A Novel Soft Starting of Squirrel Cage Induction Motor with Mitigated Torque Ripples

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ABSTRACT

This paper proposes a novel scheme for the mitigation of ripples in the starting torque of squirrel cage induction motors. Selective Harmonic Elimination (SHE) technique is adopted by eliminating selected lower order harmonics. This method in comparison with the traditional Phase Angle Control (PAC) method offers the following advantages. There is a considerable reduction in torque ripple along with reduced source current harmonics. In soft starting schemes using conventional phase angle control method, the conduction angle is varied gradually until the machine is supplied with full power. In the proposed method the total conduction duration is equally spread over the entire positive and negative half cycle periods. The conduction and non-conduction periods are symmetrically distributed over each half cycle interval. In each half cycle ten switching instants are symmetrically placed rendering quarter wave symmetry. With gradual increase in modulation index and under all possible modulation indices the switching instants are selected in such a way that the selected harmonics are eliminated from the source current. The ripples in the electromagnetic torque produced are reduced due to the elimination of selective harmonics. MATLAB/SIMULINK package has been used to simulate the proposed method. The results obtained are satisfactory and promising.

KEYWORDS: Artificial Neural Networks, MOSFETs, Phase Angle Control, Selective Harmonic Elimination, Three Phase Squirrel cage induction motors.

INTRODUCTION

Soft starting of three phase squirrel cage induction motor offers certain advantages in both electrical and mechanical domains of the drive system. Soft starting of induction motors increases the life of the electromechanical system. There is a significant saving of electrical energy with soft starting [1].

There are various schemes of soft starting are applied to the squirrel cage induction motor. Thyristors being the pioneer of all power electronic devices they have been used extensively in AC voltage controllers and in soft starting schemes as well. Thyristors used the natural commutation scheme. With AC source, with class F commutation or natural commutation, the Thyristors in general or the SCRs in particular could be switched on at any desired phase angle and the turning off of the SCR could not be controlled and it happened automatically at the zero crossing of the AC source. This scheme of control is known as the phase angle control. In phase angle control, with inductive loads, conduction would continue even after the zero crossing of the source voltage and this leads to poor power factor of the source current [2].

Source current harmonics and poor power factor of the source current are the two major problems associated with the phase angle method of soft starting of induction motor.
Force commutated devices like the MOSFETs and IGBTs are also implemented in AC voltage controllers which are used for soft starting of induction motors [3]. With force commutated devices the extinction angle control scheme came into existence. Phase angle control with conduction period starting from the zero degree extending anywhere towards the zero crossing at the next 180 degrees is known as extinction angle control [4]. Soft starting with extinction angle control offers better power factor and reduced harmonics while starting.

In [5] the authors have proposed and tested a selective harmonic elimination scheme in a single phase inverter. This scheme can eliminate four of the lower order harmonics viz. $5^{th}$, $7^{th}$, $11^{th}$ and $13^{th}$ order harmonics.

Popularly, in the case of inverters there are two basic schemes of switching. The low frequency or single pulse switching and the high frequency or multiple pulse switching. In single pulse switching, for each half cycle only a single pulse is applied and as a result the output of the inverter is the train of square pulses with positive and negative half cycles.

In multiple pulse switching, in both positive and negative half cycles there are multiple switching instants of the order of, usually an odd integer multiple of the fundamental frequency. Selective harmonic elimination is a low switching frequency scheme in which in each half cycle of the inverter there are a certain low number of switching instants symmetrically placed about each half cycle of the AC wave. In this way a certain number of lower order harmonics can be eliminated. For example if five switching instants are defined between zero and 90 degrees then four lower order harmonics can be eliminated. These switching instants depend upon the modulation index used. Whenever there is a change in the modulation index these switching angles will be changed. There are some techniques like look up tables etc. for getting the switching angles for different modulation indices [6], [7], [8], [9].

In [10] the authors have adopted a novel methodology using the Hopfield Neural Network. With this method the switching angles could be estimated within one cycle period of 20 ms following a change in the modulation index command. This methodology has been extended here in the soft starting scheme implemented in the three phase AC voltage controller topology. With reference to the control strategy adopted in the proposed method of soft starting, there is a frequent change of modulation index of the AC voltage controller as arrived from observing of the motor current, and this value is a function of the load in the motor.

