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A Novel Soft Starter for Three-Phase Induction Motors with Reduced Starting Current and Minimized Torque Pulsations

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Abstract**—*****In this paper a new firing scheme is proposed for the starting of three phase squirrel cage induction motor. The performance analysis of the motor has been carried out using a d-q axis induction motor model. Simple Firing scheme have been proposed to keep the current to a allowable limit during starting, and to eliminate starting torque pulsations. The proposed strategies have been simulated and verified Using Matlab/Simulink. These are shown to be very effective in the elimination of switching transient torques and to reduce the starting inrush current.***

Index Terms**-Induction Motor, Soft Starter, Torque Pulsations, Modeling.**

NOMENCLATURE

J	Moment of inertia in Kg-m^2
i_{ds}, i_{qs}	2-phase stator currents in Ampere
i_{dr}, i_{qr}	Transformed two phase rotor currents in Amperes
r_s, L_s	2-phase stator resistance in ohms and inductance in Henry
r_r, L_r	2-phase stator resistance in ohms and inductance in Henry referred to stator in ohms
T_e	Electromagnetic Torque in N-m
T_L	Load Torque in N-m
L_m	mutual inductance in Henry
w_r	rotor speed in rad/sec
P_o	Number of poles
V_{ds}, V_{qs}	2-phasee stator voltage in Volts.

I. INTRODUCTION

DIRECT-ONLINE starting of large ac motors may present difficulties for the motor itself and the loads supplied from the common coupling point because of the voltage dips in the supply during starting, especially if the supply to which the motor belongs is weak[1]–[4]. An uncontrolled starting may cause a trip in either overload or under voltage relay, resulting in starting failure. This is troublesome for field engineers since the motor cannot be reenergized until it cools down to an allowable temperature in a long time period. Furthermore, the number of starts per day is limited to only a few attempts. Therefore, the current and torque profiles of the motor during starting are to be carefully tailored. Conventional methods involves electromechanical reduced starting comprises of auto transformer starting, star-delta starting, resistance or reactor starting. All these methods have draw backs [2],[3] such as need for frequent inspection and maintenance, non simultaneous switching of motor phases to the supply, failures in the moving parts due to the large number of switching etc. VFD is another method where speed is varied by varying the frequency fed to the motor. Here V/f is kept constant by changing both voltage and frequency, but this method is not in common use due to the requirment of Converter and inverter stages which will results in increase of cost. Besides the developments and progress in commercial soft-starter technology[7], [8], numerous attempts have been made on the performance analyses and control techniques of three-phase induction motors (IMs) fed from a thyristorized voltage controller [9]–[11]. Utilizing a dynamic function for the triggering angle of thyristors in the voltage controller proves to be a simple and effective way to improve transient performance [12]. By employing a proper triggering function, the rate at which main flux builds up is decreased and transient torque is smoothed. But when the firing angle is larger, time taken to attain steady state becomes larger[5]. The schematic of starting of induction motor drive using a three phase voltage controller is shown in figure 1. Here, there are six thyristors labeled as T1-T6. T1 T3 and T5 are triggered at a predefined value of SCR firing angle α, while T2, T4 and T6 are triggered using 180 degrees phase shifted pulses. Figure 2 shows the Torque Pulsations and current for an uncontrolled starter during starting. These large pulsations results in Mechanical damage to the motor. This may cause shocks to the driven equipment and damage to the mechanical system components such as shafts, couplings, and gears immediately if the strength of materials are exceeded, or in the long term owing to fatigue. Also it can be seen that the starting current is 8-10 times of the motor no load current. This huge in rush of current may cause heavy dip in the supply voltage, over heating to the motor, unwanted tripping of the circuit breakers. So these current should be reduced to a safer limit. Here a new firing scheme is proposed for minimizing the torque pulsations and provide a reduced starting inrush current with in a moderate settling time. The entire system has developed in MATLAB/SIMULINK for a 415V, 4.7A, 1435rpm 50 Hz three phase induction motor.

