BULLETIN OF THE POLISH ACADEMY OF SCIENCES
TECHNICAL SCIENCES, Vol. 69(2), 2021, Article number: e136746
DOI: 10.24425/bpasts.2021.136746

A novel source side power quality improved soft starting of three-phase induction motor using a symmetrical angle controller through pic microcontroller

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Abstract. PIC microcontroller has a vital role in various types of controllers and nowadays the presence of PIC microcontroller is unavoidable in most control applications. This paper describes the enhancement of soft starting of induction motors using PIC microcontroller. Soft starting is required for the induction motors with reduced applied voltages so that the peak starting current is reduced and the startup of the motor is smooth with controlled torque and reduced mechanical vibrations, reduced starting current with correspondingly reduced bus voltage drops. While many of the available schemes of soft starting offer better results in view of smooth starting process, the proposed methodology offers soft starting as well as it cares about the source current quality. In contrast to the conventional multistep starting scheme, in this work a continuously controlled starting scheme is proposed. The three phase AC voltage controller topology is used as the core controller. In each of the half cycles, instead of a single conduction period with a single delay angle, the proposed AC voltage controller is switched symmetrically in each half cycle with multiple pulses in each quarter cycle. Symmetrically placed fixed numbers of switching pulses are used. The paper also describes the various time ratio controls namely the phase angle controller, the extinction angle controller and the symmetrical angle controller. The design aspects of the proposed soft starting scheme and the validation of the proposed system in the MATLAB SIMULINK environment are presented in this paper.

Key words: soft starting of three phase induction motor; symmetrical angle controller; AC voltage controller; power quality improvement.

1. Introduction

The induction motor of the squirrel cage type, the so-called Squirrel Cage Induction Motor (SCIM) is the work horse of the industry. The rugged structure, ease of operation and maintenance and many such features have placed the SCIM at the top of the list of candidates suitable for industrial applications. However, the induction motor suffers two drawbacks. They lack an easy speed control scheme and the drawing of a heavy current as high as seven times the rated full load current while starting. These two drawbacks are being addressed by different ways using more digital signal processing systems in association with modern power electronics. This paper is about the design development and validation of a novel source current conscious soft starting scheme for the squirrel cage induction motor. Down in the history there have been many soft starting schemes proposed and validated by various researchers [1]. As for the traditional starting schemes for the SCIM the Direct Online Starter is the simplest of all starters and it does not include any soft starting scheme but it provides a safe and convenient means of connecting the three-phase source to the three phases SCIM with additional features like overload protection and no volt protection [2].

The Star Delta starter [3] is the earliest and a widely used traditional soft starting scheme. The Star Delta starter connects the three phases SCIM to the source with voltage reduced to 1/1.732 times the line voltage. After the motor picks up speed the starter contacts are reoriented to connect the motor in delta configuration and connect the motor to the three-phase source applying the full line voltage across each phase. The auto transformer starter is yet another starting scheme for SCIM. In this starter the starting voltage is first fixed at 50% of supply voltage. After the motor has started up and reaches its rated speed then full voltage is applied to the motor using auto transformer starter [4,5]. In Start Delta starter and in auto transformer starter the basic principle is to reduce the starting voltage by a fixed fraction of full operating voltage and thus reduce the starting current. With the advent of power electronic semiconductors, right from the SCR [6], which belongs to the Thyristors family and the more modern power electronic devices like the Power MOSFET and the IGBT [7] along with modern digital signal processing units like the digital microprocessor and the Micro controllers, the soft starting schemes for the SCIM are undergoing fast changes.

Anti-parallel SCR based AC voltage controllers [8] have been used for soft starting. In SCR based soft starting schemes, in the earlier applications, fixed number of firing angles has

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Manuscript submitted 2020-09-21, revised 2021-02-05, initially accepted for publication 2021-02-27, published in April 2021

been used. SCR based soft starting uses phase angle control and it leads to reduced power factor and poor quality of source current during the starting period. However, in [9] the authors have used the extinction angle control of soft starting using MOSFETs. This scheme provided improved source side power factor. In this paper, the idea forwarded is that a symmetrically placed switching pulse with conduction periods gradually increasing from the off state to the fully running condition [10, 11]. The proposed idea has the advantages of more smooth starting process with continuously varied conduction period, improved power factor on source side, improved starting current waveform on the source side with reduced THD throughout the starting period.

The SCIM is most rugged and simplest of electrical motors. It is the most popular and most useful and simplest as well [12, 13]. The SCIM is available in single phase and three phase versions and the discussions in this paper pertain to three phase SCIM. During the transient period the entire electromagnetic and electromechanical consideration of the machine becomes very complex [14, 15]. The stator current undergoes a rapid change, the speed rapidly changes the position based mutual inductances change and the interaction of all these things operate in a complex manner during the starting period. The action of the soft starter is to govern the transient period in such a manner that stator current is within limits, the torque development is smoother with reduced mechanical vibrations, with minimal losses and with improved source side power factor and decreased source current THD. Starting from rest, if a certain small instalment of exciting voltage 'e' is applied to the stator then current starts flowing in the stator and rotor and ultimately a torque is produced. This torque will turn the rotor of the motor until motor reaches a certain steady state speed. The applied voltage e has been just sufficient to take the rotor to a new steady state speed 'n'. Since the electrical and mechanical time constants are different it takes a finite time for the rotor to reach this speed n in time 't' [16]. If more voltage is applied than 'e', which was applied in the earlier case, then the motor would produce more torque and steady state speed would become more than 'n' and that the speed 'n' would have reached at a time earlier than time 't' it took in the earlier case. Sudden application of full voltage produces large torque and the motor tries to reach the full rated speed in a short while [17]. With exciting voltages applied in small instalments the acceleration can be controlled and the motor may be guided to the rated speed in a smooth manner. This way the unnecessary high starting current may be reduced, the rate of change of mutual inductances will be reduced, the vibrations will be reduced and there are several advantages behind such a smooth starting [18].

Soft starting is a phenomenon that is applicable only during the starting period. It has nothing to do with the performance of motor under steady state running condition. All issues associated with starting process happen only for a short transient period [19]. However, in a large industrial plant with a large number of high-power motors which are frequently turned on and off the overall scenario becomes very complex and the all-round performance of the entire industry will degrade causing losses, power quality issues, frequent electromechanical maintenance activities etc. The torque produced by the SCIM is a function of square of applied voltage [20]. Soft starting is essentially the gradual rather than a sudden production of torque. Sudden production of torque happens with full operating voltage applied at one time while soft starting is about applying the voltage gradually or in a continuously variable gradual basis [15]. The three phase AC voltage regulator makes it possible to continuously or gradually increase the applied voltage so that the SCIM is started in a soft and smooth manner.

2. SCR based three phase AC voltage controllers

The only degree of freedom to implement a loss less soft starting scheme is to control the voltage applied to the motor. The AC voltage controller is a topology is best suited for this purpose [21]. The given topology of the SCR based AC voltage controller that is suitable for an R type load typically used for heat control (Fig. 1).