In an open loop soft starting scheme implemented with phase angle control the duration of conduction is gradually increased with a gradient predetermined for the machine. In the case of closed loop soft starting the slope of the period of conduction of the power control switches do not rise in a pre determined slope rather decided in real time.

As and when there is a change in the modulation index the switching angles are estimated in real time [11] and the phase angle controller with multiple switching works with the newly estimated switching instants until the next modulation index and hence the next set of switching angles is supplied.

As compared to the traditional phase angle controlled or extinction angle controlled soft starting schemes the proposed methodology offers the definite advantages of reduced torque ripple and reduced source current harmonics. The proposed method uses the digital implementation of the Hopfield Neural Network for solving the trigonometric transcendental equations pertaining to SHE PWM and thus the real time estimation [12] of the multiple switching instants of multiply switched AC voltage controllers.

The torque produced by a squirrel cage induction motor is sensitive to the applied voltage. Therefore a control and regulation of the applied voltage can be expected to produce regulated torque output which is essential in case of soft starting and hence the use of the multiple pulse switched AC voltage controllers, which in addition to soft starting gives the advantages of improved source side Power Factor and lower order harmonics eliminated source current [13, 14].

In a three phase induction motor the torque developed is a function of the stator and the rotor currents. These two currents are dependent on the applied voltage [15]. The SCR based phase control technique is the popular one. But with phase control the current fed into load will be rich in harmonics. The lower order harmonics like the $5^{th}$, $7^{th}$, $11^{th}$ and $13^{th}$ which are dominant will cause ripple in the torque produced. The source side power factor and the source side THD are also adversely affected in the phase angle controlled scheme [16]. At the present time, the power quality issues are more absorbed in power systems [17] and conventional Direct Torque Control system faces the problems of high flux and torque ripples [18].

The Proposed Multiple Pulse Ac Voltage Controller:

In the traditional phase angle control scheme the conduction starts from any desired angle and continues upto the zero crossing. At the zero crossing, because of the natural commutation phenomenon exhibited by devices of the Thyristor family like the SCR or the TRIAC, conduction stops. The same thing happens for the negative half cycle also.

In the extinction angle control conduction starts at zero degrees or at the zero crossing and continues till any desired angle. At the end of the conduction period conduction is forced to stop by any special commutation mechanism in the case of devices like SCR and the TRIAC. Removal of the gate pulse is the means of turning off the device in case power electronic devices like IGBT or MOSFET are used.
In both the phase control technique as well as the extinction angle control technique the conduction period is controllable and continuous during the conduction period.

However in the proposed technique a number of alternate ON and OFF states of conduction during each half cycle is symmetrically distributed over the entire half cycle periods leading to quarter and half wave symmetries. The conduction through the switching device during every half cycle is discontinuous and hence a freewheeling arrangement is provided to facilitate continuous of current through the load. The proposed control technique schematic diagram is shown in Figure 1.

![Proposed control technique schematic diagram](image1)

**Fig. 1:** Proposed control technique schematic diagram

Typical waveforms of output voltage for the phase angle controller, extinction angle controller and for the proposed technique are as shown in figures 2(a), 2(b) and 2(c).

(a) ![Waveform A](image2)  
(b) ![Waveform B](image3)  
(c) ![Waveform C](image4)

**Fig. 2:** Load side voltage of (a) Extinction angle (b) Phase angle and (c) SHE PWM control scheme

Selective Harmonic Elimination Technique:

The AC voltage controller based soft starting scheme is prone to increased source current harmonics. This high harmonic source current may pollute the AC source system. Therefore in this work a minimal harmonic source current technique is adopted using the SHE PWM technique.

Instead of keeping a continuous portion of every half cycle as conducting and the remaining portion of the half cycle as non-conducting as in the traditional voltage controller technique, in the proposed method the conduction periods for the entire half cycles are symmetrically distributed with alternate conducting and non-conducting periods within each half cycle. Thus quarter wave symmetry is achieved. During the period from 0 degrees to 90 degrees there are five instants with a switching transition occurring at five switching angles $\alpha_1, \alpha_2, \alpha_3, \alpha_4$ & $\alpha_5$ as shown in figure 3.