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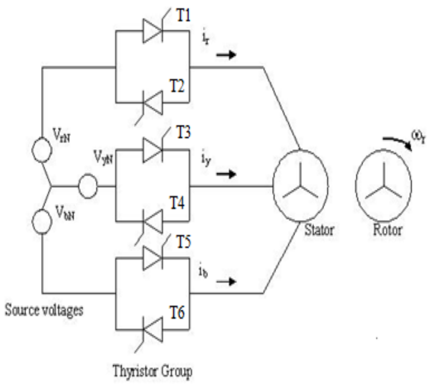

Fig 1: Induction Motor Drive with SCR Voltage Controller

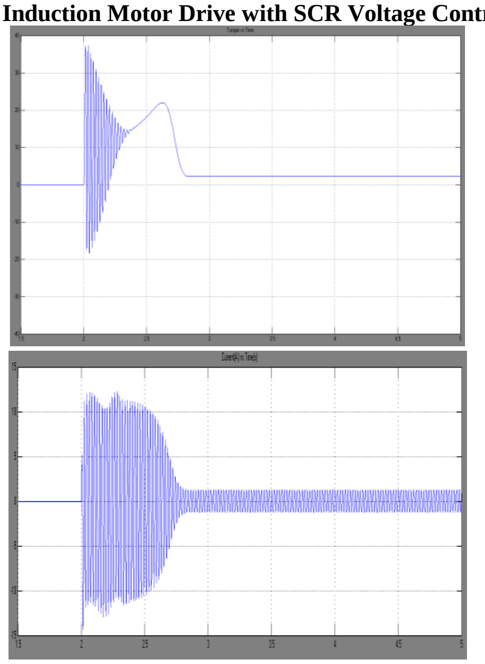

Fig 2: Torque and Current Pulsations of Induction Motor for a Controlled Starter during Starting.

II. MATHEMATICAL MODEL

The mathematical models used for simulation of the system is given in this section. This mathematical model is required further to design any type of controller to control the process[5],[6]. The dynamic equations for the induction motor are given in the following

$$\begin{bmatrix} \frac{di_{ds}}{dt} \\ \frac{di_{qs}}{dt} \\ \frac{di_{dr}}{dt} \\ \frac{di_{qr}}{dt} \end{bmatrix} = \frac{1}{\sigma}\begin{bmatrix} \frac{-r_s}{L_s} & \frac{\omega_r L_m^2}{L_s L_s} & \frac{r_s L_m}{L_s L_r} & \frac{\omega_r L_m}{L_s} \\ \frac{\omega_r L_m^2}{L_s L_s} & \frac{-r_s}{L_s} & \frac{\omega_r L_m}{L_s} & \frac{r_r L_m}{L_s L_r} \\ \frac{r_s L_m}{L_s L_r} & \frac{\omega_r L_m}{L_s} & \frac{r_r}{L_r} & \frac{\omega_r L_m}{L_s} \\ \frac{\omega_r L_m}{L_s} & \frac{r_s L_m}{L_s L_r} & \frac{\omega_r L_m}{L_s} & \frac{r_r}{L_r} \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} + \frac{1}{\sigma}\begin{bmatrix} \frac{1}{L_s} & 0 & 0 & 0 \\ 0 & \frac{1}{L_s} & 0 & 0 \\ 0 & 0 & \frac{1}{L_r} & 0 \\ 0 & 0 & 0 & \frac{1}{L_r} \end{bmatrix} \begin{bmatrix} V_{ds} \\ V_{qr} \\ 0 \\ 0 \end{bmatrix} \quad (1)$$

Where $\sigma = 1 - (L_m^2 / L_r L_s)$

V_{ds} and V_{qs} are given by

$$\begin{bmatrix} V_{ds} \\ V_{qs} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3/2} & -\sqrt{\frac{3}{2}} \end{bmatrix} \begin{bmatrix} V_{rs} \\ V_{ys} \\ V_{bs} \end{bmatrix} \quad (2)$$

and

$$\begin{bmatrix} V_r \\ V_y \\ V_b \end{bmatrix} = V_m \begin{bmatrix} \sin(\omega t) \\ \sin(\omega t - 2\pi/3) \\ \sin(\omega t + 2\pi/3 \end{bmatrix} \quad (3)$$

The electromagnetic torque is given by

$$Te = \sqrt{\frac{3}{2}} \frac{Po}{2} L_m (i_{dr} iqs - i_{qr} i_{ds}) \quad (4)$$

