

A Novel Digital Firing Scheme for Soft Starting of Three-Phase Induction Motors

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Abstract — In this paper a novel, simple and reliable digital firing scheme has been introduced for soft starting of three-phase induction motor. The switching signals are obtained from parallel port of PC computer for controlling the output voltage of three-phase ac chopper. The new proposed scheme depends on increasing the stator voltage gradually without increasing the stator current than reference value. The ac chopper used with this strategy is having six bidirectional switches. The new strategy can be used with any PC computer with any processor speed and for all the starting conditions of three-phase induction motor. The soft switching technique can be used also in speed control of induction motor after starting period. Simulation of the system is carried out by PSIM computer program. The simulation results show stable operation for different loading conditions. The simulation results have been compared with the experimental results from laboratory prototype. The experimental results are very near to simulation results.

One of the best starting techniques of squirrel cage of induction generator is accomplished by regulating the input voltage to reduce starting current to be with specified limit. In induction motors that are designed to operate with delta stator connection it is possible, during starting, to reduce the phase voltage by switching to y-connection and then switching the stator connection to delta so the phase current is reduced 3 times. Starting induction motor by phase angle control [2-4] is the most famous technique. But, this technique has many problems when it is used in speed control due to the commutation of power thyristors. Using of modern switches like IGBT or MOSFET increase the flexibility to use the converter in starting and speed control [5]. The proposed system uses active switches in starting and speed control of three-phase induction motor. The following items explain the concepts of the proposed converter.

I. INTRODUCTION

Starting refers to increasing the motor speed from stand still current and torque of an induction motor when fed directly or indirectly from power supply. When induction motor starts with direct full-voltage almost 5 to 6 times rated current is expected at starting [1]. Full starting torque is produced in this case and starting over notable loads is possible. Stator voltage decrease will lead to a starting torque, which decreases with voltage squared.

II. PROPOSED SYSTEM

The proposed system depends on increasing the terminal voltage of three-phase induction motor gradually by controlling the firing signal of three-phase ac chopper. Increasing the stator voltage continues until the stator current is increased than specific limit. The proposed system consists of three-phase ac motor, ac chopper, control circuit as shown in Fig. 1. The detailed analysis of each subsystem is given below.

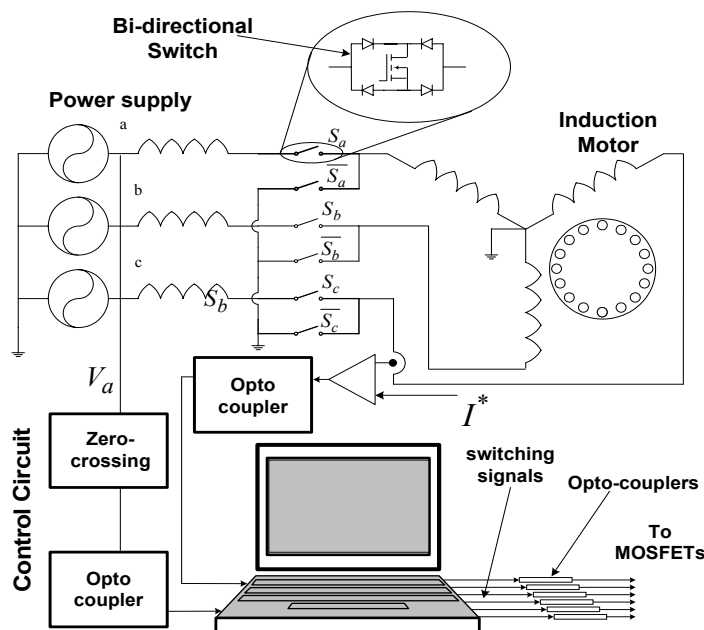


Fig. 1. The proposed soft starting system

A. Induction Motor Model

The squirrel cage induction motor that is used in this analysis is squirrel cage star connected. The mathematical model of the induction motor is represented by the following matrix differential equations:

$$[v] = p[L][i] + [R][i] \quad (1)$$

Where the components of the matrix elements are as follows:

$$[v] = [v_A \ v_B \ v_C \ v_a \ v_b \ v_c]^T$$

$$[i] = [i_A \ i_B \ i_C \ i_a \ i_b \ i_c]^T, \quad (2)$$

v_A, v_B, v_C three-phase instantaneous stator voltages;

v_a, v_b, v_c three-phase instantaneous rotor voltages;

i_A, i_B, i_C three-phase stator currents;

i_a, i_b, i_c three-phase rotor currents;

The components of inductance matrix $[L]$ and resistance matrix $[R]$ are shown in [6].