![Symmetrically located switching angles](image5)

**Fig. 3:** Illustration of symmetrically located switching angles

By this way by properly selecting the values for $\alpha_1, \alpha_2, \alpha_3, \alpha_4$ & $\alpha_5$ four select harmonics viz. the $5^{th}$, $7^{th}$, $11^{th}$ and $13^{th}$ can be minimized. The set of angles selected should also guarantee the required amplitude of the fundamental across the load. As derived from the basic Fourier theory a set of five trigonometric transcendental equations can be formed. These equations relate the five switching angles $\alpha_1, \alpha_2, \alpha_3, \alpha_4$ & $\alpha_5$ and the magnitudes of the $5^{th}$, $7^{th}$, $11^{th}$ and $13^{th}$ harmonics and also the amplitude of the fundamental 50 Hz wave.

In this set of five trigonometric transcendental equations the values for the select harmonics are set equal to zero and the magnitude of the fundamental wave is set to the required value.

After solving the set of five equations we get the select harmonics minimized and also we get the required magnitude of the fundamental wave.

During the period of soft starting the modulation index will be varied in a fixed number of steps. In this work we have selected the modulation index to be varied from 0.3 through 1 in steps of 0.1. At all modulation
indices the fundamental voltage amplitude will be according to the modulation index applied and that all throughout the starting period the selected harmonics will be absent. Since the dominant lower order harmonics are minimized the torque ripple is reduced is the observation made in this work.

The problem at hand now is to solve the set of five trigonometric transcendental equations. Since there are five equations and all of them being trigonometric transcendental the normal algebraic procedures cannot be used to solve these equations. In this work the Generalized Hopfield Neural Network has been adopted to solve the set of SHE equations.

The Hopfield Neural Network:

The Hopfield Neural Network is a single layer recurrent neural network that has a feedback arrangement. The N number of neurons used in this network are put up in a common single layer with every neuron getting feedback from all other neurons except of its own [19].

Hopfield Neural Network is also known as a gradient type network wherein once the neurons are loaded with initial external inputs the outputs of each neuron undergoes a change these changes are fed back to the neurons and as result a convergent transient happens and the outputs change continuously until the outputs of all the neurons finally attain their respective steady state values.

The initial guess of the switching angles are fed as inputs to the neurons and thus the neurons are initialized. After the initialization the network undergoes a transition process and during the transition period the switching angles undergo changes until a final set of switching angles are arrived which will remain as steady state values and these values are the switching angles required to be used in the AC voltage controller.

In the final set of switching angles, each switching angle that appears at the output of each Neuron, at the end of the transient period should guarantee the minimization of the lower order harmonics viz. 5th, 7th, 11th and 13th besides giving the required amplitude of the fundamental voltage.

Between the initial guess as applied by the user and the final steady values as obtained from the network after the network comes to a steady state the variables are steered through different values as governed by the energy function and the system parameters like the input resistance and capacitance at the input of each neuron. The resistance and capacitance values are constants and therefore it is the energy function involved in the evolution that determines the final steady state values for the variables or in other words the required solution for switching angles.

The energy function for a typical Hopfield Neural network is given by the following expression.

$$E = \sum_{i=1}^{N} \sum_{j=0}^{s} \sum_{k=1}^{p} w_{ij}(x_{i},x_{j},x_{k}) + \sum_{l=1}^{o} r_{i}(x_{l})$$

(2)

At time $t = 0$ the energy embedded in this function is of a certain value and the time derivative of this function diminishes the initial energy. A mathematical procedure to evaluate the rate of change of this energy $E$ with respect to time as given by $\frac{dE}{dt}$ will result in a negative gradient that shows that the energy function is an ever diminishing function finally reaching zero.

In the application under consideration there are five variables involved and the estimation of the five variables required five neurons. Each neuron has an activation function given by

$$\phi(j) = \frac{1}{1+\exp(-u_j)}, \quad j=1,2,...,n \quad (3)$$

It can be assumed that a system can be described by a set of five nonlinear equations of which the equations are given by

$$f(a_1,a_2,a_3,a_4,a_5) = K_1$$
$$f(a_1,a_2,a_3,a_4,a_5) = K_2$$
$$f(a_1,a_2,a_3,a_4,a_5) = K_3$$
$$f(a_1,a_2,a_3,a_4,a_5) = K_4$$
$$f(a_1,a_2,a_3,a_4,a_5) = K_5$$

(4)

Each equation of this system of equations relates a function of the variables $a_1, a_2, a_3, a_4$ & $a_5$ to the corresponding harmonic voltage. That is the first of this set of equation gives the amplitude of the fundamental voltage given by $K_1$. The next four equations respectively give the 5th, 7th, 11th and the 13th harmonic voltages. With reference to the Selective Harmonic Elimination scheme the values of $K_2 = K_3 = K_4 = K_5$ will be made equal to zero.