And the speed is governed by

$$\frac{d\omega_r}{dt} = \frac{T_e - T_L}{J} \quad (5)$$

Starting with the mathematical model of the induction motor in terms of *abc* axes quantities, all space-angle and, hence, time varying inductances are eliminated by applying the three phase to two phase transformations; to the d-q axis frame fixed to the stator. Dedicated software is developed in matlab/simulink for modeling the drive system. The matrix equation (1) is derived by the proper transformations of the quantities for which the rotor reference frame is fixed in the stator. These differential equations is used to develop a suitable system matrix for the entire model. Here r_s, r_r, L_s, L_r are the corresponding stator and rotor resistances and inductances respectively. By using transformation the time varying inductance is converted into constants irrespective of the rotor position. Matrix voltage equations can then be written as in (2) and (3) shown below and (2) shows the transformation to d-q axis components. After adding the torque balance equation (4) for dynamic operation, the model is brought into the state space form for simulation. Matlab function for measuring the speed in radians (5) as well as in rpm is also developed. These equations contribute to a mathematical simulink model. Voltage waveforms simulated is compared with the practical case and it is found to be same in both cases. So simulink model is found to be a vital tool to analyze the voltage, current and torque pulsations under steady state as well as transient conditions.

III. ANALYSIS OF TORQUE AND CURRENT PULSATIONS WITH FIXED FIRING ANGLES

Simulations were carried out to analyse the transient electro magnetic torque response and currents for different firing angles. The d-q axis model described in section II was

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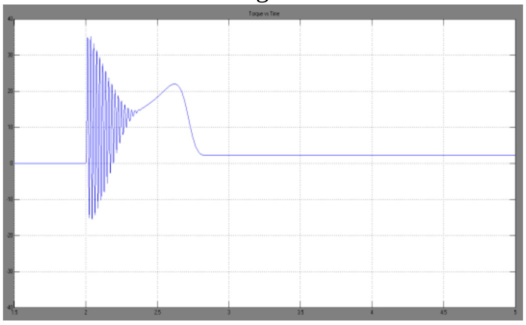
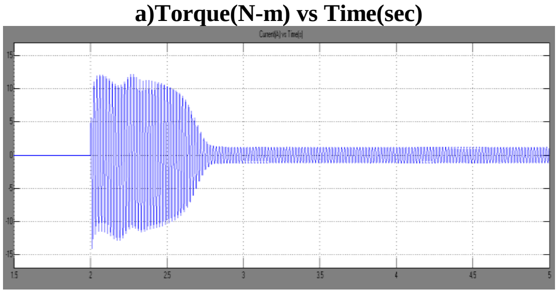
used for simulation study. The toque pulsation and current waveforms for firing angle 30^0 and 60^0 are shown in figure 3 and Figure 4 respectively. Result shows that there is no considerable improvement in the current and torque profile compared to uncontrolled starter because for most of the squirrel-cage IMs, the pf at unity slip is in the range from 0.2 to 0.3 which corresponds to a pf angle around 75^0. So when firing angle is greater than the pf angle current and torque pulsations are reduced, but time taken to achieve steady state is increased as shown in the figure 5.

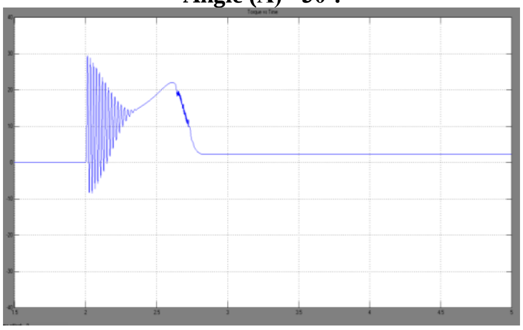


a)Torque(N-m) vs Time(sec)

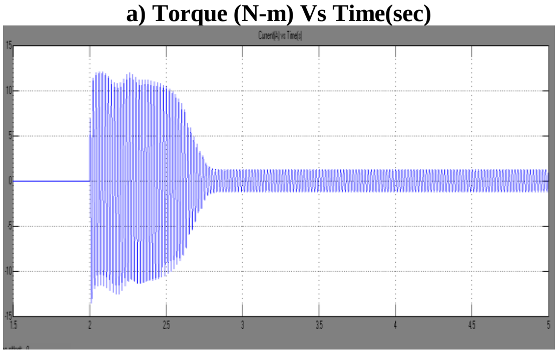


b)Current(A) vs Time(sec)

Fig 3 A) Torque Pulsation B) Current Wave Forms For Firing Angle (A) =30^0.