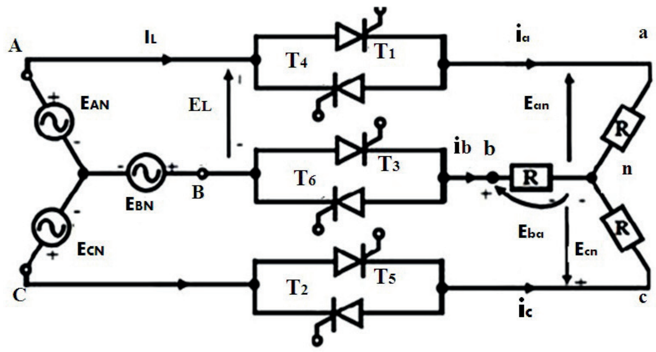

Fig. 1. Topology of the three phase AC voltage controller

With the RL load, in order to use the stored energy a freewheeling system is necessary and the AC voltage controller catering to RL load may use a freewheeling system. Phase angle control is usually used with AC voltage controllers that are built around SCRs. SCRs can be turned on at required instant but they cannot be turned off at required instant without the addition of some complex commutation arrangements [22]. The SCR however turns off naturally at zero crossings when the current through the SCR just crosses a value below the minimal current called holding current. Thus, AC voltage controllers built around SCRs are suitable for conduction period control scheme wherein the turn on instant is user defined and the turn off instant is system dependent.

3. MOSFET based AC voltage controllers

Power MOSFETs can also be used for the construction of AC voltage controllers. Figure 1 shows the topology of an AC voltage controller with power MOSFETs as the main switches. MOSFETs, unlike SCRs can be turned ON and OFF at required instants as defined or desired by the user. Hence it is possible to construct AC voltage controllers with MOSFETs with any control strategies like firing angle control, or extinction angle control or with both in every half cycle of AC sine wave. If the firing delay angle and the extinction angle are controllable then a symmetrical conduction scheme can be developed with equal conduction delay angle and extinction angle.

3.1. Phase angle control. In the basic form, in the case of phase angle control scheme, in every half cycle of AC source the firing instant in which the power control device such as SCR or MOSFET turned on is controlled. With the starting instant aligned with starting of AC cycle the full cycle of the AC wave is applied across load and current flows through the load for complete cycle. If the switching angle is delayed from zero crossing the average voltage applied across the load is reduced [23]. The simulation model of AC voltage controller is given Fig. 2. Figures 3–5 illustrate the voltage, current and FFT analysis for the phase angle controller with R and RL load.

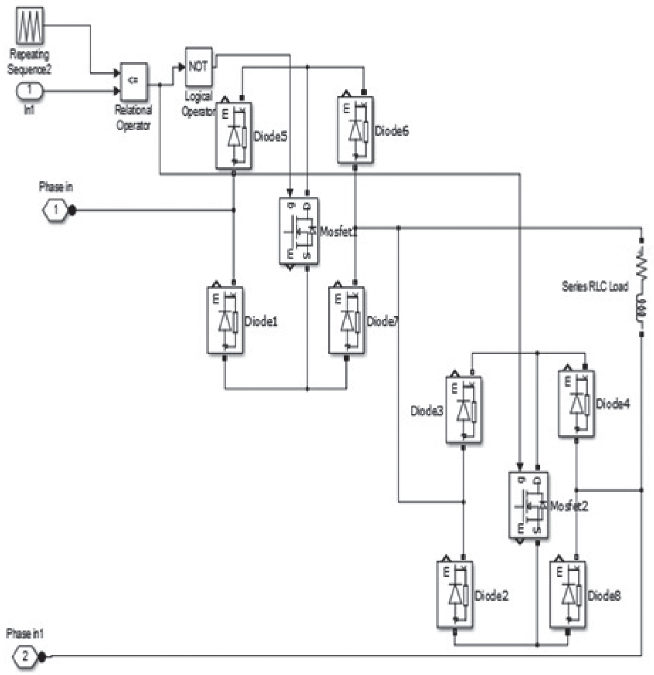

Fig. 2. The topology of the AC voltage controller implemented for the R phase with RL load

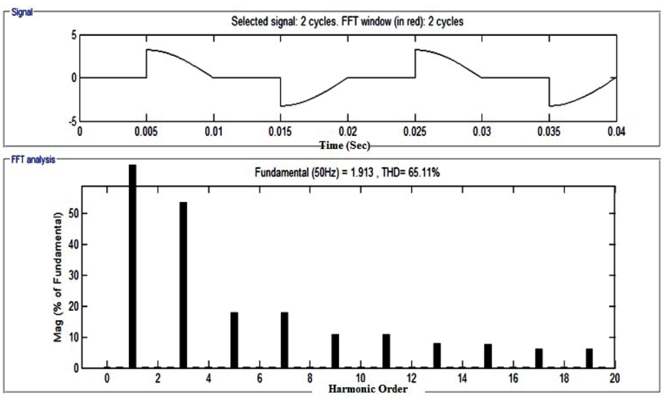

Fig. 3. With phase angle control the phase angle of the source current lags from the voltage by 32.3 degrees

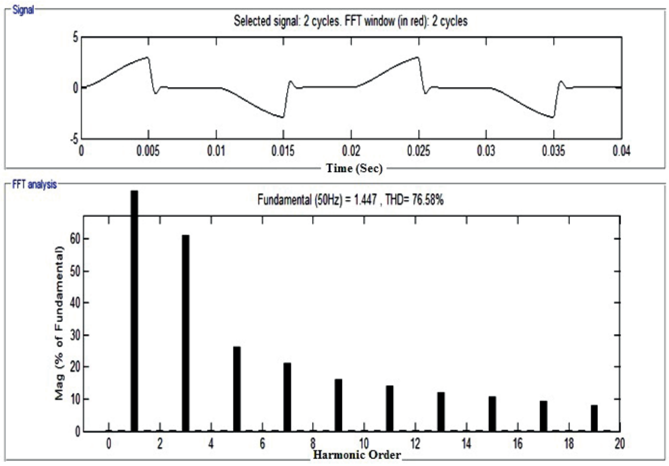

Fig. 4. Source current waveform and FFT for R

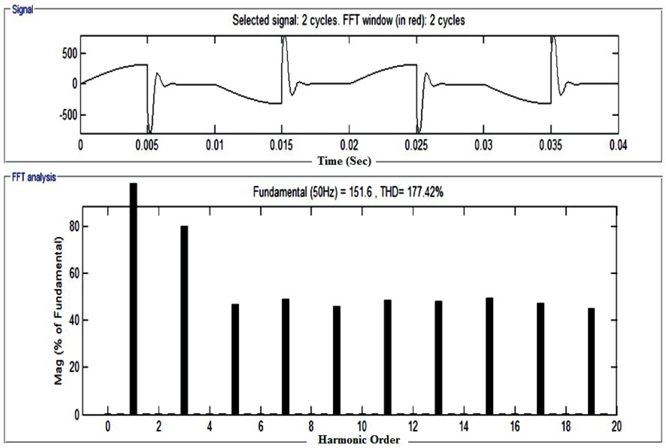

Fig. 5. Phase current with RL load – Phase angle controller

3.2. Extinction angle control. In the case of extinction angle control, in each positive and negative half cycle the turning on of power electronic switch is carried out at starting of half cycle. Conduction continues through the cycle until MOSFET is turned off by removing the gate turn on signal. Thus, conduction can be established in synchronism with the starting of sine wave and can be stopped at the desired instant. By changing the instant of stopping of conduction through the MOSFET power flow can be controlled. The performance and THD analysis are given in Figs. 6–9. Extinction angle control can be extended to the soft starting application of the three phases SCIM.