The energy function for the above set of equations is derived as follows:

$$E = \sum_{j=1}^{n} (p(x_j))^2$$

(5)
where,

\[ P_j(.) = (\Xi_j(x_1, x_2, ..., x_n) - P_j) \]

The transient dynamics of the Hopfield network is governed by the following group of differential equations:

\[ \frac{dx_j}{dt} = -\frac{\partial E}{\partial x_j} \]  \hspace{1cm} (6)

where,

\[ x_j = \phi(u_j), j = 1, 2, ..., n \]

The above equations \( f_j(.) \) is a function of variables \( x_1, x_2, ..., x_n \in \mathbb{R} \) and \( P \in \mathbb{R} \) is a real constant. Our objective is to find the values for variables \( x_1, x_2, ..., x_n \) such that it satisfies the equation (8). To obtain the solution using proposed approach an energy function has to be formulated. The energy function for the above set of equations is derived as follows:

\[ E = \sum_{j=1}^{n} (g_j(.))^2 \]  \hspace{1cm} (7)

where,

\[ g_j(.) = (f_j(x_1, x_2, ..., x_n) - P_j) \]

Equations (9) and (10) have been used for designing the proposed network. The number of neurons in network is equal to the number of variables whose value is to be determined. In the given problem, we have ‘n’ number of variables and hence the network should have ‘n’ number of neurons. The network dynamics are governed by the following differential equations:

\[ \frac{dx_j}{dt} = -\frac{\partial E}{\partial x_j} \]  \hspace{1cm} (8)

where,

\[ x_j = \phi(u_j), j = 1, 2, ..., n \]

Where \( u_j \) is the net input to the \( j^{th} \) neuron in the network and \( x_j \) is its output. In this application, the function \( \phi(u_j) \) is a linear input – output transfer function for the \( j^{th} \) neuron. Calculating the partial derivatives of Equation (8) with respect to unknown variables \( x_1, x_2, ..., x_n \) and collecting the terms of identical order will results in Hopfield equations. The coefficients and constants in the available expression give the weights and bias values for the network respectively. A suitable numerical algorithm is used to solve the differential equations governing the network dynamics.

The Trigonometric Transcendental Equations govern the symmetrically distributed AC Voltage controller.

The Fourier series expression for the output voltage is given by the following equation

\[ v_0 = \sum_{n=1}^{\infty} A_n \sin(n\alpha) + B_n \cos(n\alpha) \]  \hspace{1cm} (9)

Where \( B_n = 0 \) for \( n = 1, 2, 3, ... \) and thus the above equation reduces to:

\[ v_0 = \sum_{n=1,3,5} A_n \sin(n\alpha) \]  \hspace{1cm} (10)

The value of \( A_n \) is computed as

\[ A_n = 2V_m/\pi \sum_{i=1}^{M} (-1)^{i-1} \sin \left( \frac{(n-i)\alpha_i}{n} \right) \sin \left( \frac{(n+i)\alpha_i}{n} \right) \]  \hspace{1cm} (11)

Where \( n = 1, 5, 7, 11, 13 \) and \( i = 1, 2, 3, 4, 5 \);

The fundamental component is given by

\[ A_1 = 2V_m/\pi \sum_{i=1}^{M} (-1)^{i-1} \alpha_i - \sin \left( \frac{2\alpha_i}{2} \right) \]  \hspace{1cm} (12)

Given a desired fundamental voltage \( V_1 \) and for the elimination 5,7,11 and 13\textsuperscript{th} harmonics, the problem here is to determine the switching angles \( \alpha_1, \alpha_2, \alpha_3, \alpha_4 \) and \( \alpha_5 \) such that
\[ -\alpha_1 + \sin \frac{2\alpha_1}{2} - \alpha_2 + \sin \frac{2\alpha_2}{2} + \alpha_3 - \sin \frac{2\alpha_3}{2} + \alpha_4 + \frac{\pi}{2} = M \]

\[ -\sin \frac{4\alpha_1}{4} + \sin \frac{6\alpha_1}{6} - \sin \frac{4\alpha_2}{4} + \sin \frac{6\alpha_2}{6} + \sin \frac{4\alpha_3}{4} - \sin \frac{6\alpha_3}{6} + \sin \frac{4\alpha_4}{4} - \sin \frac{6\alpha_4}{6} + 6\alpha_5 = 0 \]

