m loading

The 220V sinusoidal voltage is generated using voltage source block from SIMULINK Library, while the output of three phase soft starter is connected to the input of a three-phase induction motor. Simulation is carried out under the following motor operating conditions: No-load, and on load. The balanced voltages were analyzed and presented graphically, while the total harmonic distortion (THD) in the output current and the resulting values were determined. The firing angle range of the Thyristors deployed are between $\alpha = (\Pi/12)$ rad. and $\alpha = (\Pi/3)$ rad. The SIMULINK model of three phase soft starter connected to a three phase motor is shown in Figure 6

6. SIMULATION RESULTS

This theory is tested on 10HP, 4 poles, 220V, three phase, 60Hz, squirrel-cage induction motor with the following parameters and observe the starting performance of the machine(Torque, Speed and Current)

Table2: 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)	0.1Kg m^2

The effect of varying parameters such as motor current, torque and speed of the three-phase induction motor are investigated and results are studied. 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 deenergized 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.

6.1 Influence of the controller Scheme on motor current:

The best way to observe the effect of three phase soft starter controller on the asynchronous motor is to compare the motor inrush current when a three-phase soft starter is used to the inrush current when a Direct on Line starter is used. 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 decrease 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). Conversely, three phase soft starter does not apply the full voltage to the motor windings at start up, rather the voltage is gently ramped up to full voltage thereby reducing 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.

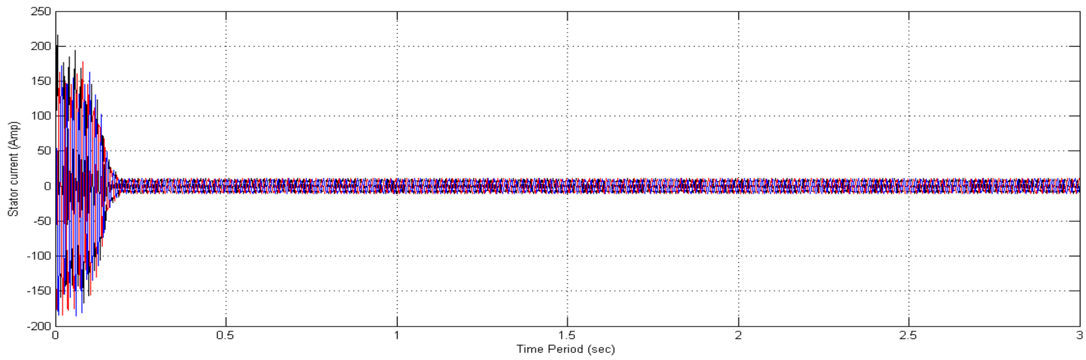

Figure7: Stator Current on No-Load (DOL)

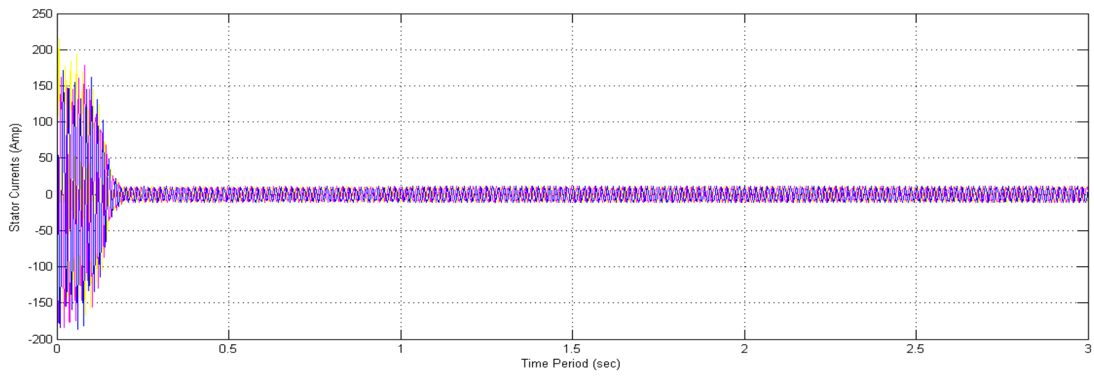

Figure8: Stator Current on a Load of 10 N-m (DOL)