3.3. Symmetrical angle controller. Similar to the phase angle control in which turn on instant is controlled, and extinction angle control in which the turn off instant is controlled, in the case of symmetrical angle control both turn on instant and turn off instant are controlled [24]. Thus, by appropriately selecting the turn on instant and turn off instant the conduction period can be made symmetrical about the peak value of incoming sine wave. Maintaining symmetry of voltage applied across load the source current THD is reduced (Figs. 10, 11) and also as this method includes the extinction angle control, that is turning off

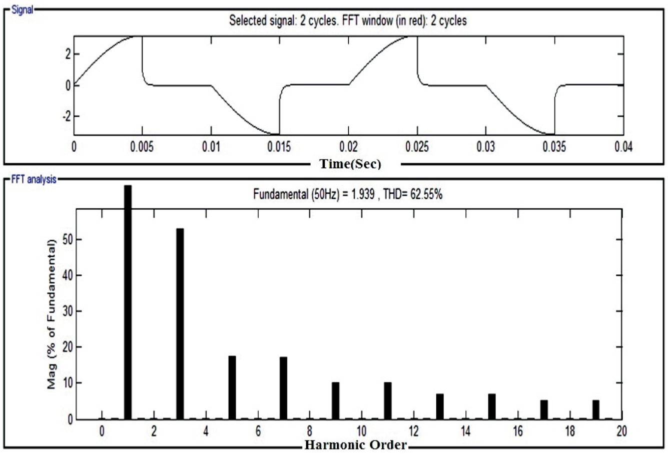

Fig. 6. The Waveforms and FFT pertaining to the load side voltage and current with R Load in the case of excitation angle control

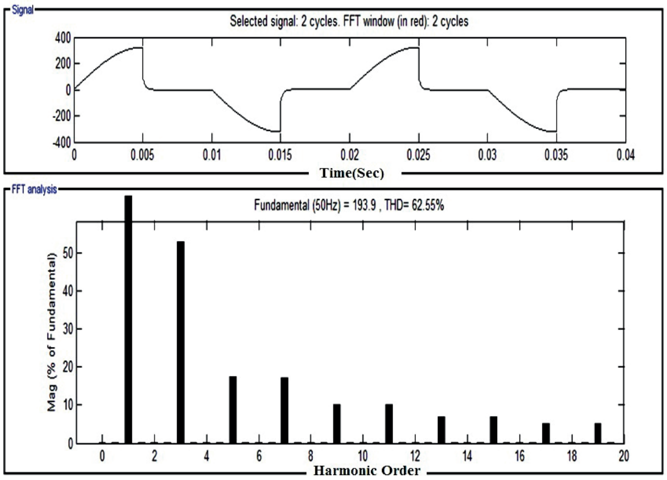

Fig. 7. The waveform of load side voltage in the case of extinction angle controller and its FFT

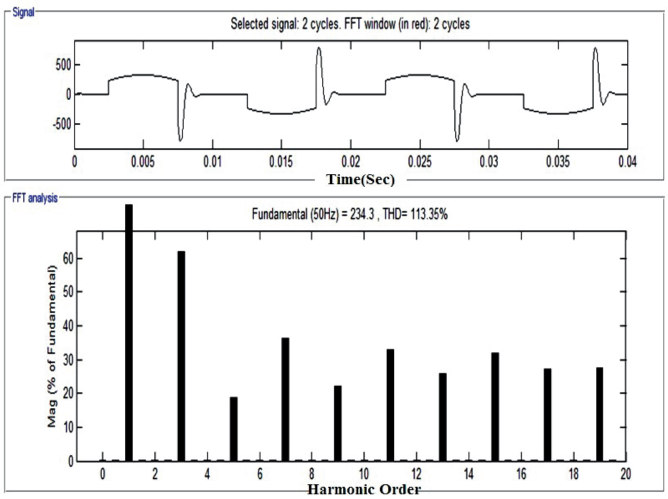

Fig. 8. Load side voltage with RL load – Extinction angle controller

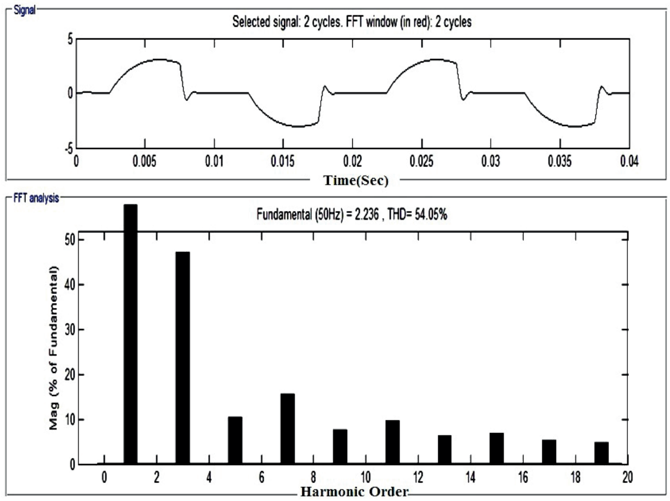

Fig. 9. Source current of an extinction angle controller with 50% duty cycle

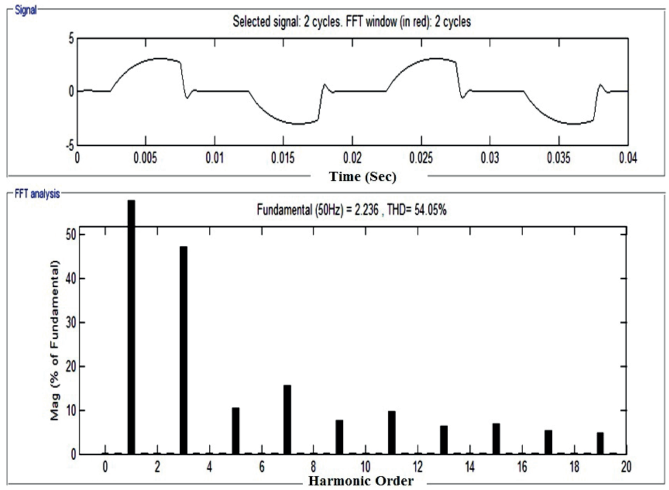

Fig. 10. The waveform and FFT of the R phase source current with Symmetrical angle controller with RL load

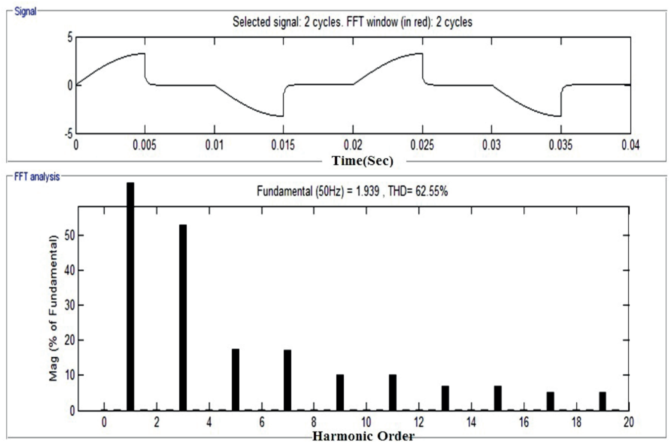

Fig. 11. The waveform and FFT of the source current with symmetrical angle controller for 50% conduction

before the zero crossing the power factor of the source current also increases. The simple symmetrical angle control can also be extended for soft starting of the three phase SCIM. The relevant waveforms of symmetrical angle based soft starting are shown in Fig. 12.