It is clear from the above equation that the supply currents are directly proportional to stator voltages.

The developed electromagnetic torque can be represented as [2]:

$$T_M = J_M \frac{d\omega_r}{dt} + k_M(\theta_M - \theta_L) \quad (3)$$

The load torque also is shown as:

$$T_L = -J_L \frac{d\omega_r}{dt} + k_M(\theta_M - \theta_L) \quad (4)$$

The mechanical equation motion can be written as:

$$T_M - T_L = (J_M + J_L) \frac{d}{dt} \omega_r \quad (5)$$

where,

T_M motor torque;

T_L load torque;

J_M inertia of the motor rotor;

J_L inertia of the driven unit;

k_M spring constant between the motor rotor and the driven unit;

θ_M torsional angle of the motor rotor;

θ_L torsional angle of the driven unit.

ω_r instantaneous angle velocity of the rotor.

B. AC Chopper

The ac chopper under study consists of six bidirectional switches as shown in Fig. 1. Three switches are connected in series with stator terminals of the motor and another three are used to provide freewheeling path across stator windings. In this study Extinction Angle Control (EAC) strategy has been used to control the ac chopper to perform soft starting of the three-phase induction motor. EAC strategy is carried out by switching ON the series switch of phase a , (S_a) at zero crossing point of supply phase voltage, then switching it OFF at angle $(\pi - \alpha)$ as shown in Fig. 2. The series switch of phase a (S_a) is in ON state when $0 < \omega t < \pi - \alpha$, in the same time the shunt switch of phase a , (\bar{S}_a) is OFF.

The switching state will reversed when $\pi - \alpha < \omega t < \pi$. The switching state in the negative half cycle of supply

voltage is same as in positive half cycle. So, the frequency of the switching function is double the supply frequency. The switching signals of the other two phases are shifted from the switching signal of phase a by 120° . The time variation of fundamental component of motor phase voltage is:

$$v_{r1}(t) = \frac{V_m(\pi - \alpha)}{\pi} \sin\left(\omega t - \frac{\alpha}{2}\right) + \frac{V_m \sin \alpha}{\pi} \sin\left(\omega t + \frac{\alpha}{2}\right) \quad (6)$$

$$\text{Then, } V_{r1} = \frac{V_m}{\sqrt{2} \pi} \sqrt{\sin^2(\alpha) + (\pi - \alpha)^2 + (\pi - \alpha) \sin(2\alpha)} \quad (7)$$

The relation between the rms component of fundamental component of phase voltage and angle α is shown in Fig. 3. It is clear from (7) and Fig. 3 that the fundamental component of the voltage at the terminal of the motor, V_{r1} , is inversely proportional to the value of angle α . So the fundamental voltage can be increased by reducing the off-angle, α . Increasing the fundamental voltage increases the induced torque, so the induction motor starts when the induced torque becomes greater than the load torque.

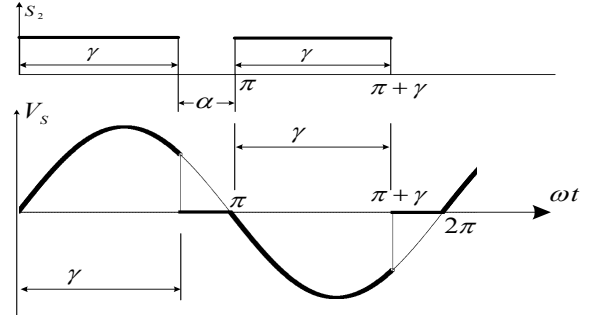


Fig. 2. Switching function and motor-terminal voltage of one of series switches in case of EAC.