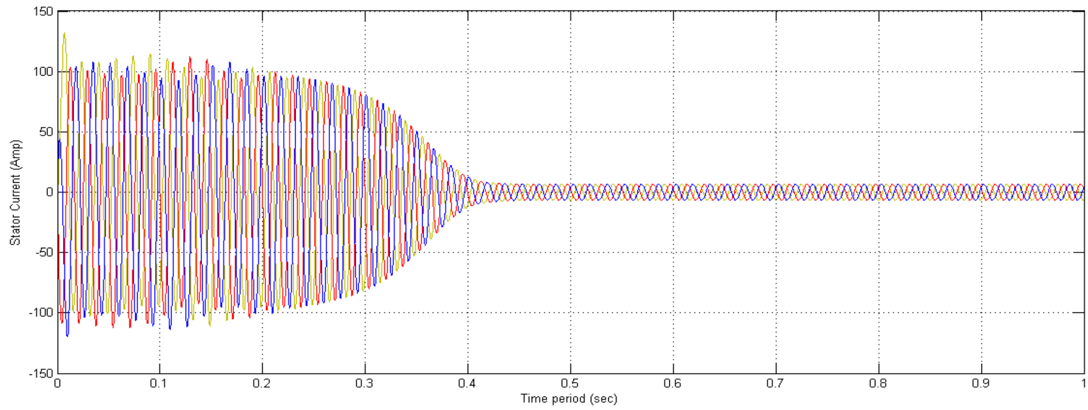

Figure9: Stator Current on No-Load (Soft Start)

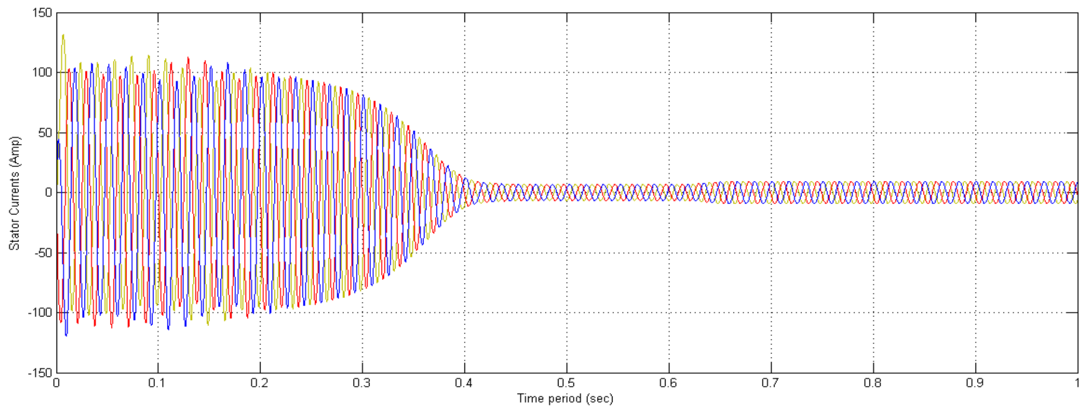

Figure10: Stator Current on a load of 10 N-m (Soft Start)

6.2 Influence of the controller Scheme on motor torque:

It is observed that the asynchronous 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 Figure 11 and figure 13. With soft starter, the simulation of the electromagnetic torque characteristics are shown in Figure 12 and figure 14 under various loading conditions and it is observed that the starting torque is reduced compare to the DOL starter

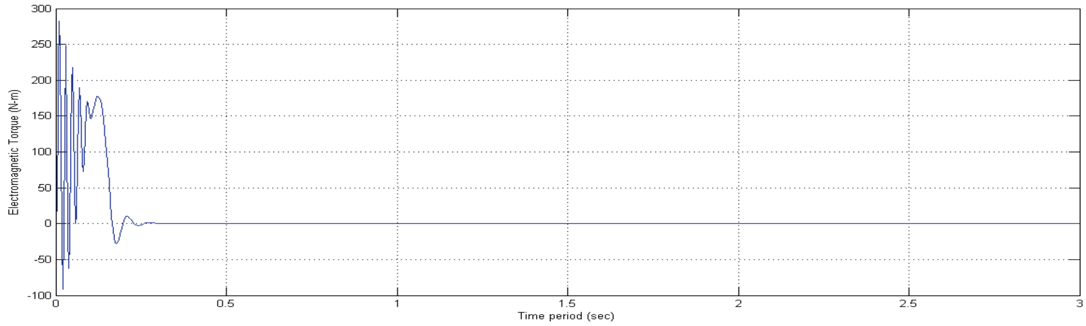

Figure11: Electromagnetic Torque on No-Load (DOL)