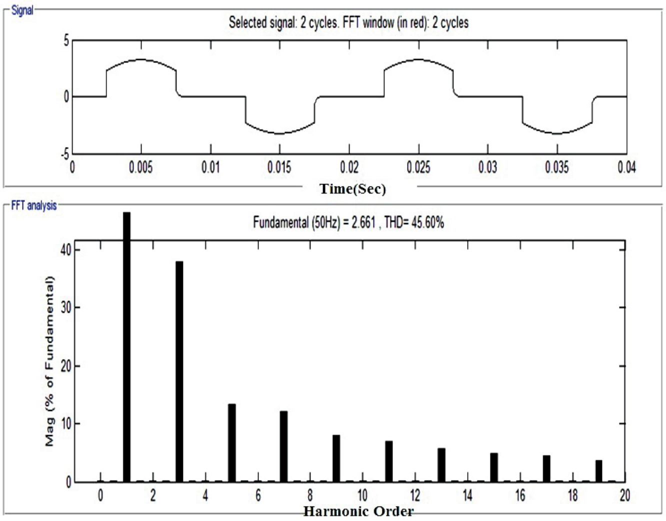

Fig. 12. The source current and FFT of a symmetrical angle controller

The objective of the soft starting scheme is to drive the stator current in a controlled manner such that the source current gradually increases in a soft manner such that the motor accelerates from zero RPM state to final steady state without drawing a heavy starting current. With the application of a continuously controlled source voltage this ideal current may be obtained and the resulting developed torque. But it is not possible to obtain this linearly rising source voltage with the help of the available power electronic switches. Power electronic switches are controlled in the time axis while the resulting currents and voltages, after due filtering show up continuous control in the amplitude. In the proposed method three pulses in total are used for every half cycle. These pulses have on and off periods. If the widths of each of the pulses are so arranged by turning on and off the power electronic switches the average value may be made equal to the ideal starting current. Soft starting although has several advantages it has a main disadvantage that total starting period is increased. So, it is convenient to design soft starting scheme by first fixing the total starting period. If the total starting period is decided, the slope of rise in starting current begins from zero, the rated value can be calculated. Going by an example if rated voltage is 380 V Line to Line and if the total starting period will be 30 seconds then the slope at which applied voltage should gradually rise is given as 380/30 Volts per second. During this transition period, each cycle has an area and this area rises gradually as per the slope used. With power electronic switches the applied source voltage is not altered but through the power electric switches only. The turning On and Off of symmetrical angle control are selected in real time, so that the area of conduction in each cycle equals to the corresponding cycle in the ideal starting voltage. Considering a 50 Hz power system with 380 V as the line voltage, if the starting period is 30 seconds then the total number of cycles covering the starting period will be 1500. Each cycle starting from the 0^{th} cycle will have an area that is distributed linearly over 1500 cycles. The 1500^{th} cycle will have full area or conveniently an area of 1Per Unit. In the proposed five pulse symmetrical angle controller, the ON durations in each pulse are kept in such a way, that the total ON period and hence the area of conduction of each pulse equals the area of the corresponding cycle of the ideal or reference voltage that progresses gradually.

The mathematical considerations are System frequency 50 Hz., Source Voltage 3 phase 380 V, 50 Hz, Motor rating 10 kW, 380 V, 50 Hz, Number of poles of motor 4, rated speed 1440 RPM, starting transient period considered 1 Seconds, Number of cycles covered during starting period 50. In the proposed soft starting scheme three pulses are used in every half cycle and these three pulses are centred at the 45 degrees, 90 degrees and the 135 degrees' points of the positive half cycle and at 225 degrees, 270 degrees and at 315 degrees. The total period of half cycles with 50 Hz system is 10000 microseconds. At the end of the 1500th cycle the total duration of conduction will 10000 microseconds in each cycle. The total duration of conduction in the first cycle should be $10000/1500 = 6.667$ microseconds divided equally for the three pulses which will be 2.22 microseconds. This duration 2.22 microseconds will be added uniformly to all the three pulses in each cycle and this increment of conduction period increases until the total period of conduction becomes 10000 microseconds at the end of the 1500th cycle. The proposed scheme of soft starting was simulated in the MATLAB SIMULINK environment (Fig. 13).

4. Results and discussions on simulations

By considering the three different time ratio controls namely the Phase Angle Control, the Extinction Angle Control and the Symmetrical angle control are implemented in R load, RL load and finally in the case of an Induction Motor. The results of all control methods have been recorded with the waveforms and the FFT. Figs. 14–17 illustrate the rise of voltage and current at the time of starting and Figs. 18–21 illustrate the speed, electromagnetic torque, starting current, THD and Power Factor while starting the Three Phase Induction motor. It is clear that compared to the traditional phase angle control scheme the other techniques like the extinction angle control and the symmetrical angle control perform better. The best of the three schemes is the Symmetrical Angle controller. With the three-time ratio control schemes the performance with R load and RL are first studied and recorded. Then the SCIM was connected and the performance parameters were recorded.

These results have been obtained and given in Tables 1, 2 and 3 with a proposed three phase voltage controller with R load, RL load and Squirrel cage induction motor as load with the period of conduction increased gradually over a period of 1 sec. The total number of cycles passed on is 50. The total power delivered to the load, the range of power factor, the THD