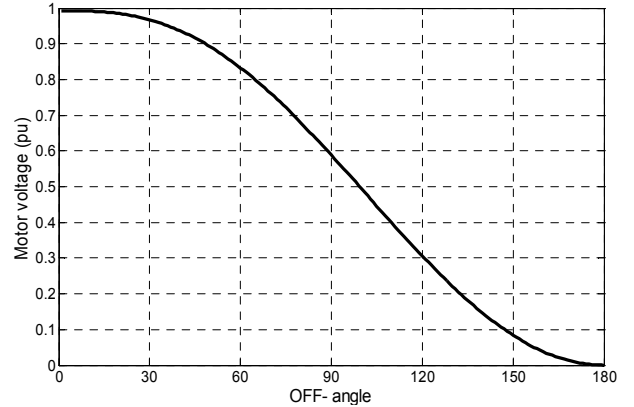


Fig. 3. Variation of motor voltage with the OFF angle α .

C. Control Circuit

In the system under study the standard parallel port of the PC is used to generate the switching signals for ac chopper. High level programming languages such as Visual Basic is used for driving the parallel port of PC. The control system is starting at certain conduction angle γ and it will check the motor current, I . If the motor current is lower than the reference value, I^* the control system increases the conduction angle, γ by $\Delta\gamma$ otherwise it will reduce the conduction angle by the

same increment as shown in Fig. 4. If the conduction angle becomes 180° the control system turns off all three shunt switch and the motor works normally with only the three series switches. In case of γ becomes equal to π and the motor didn't run the system will switch off all switches.

In the system under study the standard parallel port of the PC is used to generate switching signals. PC parallel port is a D-shaped female connector and has 25 pins as shown in Fig. 5. It provides eight output pins (2-9), five input pins (10-13,15), four bidirectional pins (1,14,16,17) and pins (18-25) are all ground pins. High level programming languages such as Visual Basic is used to driving the parallel port of PC. Due to slow timers supplied with Visual Basic programming language a high resolution timer must be developed by using the API (Abdication Programming Interface) functions which are available in the Windows system.

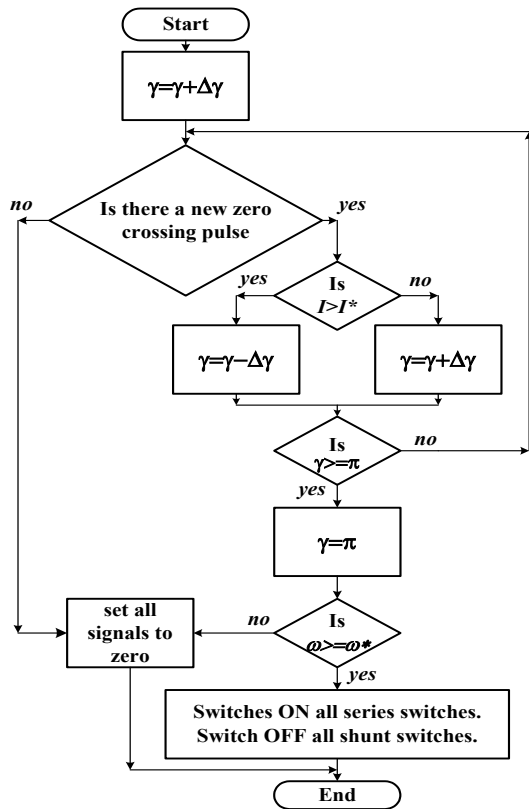


Fig. 4. Flowchart of the proposed soft starting control logic.

It is necessary to synchronize the output parallel port pulses with the supply voltage. So, zero-crossing detector should be used to send a pulse to the program in the beginning of each cycle via the input pins of the parallel port. Zero crossing detector is designed using op-amp as shown in Fig. 6. Opto-coupler isolator has been used to isolate the parallel port pins from the power circuit. The opto-coupler used in the circuit is 4n32. Six opto-couplers are used between the output pins of parallel port and the gate of each switch. Also a suitable resistor between the output pin and the opto-isolator to

limit the current to value less than 5mA, this depends on the value of the resistor and the V_{cc} of the opto-isolator. A different dc power supplies are designed for biasing different control circuits.

The motor current has been detected by using current sensor and has been compared with reference point of motor current, I^* by using simple comparator. The output signal from the comparator is high when $I^* > I$ otherwise the output pulse will be low. The output of the comparator will be connected to pin #12.