(13)

\[ \begin{bmatrix}
-\alpha_1 + \sin \frac{2\alpha_1}{2} + \alpha_2 - \sin \frac{2\alpha_2}{2} - \alpha_3 + \sin \frac{2\alpha_3}{2} - \alpha_4 - \sin \frac{2\alpha_4}{2} + \frac{\pi}{2} \\
-\sin \frac{4\alpha_1}{4} + \sin \frac{6\alpha_1}{6} + \sin \frac{4\alpha_2}{4} - \sin \frac{6\alpha_2}{6} + \sin \frac{4\alpha_3}{4} - \sin \frac{6\alpha_3}{6} + \sin \frac{4\alpha_4}{4} - \sin \frac{6\alpha_4}{6} + \frac{6\alpha_5}{6} \\
-\sin \frac{10\alpha_1}{10} + \sin \frac{12\alpha_1}{12} + \sin \frac{10\alpha_2}{10} - \sin \frac{12\alpha_2}{12} + \sin \frac{10\alpha_3}{10} - \sin \frac{12\alpha_3}{12} + \sin \frac{10\alpha_4}{10} - \sin \frac{12\alpha_4}{12} + \sin \frac{10\alpha_5}{10} \\
-\sin \frac{12\alpha_1}{12} + \sin \frac{14\alpha_1}{14} + \sin \frac{12\alpha_2}{12} + \sin \frac{14\alpha_2}{14} + \sin \frac{12\alpha_3}{12} + \sin \frac{14\alpha_3}{14} + \sin \frac{12\alpha_4}{12} + \sin \frac{14\alpha_4}{14} + \sin \frac{12\alpha_5}{12}
\end{bmatrix} = 0 \]

Where,

\[ M = \frac{V_m'}{2V_m} \]

\[ V_m' = \text{Maximum value of fundamental output voltage} \]

\[ V_m - \text{maximum value of the supply voltage} \]

\[ M - \text{Normalized fundamental output voltage} \]

This is a system of five nonlinear algebraic transcendental equations in the unknown values \( \alpha_1, \alpha_2, \alpha_3, \alpha_4 \) and \( \alpha_5 \).

The energy function for the above system of equations is given by

\[ E = \frac{-0.5}{2} \left( \frac{-\alpha_1 + \sin \frac{2\alpha_1}{2} + \alpha_2 - \sin \frac{2\alpha_2}{2} - \alpha_3 + \sin \frac{2\alpha_3}{2} - \alpha_4 - \sin \frac{2\alpha_4}{2} + \frac{\pi}{2}}{M} \right)^2 + \]

\[ \left( \frac{-\sin \frac{4\alpha_1}{4} + \sin \frac{6\alpha_1}{6} + \sin \frac{4\alpha_2}{4} - \sin \frac{6\alpha_2}{6} + \sin \frac{4\alpha_3}{4} - \sin \frac{6\alpha_3}{6} + \sin \frac{4\alpha_4}{4} - \sin \frac{6\alpha_4}{6} + \frac{6\alpha_5}{6}}{6\alpha_5} \right)^2 + \]

\[ \left( \frac{-\sin \frac{10\alpha_1}{10} + \sin \frac{12\alpha_1}{12} + \sin \frac{10\alpha_2}{10} - \sin \frac{12\alpha_2}{12} + \sin \frac{10\alpha_3}{10} - \sin \frac{12\alpha_3}{12} + \sin \frac{10\alpha_4}{10} - \sin \frac{12\alpha_4}{12} + \sin \frac{10\alpha_5}{10}}{10\alpha_5} \right)^2 + \]

\[ \left( \frac{-\sin \frac{12\alpha_1}{12} + \sin \frac{14\alpha_1}{14} + \sin \frac{12\alpha_2}{12} + \sin \frac{14\alpha_2}{14} + \sin \frac{12\alpha_3}{12} + \sin \frac{14\alpha_3}{14} + \sin \frac{12\alpha_4}{12} + \sin \frac{14\alpha_4}{14} + \sin \frac{12\alpha_5}{12}}{14\alpha_5} \right)^2 \]

(14)