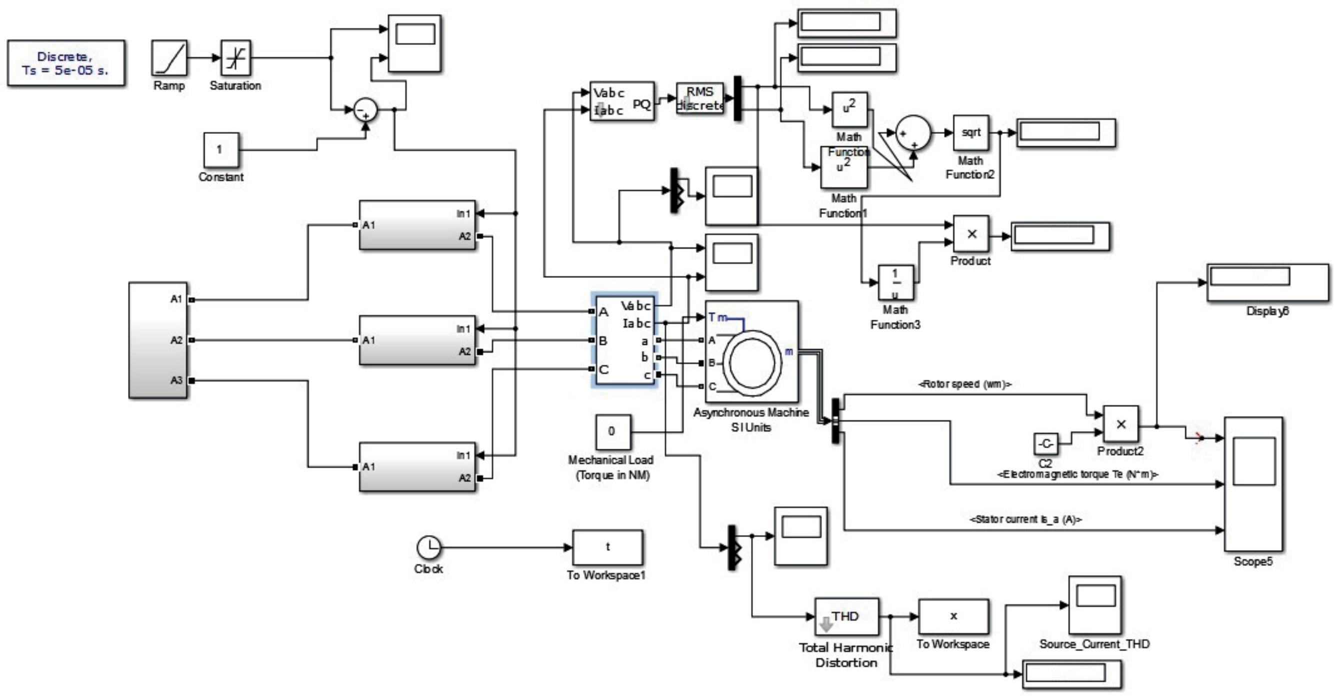

Fig. 13. Simulink model for measuring Power Factor and THD

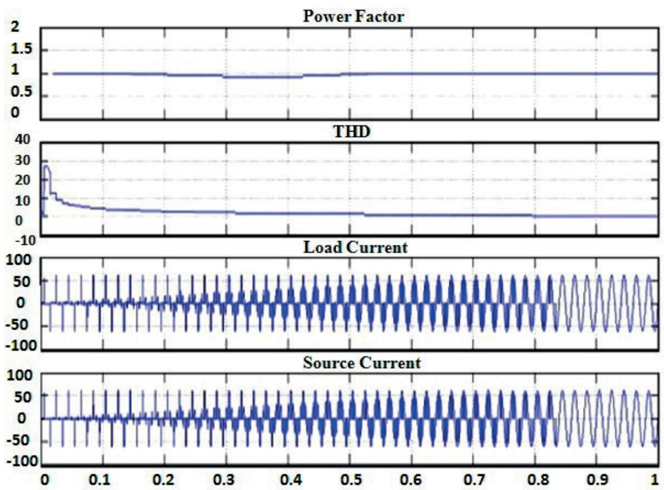

Fig. 14. Rise of voltage and current when the multiple pulse PWM symmetrical angle control is implemented in the case of an RL load

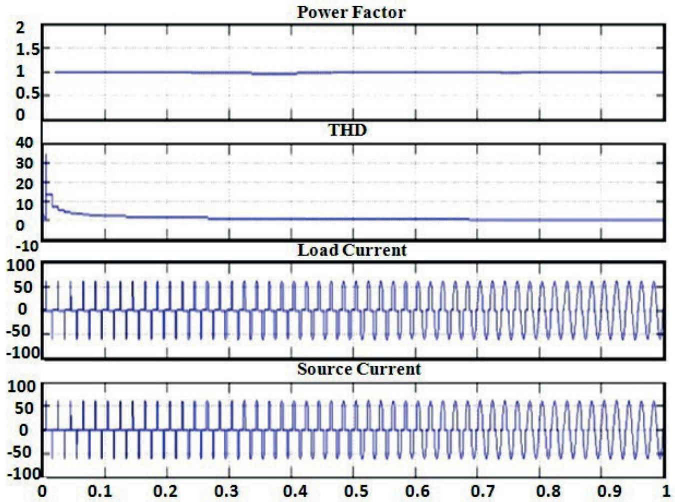

Fig. 15. Rise of voltage and current when the Single pulse PWM symmetrical angle control is implemented in the case of an RL load. Order of the signals from top: Power factor, THD, Load Current and Load side voltage

are recorded and compared. The power factor is also maintained always high over the entire control period. The THD is maintained throughout to be less than 5%. In the case of phase angle control and extinction angle control the power factor increases gradually as the conduction angle increases. The THD is less than 4% for extinction angle control while it is near 10% for phase angle controller [25, 26]. Similar readings were observed with RL load also. Then the SCIM was started with four schemes and readings have been recorded and presented here. It can be concluded that symmetrical angle controller and multiple pulse symmetrical angle controller are better two candidates and the extinction angle controllers along with phase angle controller are less suitable for soft starting. Although the performance of Multiple pulse and the single pulse Symmetrical angle controllers are both in terms of minimal starting time, low THD on the source current and improved PF, it can be concluded that the symmetrical angle controller is better than multiple pulse symmetrical angle controller considering the mathematical overheads and the complications involved in engineering of multiple pulse symmetrical pulse based soft starting.

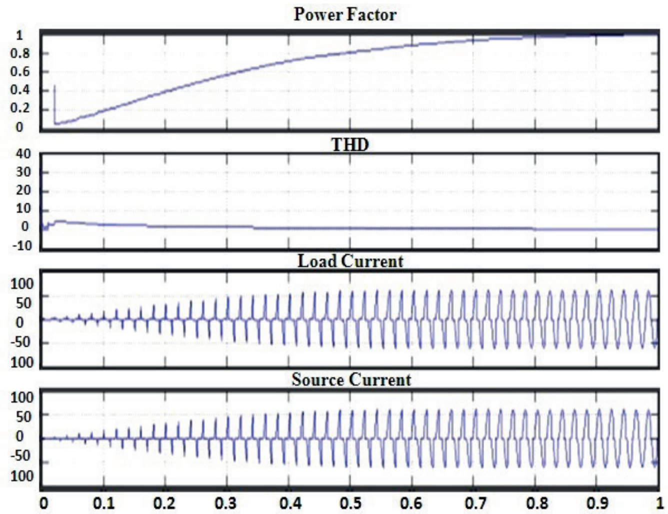

Fig. 16. Rise of voltage and current when the extinction angle control is implemented in the case of an R load

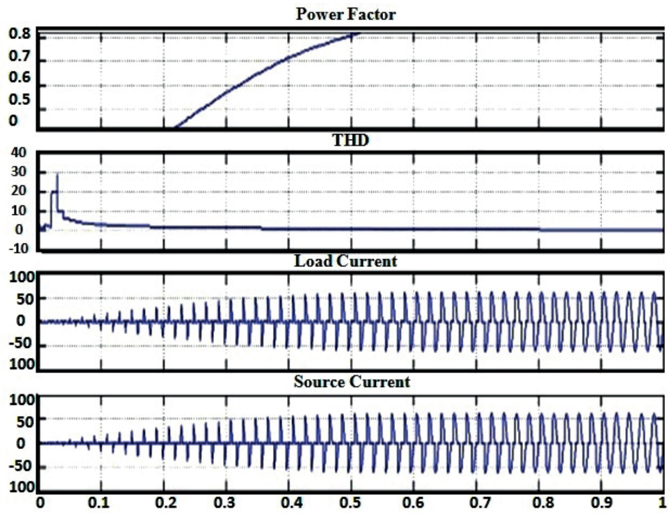

Fig. 17. Rise of voltage and current when the extinction angle control is implemented in the case of an RL load

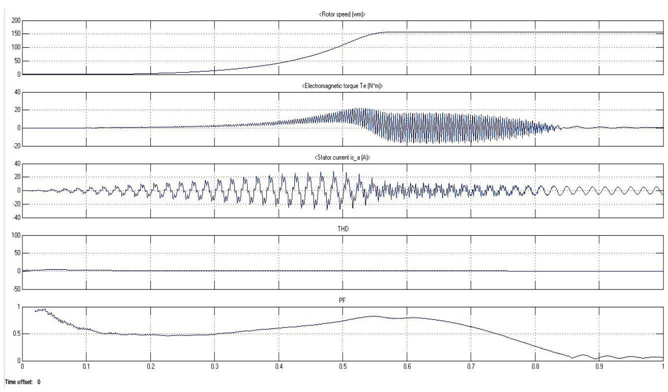

Fig. 18. Speed, electromagnetic torque, starting current, THD and Power Factor while starting the Three Phase Induction motor with Multiple Pulse Symmetrical Angle controller

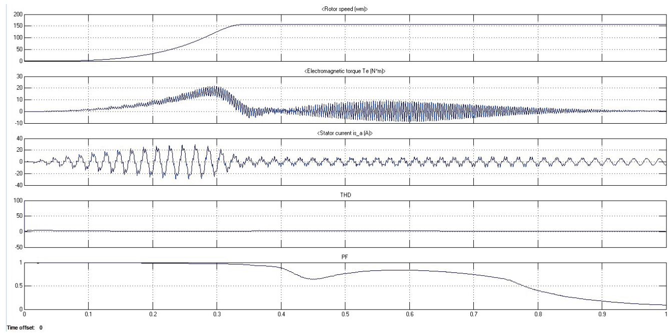

Fig. 19. Speed, electromagnetic torque, starting current, THD and Power Factor while starting the Three Phase Induction motor with Single Pulse Symmetrical Angle controller