The power circuit consists of the following:

- 1- The power MOSFET n-channel (Part # IRFPC50) has a $V_{DSS}=600V$ and $I_d=11A$
- 2- The ultra-fast recovery diodes used in bidirectional switch is (#RURP860) has a high-reverse voltage (600 V), low-forward voltage drop (1.5 V at 8 A),
- 3- Snubber circuit to protect the power MOSFET.
- 4- Three-phase supply and induction motor.
- 5- Current sensor and comparator.

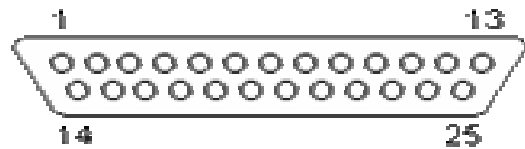


Fig. 5. PC parallel port, D-shaped female connector.

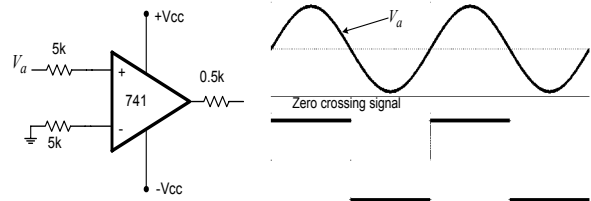


Fig. 6. Zero crossing circuit and its output signal along with phase a voltage.

III. SIMULATION AND EXPERIMENTAL RESULTS

The simulation of the system under study has been carried out using PSIM computer program [7]. A 380V, 3.81 A, 1.0 kW, 60 Hz and 4 poles induction motor was used in the simulation and experimental study. Its parameters are shown in Table (1).

Table (1) The induction motor parameters.

R_s Ω	R_r Ω	$L_s = L_r$ H	L_m H	n,rpm	J_M+J_L
3.13	1.74	0.00833	0.1369	1770	67 m.sec

A. Simulation Results

Fig. 7 shows the time variation of line current, motor speed and induced torque of the motor when starting the motor directly from rated voltage supply. Fig. 8 shows the time variation of motor current, speed, rms value of motor current, and the conduction angle γ . It is clear from Fig. 7 that the starting current without soft starting means is about 7 times full load current. But, as shown in Fig. 8 the starting current does not exceeds the

specified limits $I^* = 3$ times the full load current as an example.

B. Experimental Results

The experimental results were obtained from the proposed system that described above. The waveforms were captured using Fluck'192 digital scopemeter. Fig. 9 shows the phase voltage (top waveform) at the motor terminals and supply current (down waveform) during

starting period at $\alpha = 30^\circ$. Fig. 10 shows the phase voltage (top waveform) at the motor terminals and motor current (down waveform) during starting period at $\alpha = 30^\circ$. Fig. 11 shows the time variation of starting motor current (top waveform) and motor speed (down waveform). It is clear from Fig. 11 that the motor current does not increase than the specified limit I^* .

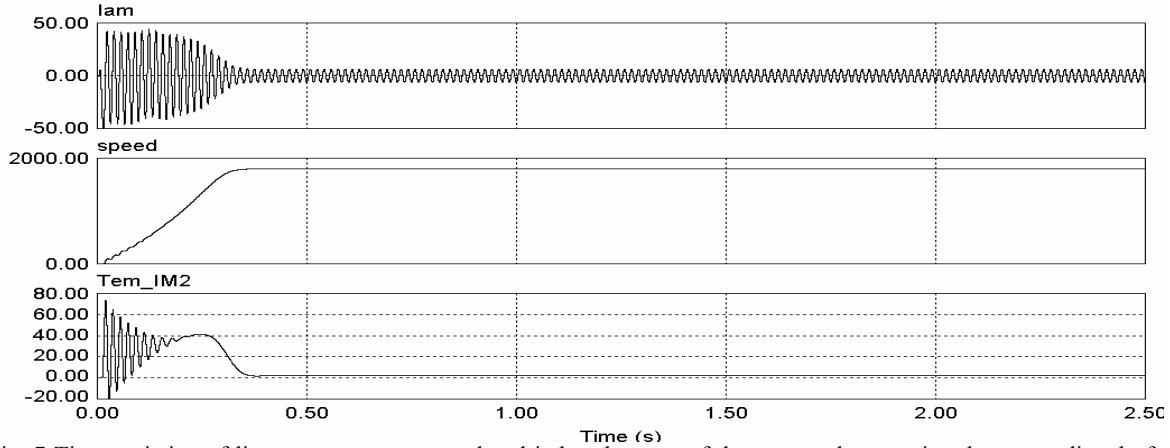


Fig. 7 Time variation of line current, motor speed and induced torque of the motor when starting the motor directly from rated voltage supply.