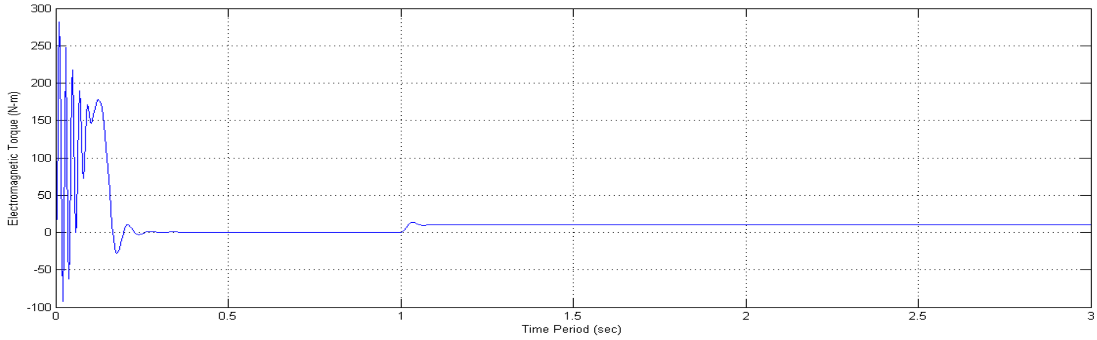

Figure12: Electromagnetic Torque on a load of 10 N-m (DOL)

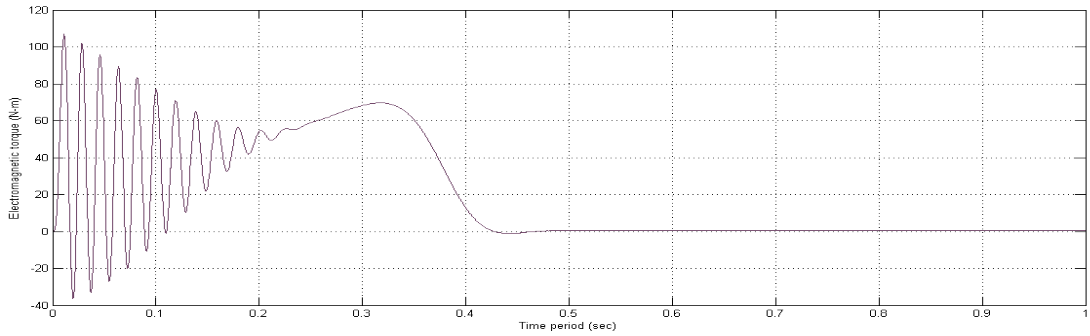

Figure13: Electromagnetic Torque on No-Load (Soft start)

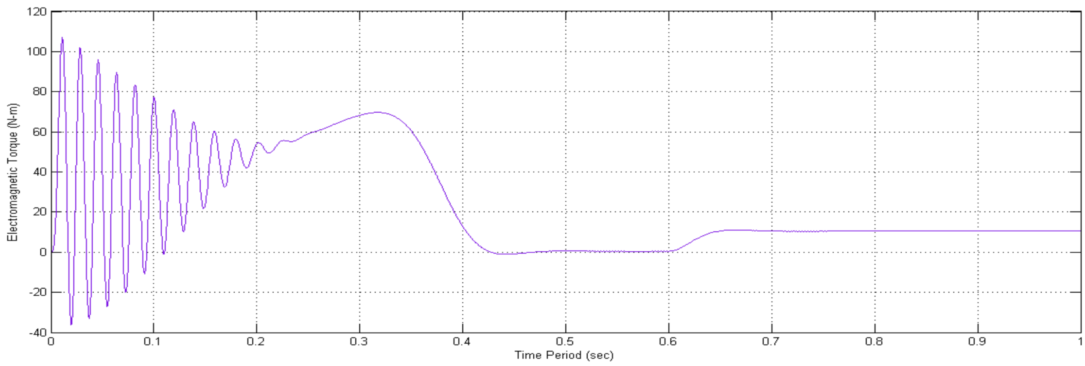

Figure14: Electromagnetic Torque on a load of 10 N-m (Soft Start)