The differential equation governing the behavior of the network dynamics is calculated using energy function and is given as follows:

\[ \frac{d\alpha_1}{dt} = \frac{-dE}{d\alpha_1} \]

\[ \frac{d\alpha_2}{dt} = \frac{-dE}{d\alpha_2} \]

\[ \frac{d\alpha_3}{dt} = \frac{-dE}{d\alpha_3} \]

\[ \frac{d\alpha_4}{dt} = \frac{-dE}{d\alpha_4} \]

\[ \frac{d\alpha_5}{dt} = \frac{-dE}{d\alpha_5} \]

(15)

Matlab / Simulink Simulation And Results:

This chapter presents some of the important subsystems of the implementation of the proposed soft starting scheme in the MATLAB SIMULINK environment.

The specifications of the motor used are as follows:

Type: Squirrel Cage Induction Motor
Power: 5.4 HP, 4 KW  
Voltage: 440 V (Three Phase)  
Frequency: 50 Hz  
Speed: 1430 RPM

The Full Simulation Model with Phase angle Controller is shown in figure 4. The three main blocks are the AC three phase voltage source, the three phase AC voltage controller blocks and the three phase induction motor. The three AC voltage controllers are in three distinct blocks each containing a single phase AC voltage controller unit with the main switch and the freewheeling switch arranged in a bridged diode format as shown in figure 6.

Fig. 4: AC Voltage Controller with Phase controller scheme.

There are two metering blocks for the measurement of three phase voltages and currents on the source and the motor sides. Using the voltage and the current measurement blocks on the source side the input power factor and the input THD are monitored.

The sequence of modulation indices to be applied is generated using the repeating sequence block and after the motor is started the output values will be maintained at one level.

The complete system of the soft starting scheme using the SHE PWM based AC voltage controller is shown in figure 5.

Fig. 5: AC voltage controller with SHE PWM scheme.

Figure 6 shows the main and the freewheeling switches connected within a diode bridge network enabling bi directional use of a single MOSFET for main current and another single MOSFET for freewheeling.

Fig. 6: MOSFET switching unit

Figure 7 shows the SHE PWM switching angle calculation unit and the switching pulse generation unit for one phase only. Similar units will be used for the other two phases with appropriate phase angle shift of 120 degrees and 240 degrees respectively.
Fig. 7: Switching pulse generation unit.

Figure 8 and Figure 9 show a sample of the load side output voltage, the Fast Fourier Transformed spectrum of the output voltage with quarter and half wave symmetries, Electro mechanical parameters of soft starter using phase angle and SHE PWM controlled AC voltage controller respectively.

Fig. 8: Voltage and other parameters: (a) The Output voltage, (b) Spectrum of the output voltage and (c) Electro Mechanical Parameters of soft starter using phase angle controlled AC voltage controller.
With reference to figure 8(b), it is clear that the AC voltage waveform of the phase angle controller is rich in all odd harmonics and this harmonics will affect the operation of the induction motor.

The spectrum of the output voltage as shown in figure 9(b) reveals that the 5\textsuperscript{th}, 7\textsuperscript{th}, 11\textsuperscript{th} and the 13\textsuperscript{th} order harmonics are eliminated at the output voltage. The 3\textsuperscript{rd}, 9\textsuperscript{th} and the 15\textsuperscript{th} order harmonics are triplen harmonics and they will be absent naturally when the system is operated as a three phase AC voltage controller.

With reference to figures 8(c) and 9(c), it is evident that stator current is limited in SHE PWM based soft starter and the torque produced in SHE PWM based soft starting is smoother as compared to the phase angle controlled soft starting.

RESULTS AND DISCUSSION

The core objective of this work is to show while implementing soft starting with the AC voltage controller for the squirrel cage induction motor as compared to the conventional phase angle control with single on state and off state over every half cycle, the Selective Harmonic Elimination technique with multiple on and off states over every half cycle offers some advantages.

As supported by the rich theory available in literature it can be expected that with SHE PWM technique some of the lower order harmonics can be eliminated in the source current of an AC voltage controller for any modulation index.

In this work this basic theory is extended to the application of the soft starting of three phase squirrel cage induction motors. Since some of the dominant lower order harmonics are eliminated using the SHE PWM technique the torque pulsations can be reduced.

It has already been established in literature that as compared to the phase angle control scheme the extinction angle control scheme offers better source side power factor. The Selective Harmonic Elimination PWM with multiple pulses of conduction and non conduction over every half cycle symmetrically placed in every half cycle with quarter wave symmetry can also lead to improved power factor in the source side.