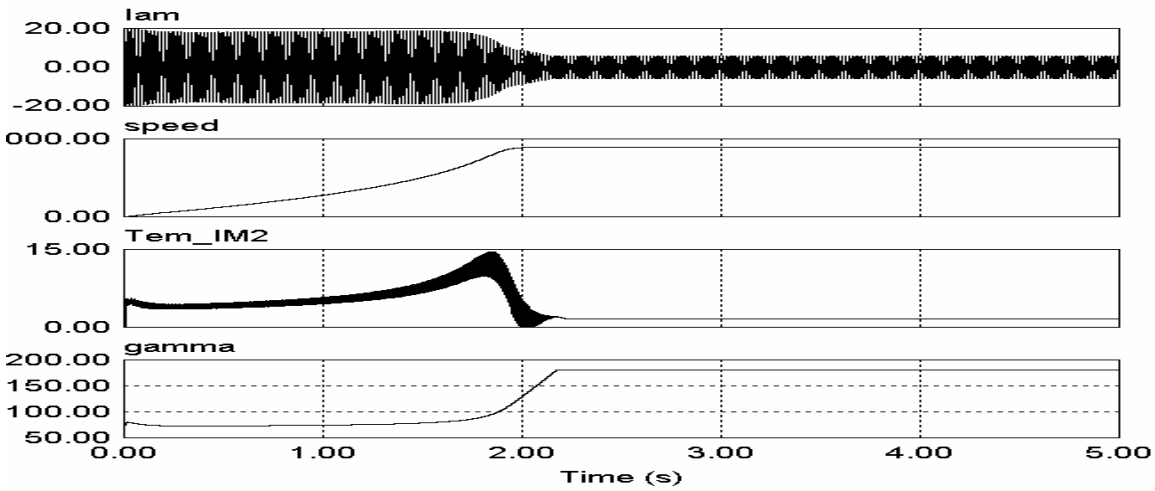


Fig. 8. Time variation of motor current, speed, rms value of motor current, and the conduction angle γ .

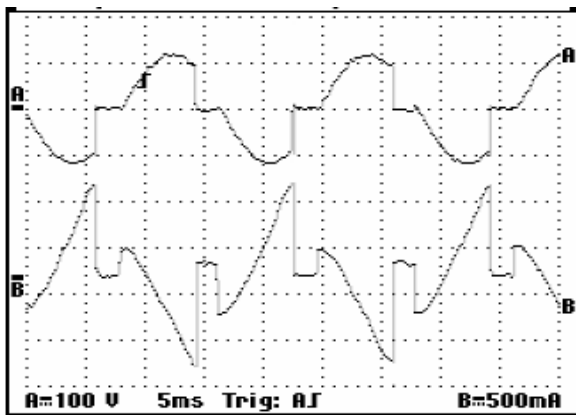


Fig. 9 Motor terminal voltages and supply current of phase a at $\alpha = 30^\circ$

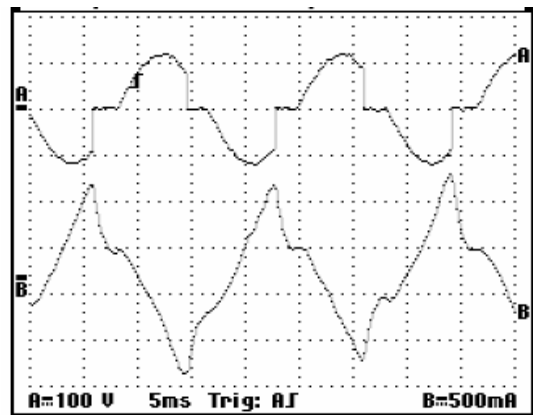


Fig. 10. The voltage at the motor terminals and motor current at $\alpha = 30^\circ$.