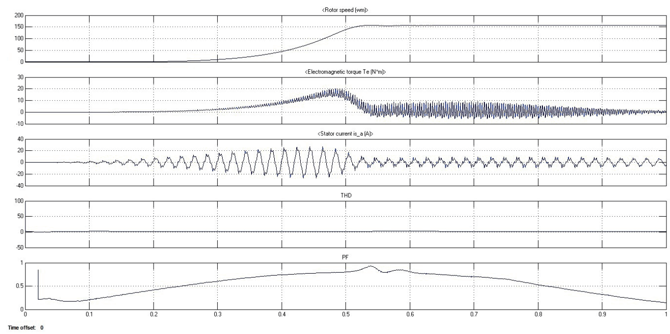

Fig. 20. Speed, electromagnetic torque, starting current, THD and Power Factor while starting the Three Phase Induction motor with Extinction Angle controller

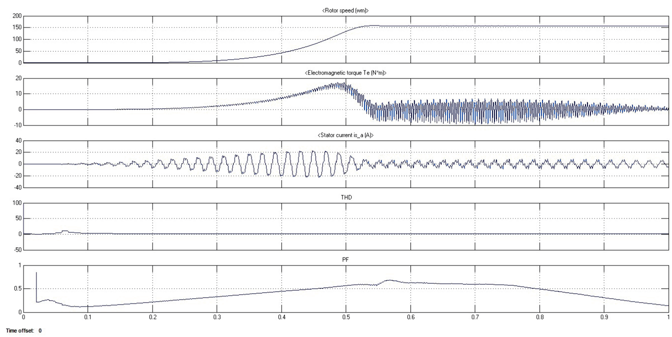

Fig. 21. Speed, electromagnetic torque, starting current, THD and Power Factor while starting the Three Phase Induction motor with Phase Angle controller

Table 1
R Load (5 Ohms) across the 380 V, 50 Hz supply

Method	Starting time (sec)	T_{max} (Nm)	THD max	PF range	Energy consumed in Joules
MPSPWM	0.55	20	5.0	0.5–1	612
SPSPWM	0.33	21	4.8	0.95–1	573
EAC	0.52	20	3.2	0.2–0.93	553
PAC	0.55	17.5	10	0.2–0.7	578

Table 2
RL Load (R = 5 Ohms, L = 10 mH) across the 380 V, 50 Hz supply

Method	THD Maximum	PF Minimum	Energy Consumed in kilo Joules
MPSPWM	5.0	0.91	13.55
SPSPWM	4.8	0.95	18.00
EAC	3.2	Gradual	12.35
PAC	10	Gradual	12.29

Table 3
Squirrel cage Induction motor as load across the 380 V, 50 Hz supply

Method	THD Maximum	PF Minimum	Energy Consumed
MPSPWM	4	0.8	7420 J
SPSPWM	4	0.85–1	11.47 KJ
EAC	2.5	Gradual	7825 J
PAC	2.5	Gradual	7759 J

5. Experimental verification

An experimental verification prototype has been built (Fig. 22) to validate the proposed idea of soft starting of the SCIM.

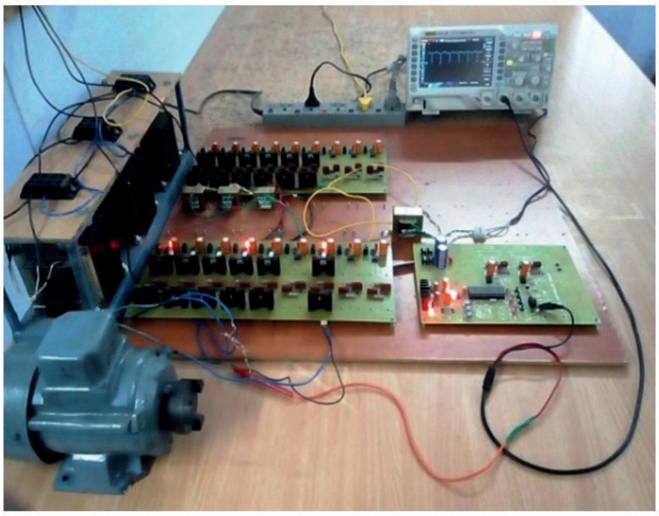

Fig. 22. Experimental prototype of the proposed soft starting scheme for the Induction Motor

The PIC16F877A features 256 bytes of EEPROM data memory, self programming, an ICD, 2 Comparators, 8 channels of 10-bit Analog-to-Digital (A/D) converter, 2 capture/compare/PWM functions, the synchronous serial port can be configured as either 3-wire Serial Peripheral Interface (SPI) or the 2-wire Inter-Integrated Circuit (I^2C) bus and a Universal Asynchronous Receiver Transmitter (USART). All of these features make it ideal for more advanced level A/D applications in automotive, industrial, appliances and consumer applications.

The methodology of implementing the soft starting of the SCIM using extinction angle control scheme implemented, as an experimental prototype is discussed in this section. A three phase AC voltage controller is used as the main power control system. In each phase of the source power supply anti series or back-to-back connected MOSFETS are used in series with the phase windings of the motor. For each of the switching module, consisting of two MOSFETs, a common gating signal is used and this signal is passed to the gate of the MOSFETs through optocouplers of type MCT 2E. There is a Zero Crossing Detector (ZCD) used for each phase and these ZCDs detect the zero crossing in each phase for both positive and negative half cycles. In the case of extinction angle controller, after the zero crossing is detected in each cycle the MOSFETS are switched ON. The MOSFETSs once switched on remain in the ON state for a predetermined period, in each cycle, and thus conduct only for a specific period of conduction and at the end of this period the MOSFETs are turned OFF by removing the switching pulse. If these switching pulses start at each zero crossing and keep the MOSFETs in conduction mode for the complete cycle then it is like Direct on Line starting shown in Fig. 23. However, with soft starting schemes the duration of conduction in each cycle is gradually increased from a small duration of conduction and the duration of conduction gradually increases until the full conduction in each cycle is reached. This reduces the starting current shown in Fig. 24.

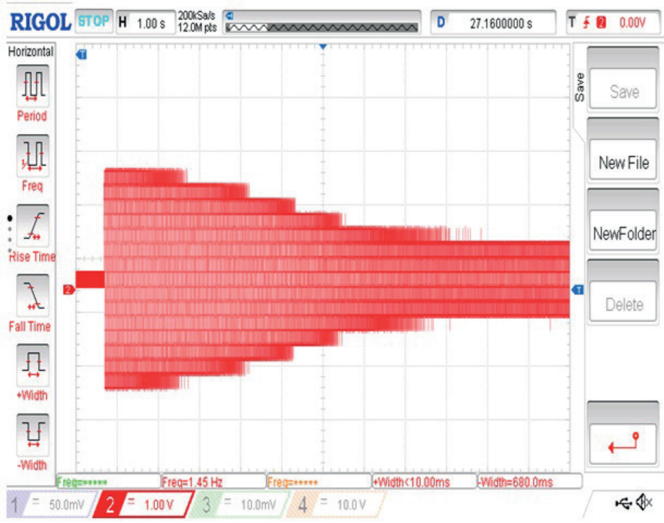

Fig. 23. Starting current of the SCIM with Full conduction periods (DOL or Sudden Starting

In order to compare the performance of the soft starting scheme with the DOL starting scheme both soft starting and DOL starting have been carried out. For the purpose of DOL starting the conduction period in each cycle was kept at 100% and the resulting stator current with high starting current at starting has been observed and the waveform of the starting current for the R phase stator winding is shown in Figs. 25 and 26.