6.3 Influence of the controller scheme on the motor speed:

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 Figure 15 on no load and settled at the final speed of 185.2 rad/sec when a load of 10Nm was applied to the motor shaft as shown in Figure 16. But with a three-phase soft starter controller, the speed settled at 188.5 rad/sec at no load as shown in Figure 17 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 Figure 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 three-phase soft starter is used.

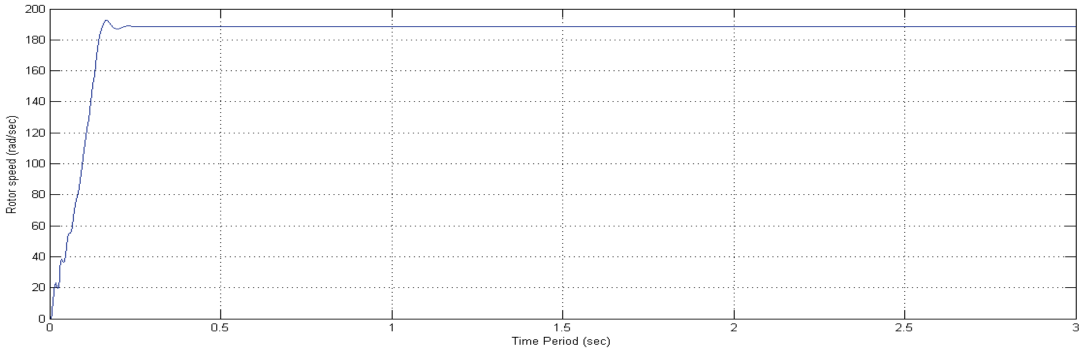

Figure15: Rotor Speed on No-Load (DOL)

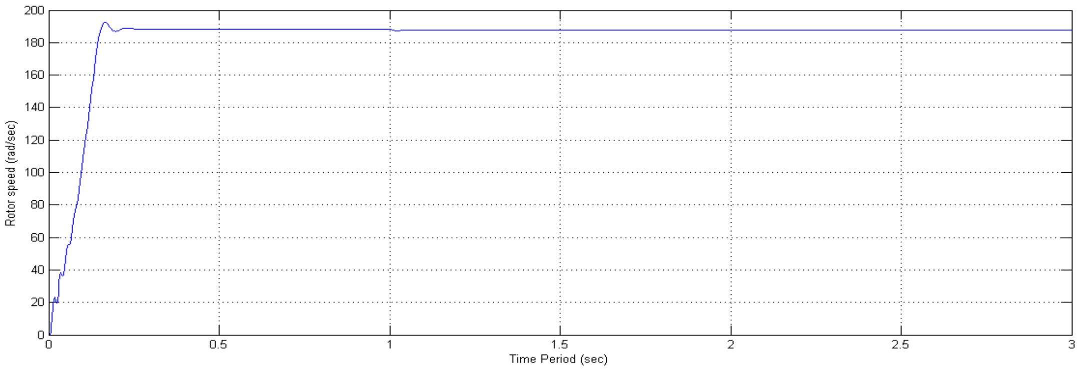

Figure16: Rotor Speed on a load of 10 N-m (DOL)

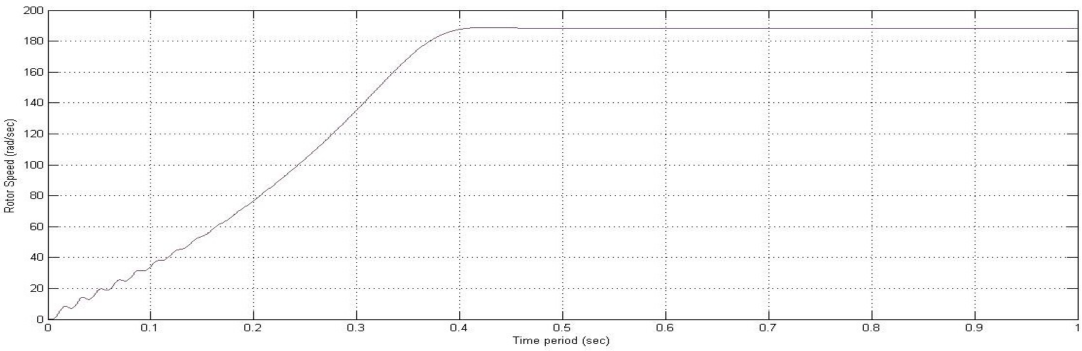

Figure17: Rotor Speed on No-Load (Soft Start)