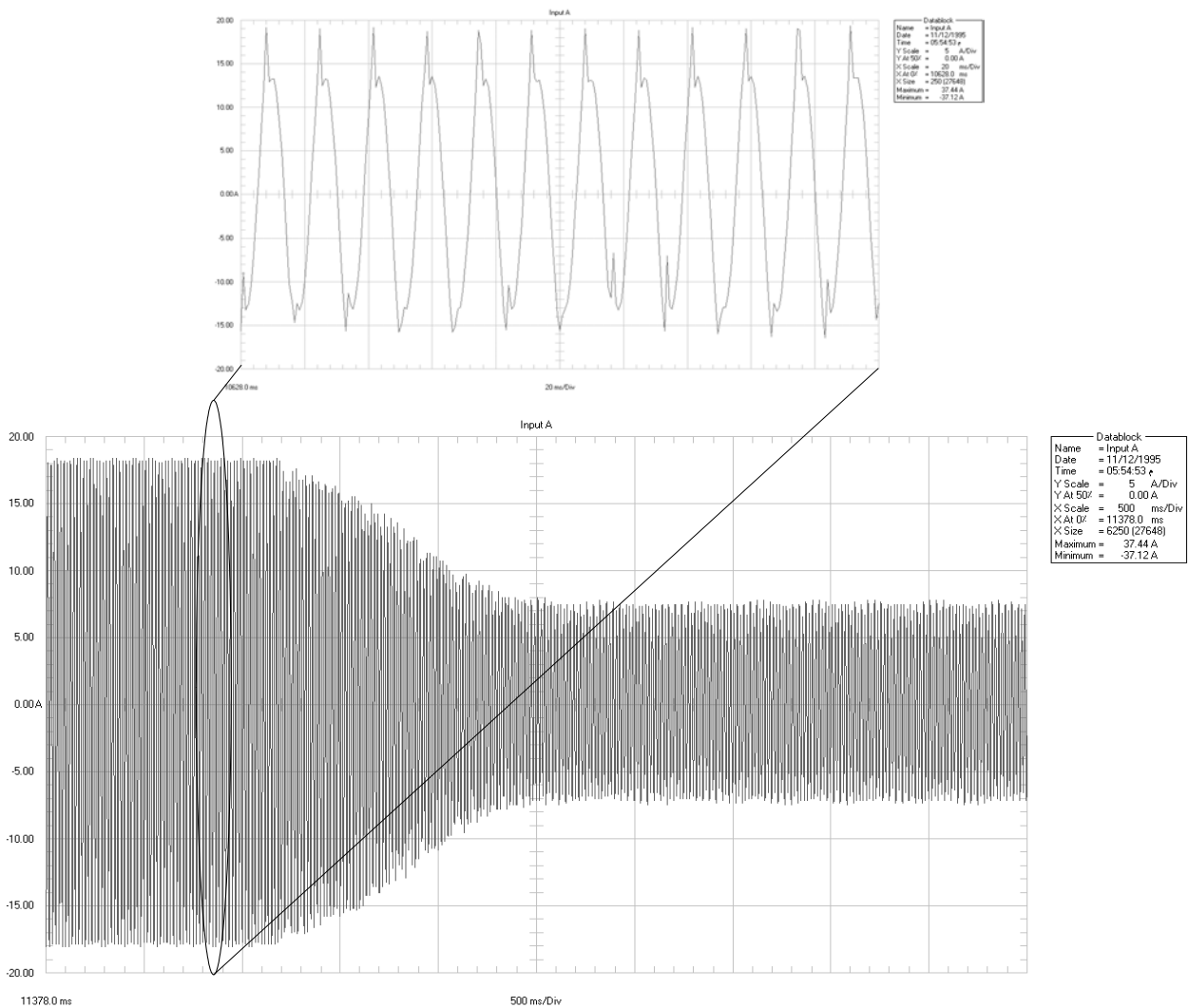


Fig. 11. Experimental time variation of starting motor current.

IV. CONCLUSION

In this paper high starting current of three-phase induction motor has been controlled to be under specified limit by using a novel digital technique. The soft starting system uses ac chopper in regulating the voltage going to the induction motor. The ac chopper is controlled by using parallel port of PC. The logic of the control system has been carried out by using Visual Basic language. This novel soft starting system efficiently starts the induction motor without increasing the starting current than the specified limits. The simulation and experimental results show the superiority of the new proposed system.

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