A MATLAB / SIMULINK based simulation has been carried out with a three phase AC voltage controller as the soft starting element controlling the starting of a Squirrel Cage induction motor.

The results of the simulation are given as follows. Figure 10 and 11 show the waveforms pertaining to all the important parameters in the case of phase angle control based soft starting and SHE PWM based soft starting.
Fig. 10: Comparison of the simulation results: (a). Growth of speed, (b). Source current, (c). Torque ripple, (d). power factor and (e). THD in the case of phase angle control based soft starting and SHE PWM based soft starting technique at no load.
Fig. 11: Comparison of the simulation results: (a). Growth of speed, (b). Source current, (c). Torque ripple, (d). power factor and (e). THD in the case of phase angle control based soft starting and SHE PWM based soft starting technique at load.

Table 1: Comparison of Simulation Results

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Parameters</th>
<th>At No load</th>
<th>At Load torque of 3Nm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Conventional PAC</td>
<td>Proposed SHE</td>
</tr>
<tr>
<td>1.</td>
<td>Speed = 1500 RPM</td>
<td>t = 0.21 s</td>
<td>t = 0.17 s</td>
</tr>
<tr>
<td>2.</td>
<td>Source current at t = 0.05 s</td>
<td>50A</td>
<td>28A</td>
</tr>
<tr>
<td>3.</td>
<td>Torque ripple</td>
<td>2300</td>
<td>154.5</td>
</tr>
<tr>
<td>4.</td>
<td>Power factor</td>
<td>0.8 to 0.2</td>
<td>0.94 to 0.8</td>
</tr>
<tr>
<td>5.</td>
<td>THD</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

It can be concluded from the figures 10 (a to e), 11 (a to e) and Table 1 that in both the cases of no load and with a load torque of 3Nm the generation of torque are more gentle in the case of the SHE PWM based soft starting. In the case of phase controlled soft starting torque oscillates wildly which may lead to much mechanical vibrations and noise.
Power factor which is an important measure exhibits a very good behavior in the case of SHE PWM based starting. In the case of SHE PWM based starting the power factor is continuously well close to 0.94 or above. In the case of phase angle control the power factor is swinging between 0.8 and 0.2.

As far THD the SHE PWM based soft starting as well as the phase controlled starting exhibit lower values. However the SHE PWM based soft starting offers a THD that is close to 1 while the phase angle controlled soft starting offers a THD that is between 2 and 1.

The proposed scheme of soft starting contributes for three basic issues of drives viz. improved source utilization by the way of improved source power factor, improved power quality on the source side leading to power quality pollution under check and also, the torque ripple is reduced, the system reduces vibrations and hence increases the life of the driving motor every element in the driven chain of mechanical system as well.

The major advantage of this method is that the motor under consideration can be started in any number of steps. For example it can be started in the star delta voltage ratio with just two steps. It can also be started like a DOL starter with a single step. If necessary, as may be decided by the size of the motor and the load thereon the scheme can be used with more number of steps. In all cases the switching angles for the SHE PWM will be calculated on line and in all steps the lower order harmonics are eliminated. Thus torque ripple minimization is guaranteed in all steps of soft starting.

It is true that any motor which is started usually runs for periods much more than the period of starting transient. However where there are a large number of motors and especially when they are frequently started and stopped the parameters considered above will have significant bearing. Also it is important to consider vibration during starting should be reduced as much as possible to lengthen the trouble free operation of the associated mechanical system, which in this work is suggested through reduction of starting torque ripple.

Conclusion:

This novel system has been proposed mathematically validated and developed with the sole commitment of providing a soft starting scheme that is soft for both mechanical and electrical subsystems that use squirrel cage induction motor as the main driving element. The authors were motivated by the recent, repeated failures of the coal handling conveyor system in a nearby thermal power plant that uses more than hundred squirrel cage induction motors operated with 33KV. The proposed system has been demonstrated by MATLAB/SIMULINK simulation with gradual increase in modulation index, as the soft starting is in action, under all modulation indices the switching instants are so selected such that during the entire process of soft starting the selected harmonics $5^{th}$, $7^{th}$, $11^{th}$ and $13^{th}$ are eliminated from the source current and the authors hope that it will be of immense use to the industry.

REFERENCES