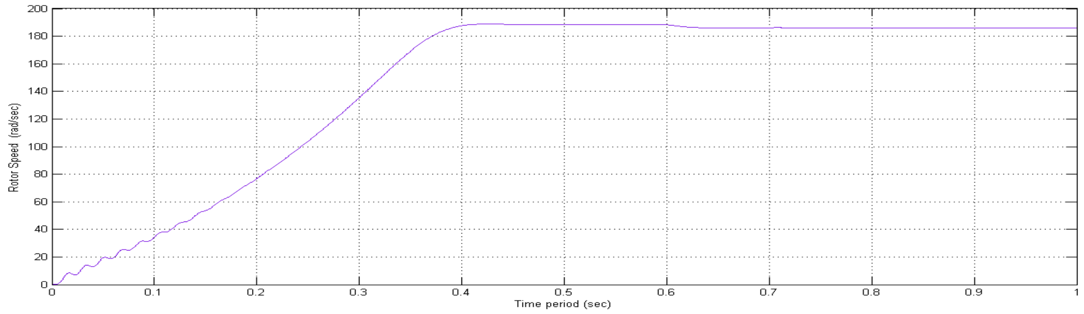

Figure18: Rotor Speed on a load of 10 N-m (Soft Start)

6.4 Transient behavior for variation of input voltage:

When the induction motor runs in steady state if there is any changes in supply voltage then the corresponding Stator currents, Rotor Speed and Electromagnetic torque gets Changes and reaches steady state with small transients upto 0.02 sec.

The Stator current shows transient behavior and slowly reaches steady state that transients' currents are relatively small as compared to starting current that behavior is shown in figure 19.

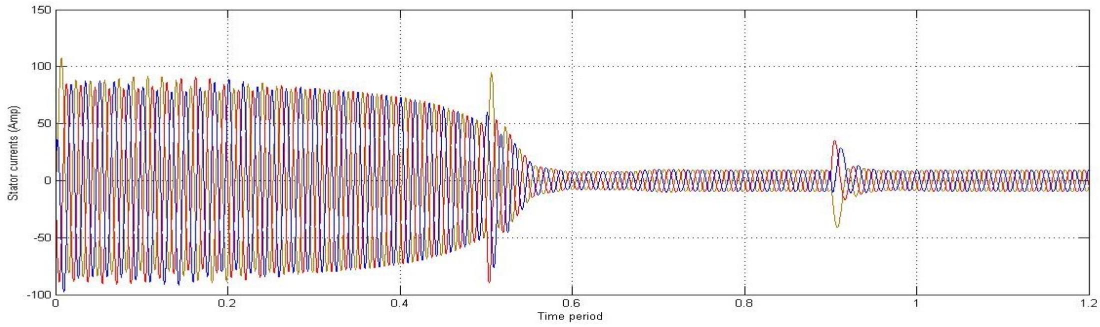

Figure19: Stator Current on a load of 10 N-m with variation in input voltage (Soft Start)

The speed will decrease by changing the voltage in the line. Speed drops from the 188.6 rad/sec to 185 rad/sec. The behaviorof speed is shown in figure 20.