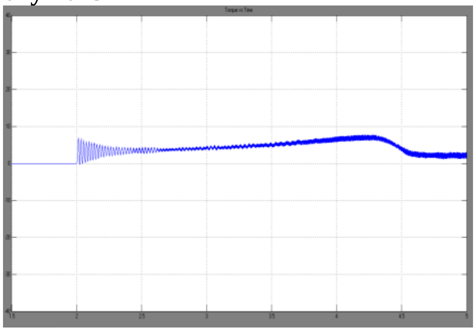


a) Torque (N-m) Vs Time(sec)

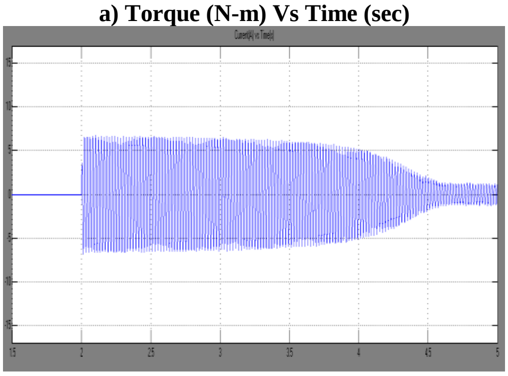


B) Current (A) vs time (sec)

Fig 4 A) Torque Pulsation B) Current Wave Forms For Firing Angle (A) =60^0.

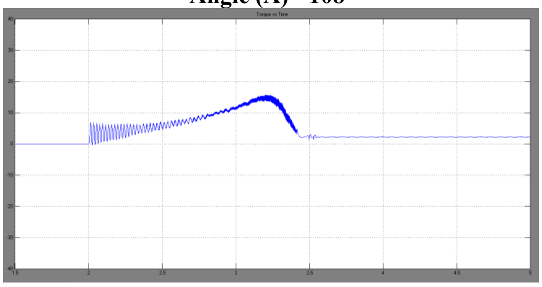


a) Torque (N-m) Vs Time (sec)

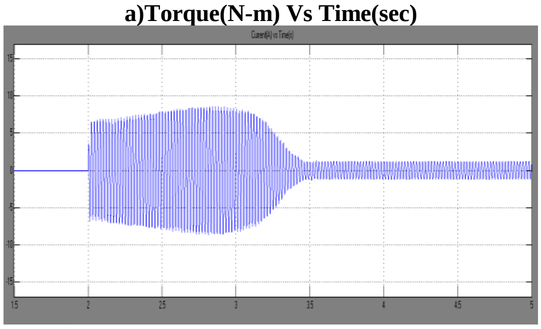


b)Current(A) vs time(sec)

Fig 5 A) Torque Pulsation B) Current Wave Forms For Firing Angle (A) =108^0



a)Torque(N-m) Vs Time(sec)



b)Current(A) vs time(sec)

Fig 6 A) Torque Pulsation B) Current Wave Forms For Firing Angles Varies From 108^0 To 0^0

IV .PROPOSED CONTROL SCHEME

From the analysis it is found that at lower firing angle the current and torque pulsations are higher with lower settling time and at larger firing angle current and torque pulsations are minimum with higher value of settling time. Using the new firing scheme motor is started with higher firing angle (say 180^0). The firing angle is reduced in steps and brings to zero so as to increase the voltage gradually. The results obtained are shown in fig 6. It is seen that the starting current is nearly the rated current and torque pulsations are minimized with a

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moderate value of settling time. So this firing scheme is suitable for the three phase squirrel cage induction motor to obtaining perfect current and torque profile during starting.

V.CONCLUSION

In this paper a new firing scheme is proposed to start the three phase induction motor with reduced current and minimized torque pulsation. Simulation results are used for analyzing the current and torque pulsation at various firing angle. From the analysis, it is found that with larger firing angles though the magnitudes of current and torque pulsations are lower, it takes more time to achieve steady state. In the proposed firing scheme motor is started from larger value of firing angle (say $108^{0)}$ and is gradually reduced to zero, so that nearly perfect current and torque profiles can be obtained during starting. Using the proposed strategies, a good acceleration profile can be tailored by smooth pulsation-free torques over the entire starting period.

APPENDIX

Induction motor details

Three phase, 415V, 4.7A, 1435rpm, 50Hz

Stator resistance, rs= 4.5 Ω

Rotor resistance, rr=4.5 Ω

Magnetizing inductance, Lm=1.296H

Stator inductance, Ls=1.3381H

Rotor inductance, Lr=1.3385H

Moment of inertia, J=0.00605 kgm2

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