With the soft starting in action, during the starting period the conduction angle is gradually increased from zero and during the low conduction periods the stator current is very low and

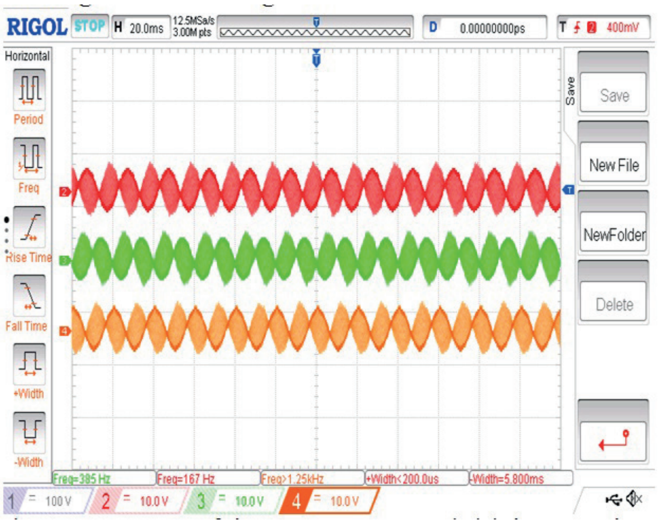

Fig. 24. Segment of the stator current at initial stage when the SCIM is soft started

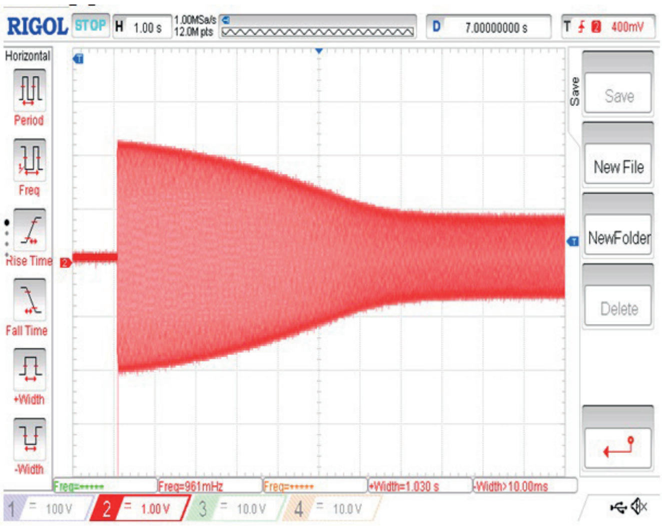

Fig. 25. Soft starting implemented with fixed 60% conduction period in each cycle

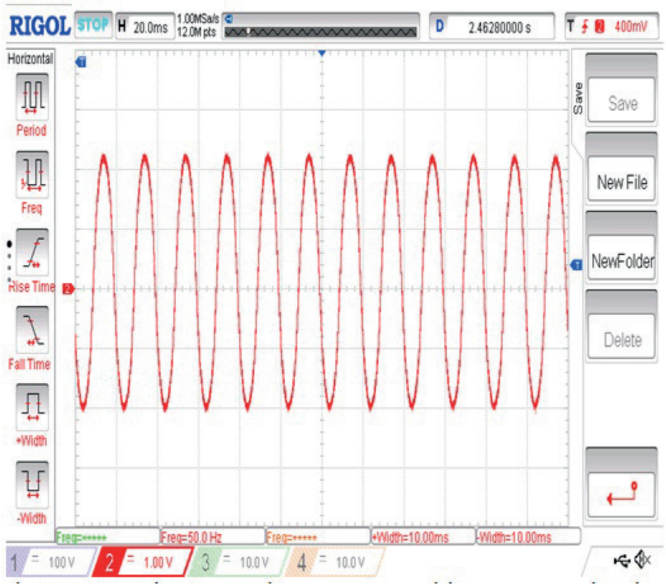

Fig. 26. R phase starting current with 80% conduction period starting

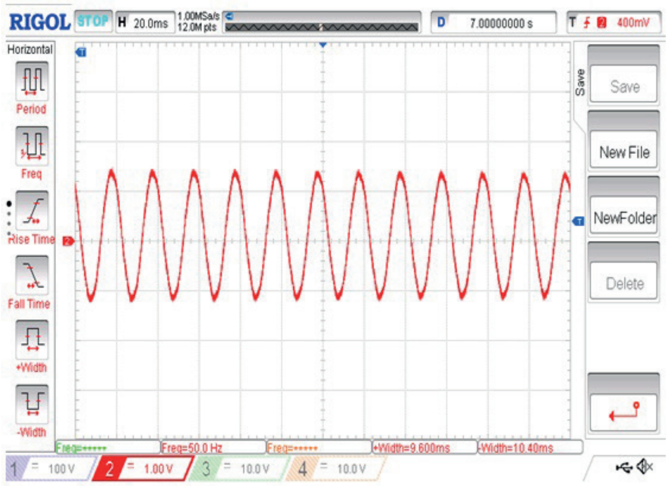

Fig. 27. R phase current at the final steady state

is significantly distorted as shown in Fig. 23. Figure 28 corresponds to 90% conduction throughout the starting period while Fig. 29 corresponds to 20% conduction angle during the starting period. Thus, with the proposed methodology it is possible to start the SCIM with any desired fixed conduction periods. Such an arrangement is necessary when the gradual increase of conduction angle may be avoided so as to reduce the starting period.

With extinction angle controller it is only a finite period of conduction that happens in every cycle and this period is increased gradually until the machine reaches the required rated speed. This causes the waveform of the voltage across the output to be non sinusoidal and rich in harmonics. However, with the SCIM as the load, the stator current of the motor is quite sinusoidal with a THD as low as 1.23% even during the early starting phase. Figures 24 and 27 show the stator current to be nearly sinusoidal.

Figures 28 and 29 show the switching pulses with different duty cycles. These pulses are applied to the MOSFETs in synchronization with the ZCD.

Figure 28 shows the train of switching pulses when the conduction angle is increased from 0 towards 180 degrees. However, Figs. 30 and 31 show the image of the train of switching pulses for the complete starting period when the motor is started with a fixed conduction period of 80% and 90%.