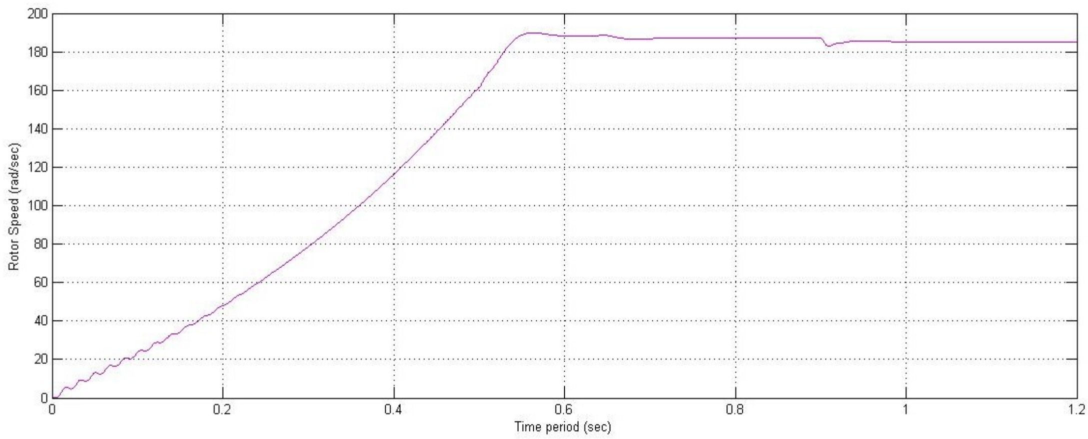

Figure20: Rotor speed on a load of 10 N-m with variation in input voltage(soft start)

The Electromagnetic torque was slightly changing 0.02 N-m by variation of voltage. That transient behavior was shown in figure 21.

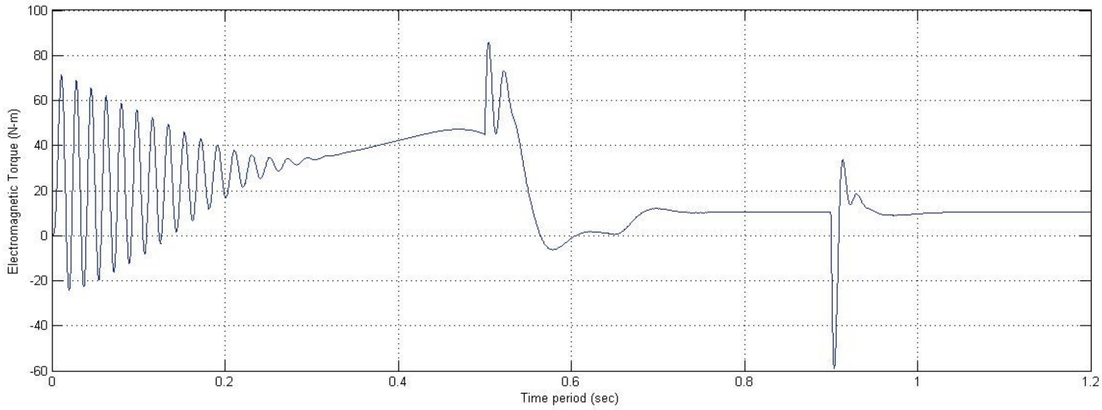

Figure21: Electromagnetic Torque on a load of 10 N-m with variation in input voltage (Soft Start)

6.5 Harmonic distortion (HD) 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 2 through table 4. The range of firing angle investigated was between α = (Π/12) rad. and α = (Π/4) rad. During the simulation, the various loadings were applied at t=1s and the THD records were taken at t=1s.

Table3: THDs of Current for Soft Start at t = 1s, different firing angles with load

Load Torque T (N-m)	Firing angle (α)	Total Harmonic Distortion		
		A	B	C
0	$\pi/12$	0.6352	0.6127	0.6414
	$\pi/6$	0.692	0.6101	0.7021
	$\pi/4$	1.242	0.9849	1.355
10	$\pi/12$	13.319	13.349	13.373
	$\pi/6$	9.483	9.836	9.38
	$\pi/4$	0.9377	0.9256	0.987

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 (Π/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.

7. CONCLUSION

The proposed scheme proved effective for the transient behaviour of the machine. It is observed that the motor performs satisfactorily at the firing angle of (Π/6) rad., but when the magnitude of the firing angle is increased beyond the value of (Π/6) rad., the motor become unstable. For steady state operations of the drive system, the safe firing angle of the thyristor should be ≤ (Π/6) rad. It is observed that for the sudden change of voltage in line the motor shows some transients and causes the change in speed, torque and currents that are relatively small as compared to starting transient behaviour. 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 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 conditions.

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