With soft starting in action the stator current is limited to a fixed value without any initial shoot up. The starting current is uniform over the entire starting period. This reduces the usual high starting current and the undue mechanical vibrations during starting. The starting current with soft starting applied is as shown in Fig. 32. The same experimental gadget could be used for testing the performance of the DOL, the phase angle control, the extinction angle control and the multiple pulse chopper-based controllers. The THD of the starting current with

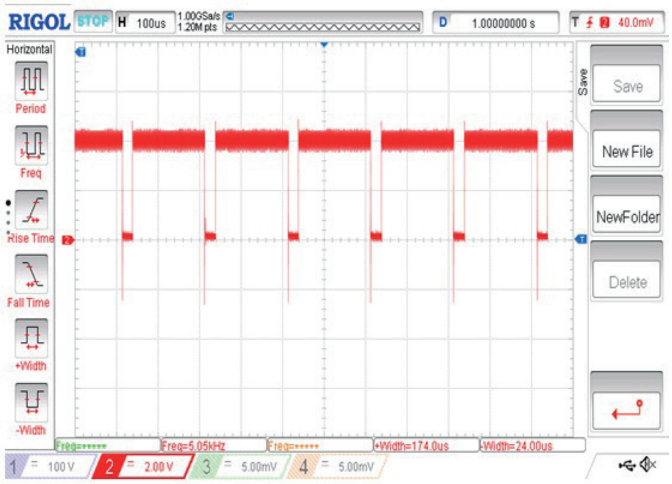

Fig. 28. Switching pulse with 90% conduction in each cycle

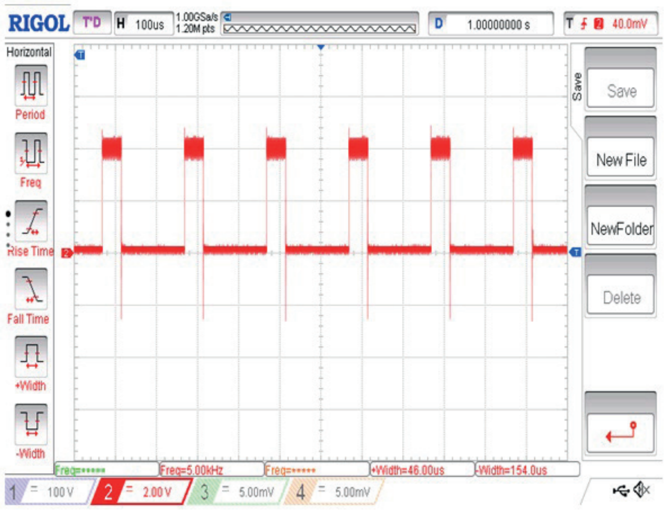

Fig. 29. Switching pulses with 20% conduction at starting

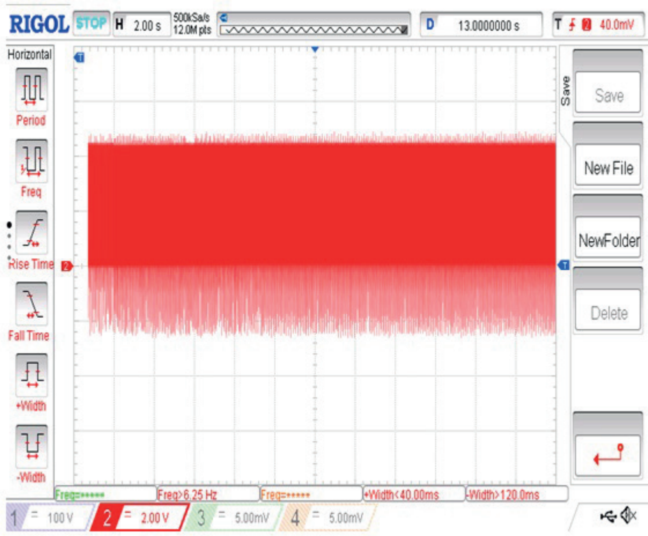

Fig. 30. Switching pulses with gradually increased ON period for soft starting

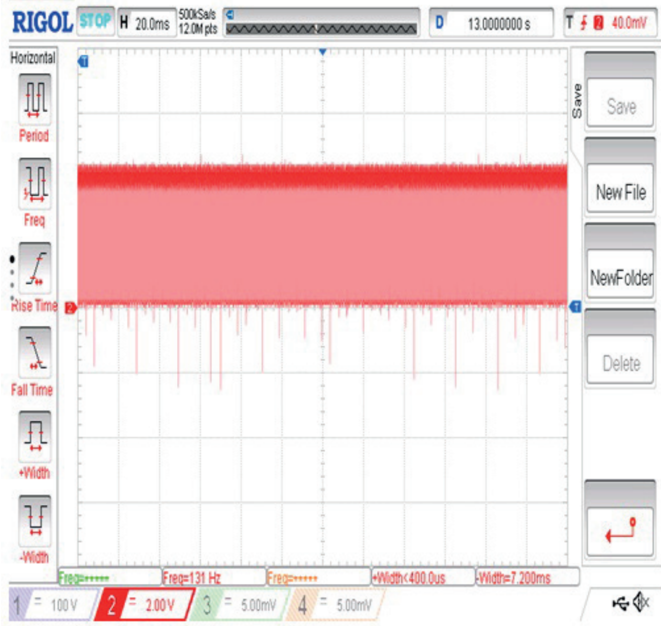

Fig. 31. Switching pulses with fixed 90% duty cycles for DOL starting

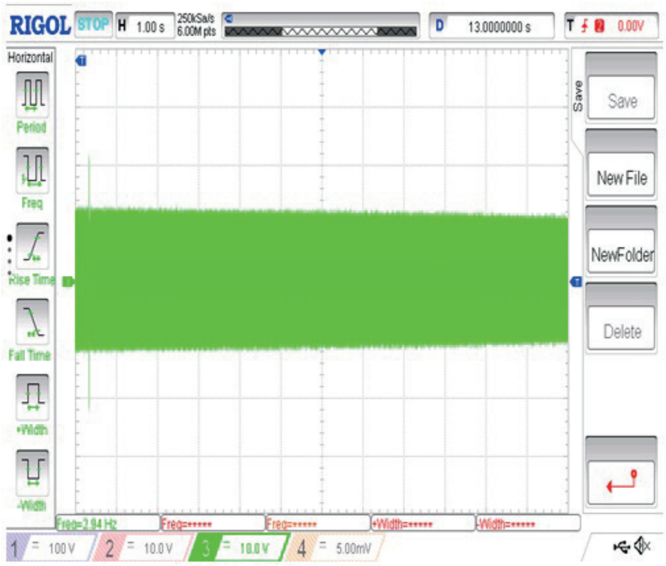

Fig. 32. Stator current that does not exhibit any initial high starting current with soft starting applied

50% conduction period was observed for both extinction angle controller and the phase angles controller implementations for soft starting of the SCIM.

6. Conclusion

PIC microcontroller based on a novel soft starting scheme for the squirrel cage induction motor has been proposed. The proposed idea used a multiple pulse symmetrical angle control with linearly increasing conduction periods spread over a starting period of 30 seconds. The proposed idea has been validated and the results are deeply investigated using MATLAB SIMULINK simulation. The other soft starting schemes like the phase angle controller, the extinction angle controller and the single pulse symmetrical angle controller were also tested. The results reveal that the performance of the proposed multiple pulse symmetrical angle control based soft starting scheme using PIC microcontroller is better than the other starting schemes in terms of reduced source current harmonics and increased power factor. The experimental verifications also confirm the superiority of the Extinction Angle Controller based soft starting scheme as compared to the Phase Angle Controller based soft starting scheme.

Table 4
Specifications of proposed soft starting scheme

Components	Value / Specifications
SCIM	380 V, 50 Hz, 0.5 HP
Source V and F	3 Phase, 380 V, 50 Hz
Controller	PIC 16 F 877A
Opto Coupler	MCT 2E
MOSFETs	IRF 840
Snubber circuit	R = 47 E; C = 0.1 MFD; Diode 3 A
Zero Crossing det.	IC 741

Table 5
Comparisons of phase angle control and extinction angle control

Conduction period kept at 50%		
Type	THD	Power factor
Phase Angle Control	12.8	0.45
Extinction Angle Control	4.6	0.74

Acknowledgements. Authors are grateful to Dr. N. Jeyaraj, Chairman, SBM College of Engineering and Technology, Dindigul, Dr. Chinna Durai Abudullah, Correspondent, Syed Ammal Engineering College, Ramanathapuram and the management of V.S.B. Engineering College, Karur, for providing facilities and encouragement to carry out the above research work.

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