SELECTIVE HARMONIC ELIMINATION IN CURRENT SOURCE INVERTER FED INDUCTION MOTOR DRIVE

A DISSERTATION

Submitted in partial fulfillment of the requirements for the award of the degree
of
MASTER OF TECHNOLOGY
in
ELECTRICAL ENGINEERING
(With Specialization in Power Apparatus and Electric Drives)

By

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CANDIDATE'S DECLARATION

I hereby declare that the work that is being presented in this dissertation report entitled **"SELECTIVE HARMONIC ELIMINATION IN CURRENT SOURCE INVERTER FED INDUCTION MOTOR DRIVE"** submitted in partial fulfillment of the requirements for the award of the degree of **Master Of Technology** with specialization in **Power Apparatus and Electric Drives,** to the **Department Of Electrical Engineering, Indian Institute Of Technology, Roorkee**, is an authentic record of my own work carried out, under the guidance of **Dr. S. P. Gupta,** Professor, Department of Electrical Engineering and **Dr. G. K. Singh,** Professor, Department of Electrical Engineering.

The matter embodied in this dissertation report has not been submitted by me for the Award of any other degree or diploma.

Date: 29|Jun|07

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This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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ABSTRACT

With the advent of power electronic devices, the use of AC motors for variable speed drives is increasing. PWM Inverters are mainly used to feed the induction motor because of the ease of obtaining variable frequency and variable voltage. Among various PWM techniques, the Selective Harmonic Elimination (SHE) PWM technique has the advantage of operating at reduced inverter switching frequency, besides eliminating the desired harmonics. CSI fed induction motor drives are used in high power adjustable speed drives because of its inherent advantages such as four quadrant operation, short circuit protection, supply voltage variation immunity etc.

In this thesis work SHE technique is applied to the CSI to eliminate the lower order harmonics, besides minimizing the THD. Switching angles are calculated for eliminating lower order harmonics by equating the corresponding harmonic current equation (obtained from Fourier series expansion of the output waveform) to zero. This requires numerical techniques to obtain the switching angles as the equations are transcendental in nature. NAG subroutine E04UCF is used for solving such a set of Non linear, transcendental equations.

A SIMULINK model of SHE CSI is simulated using the switching angles calculated above and its harmonic spectrum is to be studied. A logic circuit is developed to generate the firing pulses sequences for the CSI to obtain the desired SHE output pattern.

A model of SHE CSI fed Induction motor drive is simulated using the SIMULINK software of MATLAB. An effort is made to achieve the speed control of Induction motor fed from SHE CSI by using slip speed control.

ABBREVIATIONS and NOTATIONS

SHE	Selective Harmonic Elimination
CSI	Current Source Inverter
VSI	Voltage Source Inverter
THD	Total Harmonic distortion
PWM	Pulse Width Modulation
DC	Direct Current
AC	Alternating Current
LUT	Look Up Table
NAG	Numerical Algorithms Groups
V/F	Voltage/Frequency
ASCI	Auto Sequentially Commutated Inverter
m	modulation index
ω_m	Actual speed
ω_m^*	Reference speed
ω_{sl}	Slip speed

CONTENTS

CHAPTER 1

INTRODUCTION

1.1 Over View:

Inverter converts DC power into AC power at desired output voltage and frequency. Inverters are of two types Voltage Source Inverter (VSI) or Current source Inverter (CSI). Current source Inverters (CSI) topologies are used in high power adjustable speed drives, where four quadrant operation, supply voltage variations immunity and inherent short circuit protection are important. The simplicity and robustness of the current-source inverter, as well as the inherent advantages of the induction motor, make the combination of these elements into a drive system an attractive proposition.

The output current waveform of an ideal CSI should be sinusoidal. The current waveforms of practical inverters are, however, non sinusoidal and contain certain harmonics. These harmonic currents causes a number of problems, such as equipment heating, derating of the motor, ripple in torque, equipment malfunction, communications interference, etc. The harmonic contents of output voltage can be minimized or reduced significantly by switching techniques of available high speed power semiconductor devices.

There are various methods of eliminating harmonics from the output of the inverter such as by using filters, Pulse Width Modulation techniques, multilevel inverters etc. PWM techniques are the preferred one because they not only eliminate the harmonics but also control the fundamental voltage. There are various PWM techniques such as Sinusoidal PWM, Multiple pulse PWM, Selective Harmonic elimination PWM, Centroid PWM etc...The higher order harmonics present in the inverter output can be eliminated by using the filters. But lower order harmonics are difficult to eliminate using filters because the filter size increases as the frequency decreases. The lower order harmonics causes more ripples in the torque and speed and increased losses in the machine. In addition to this, in CSI there is possibility of occurrence of resonance between output filters and the lower order harmonics [12]. Thus particular attention is given to eliminate the lower order harmonics in the Harmonic elimination techniques.

In Selective Harmonic elimination technique any undesired harmonics can be eliminated from the output of the inverter, by chopping the output waveform of the basic square wave inverter. The SHE offers certain advantages over the other PWM techniques such as the acceptable performance at lower switching frequency, direct control of the harmonics in the output wave, to leave the triplen harmonics so as to take the advantage of the circuit configurations in the three phase system etc. Thus SHE can be used to eliminate the lower order harmonics from the inverter output.

1.2 Selective Harmonic Elimination in Current Source Inverter:

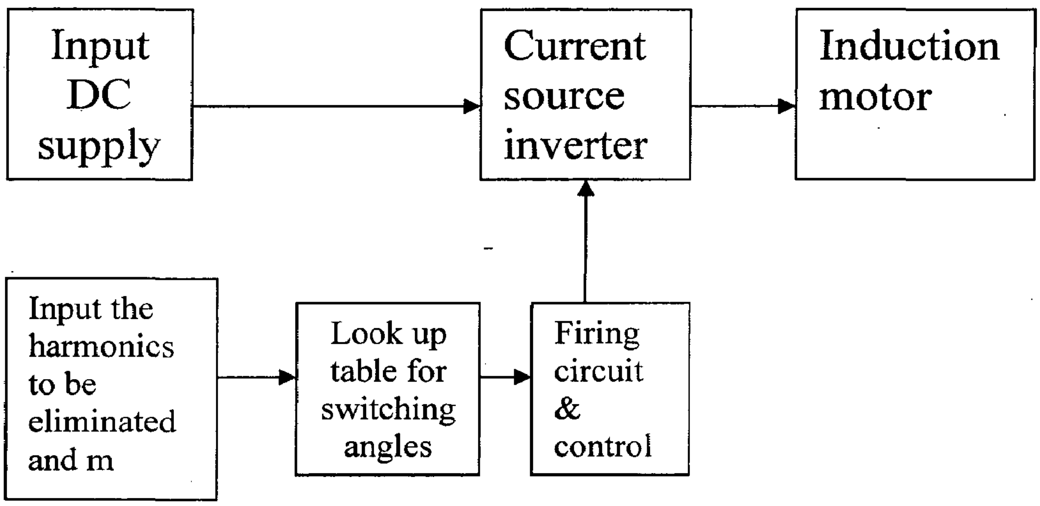


Fig. 1.1 SHE in CSI fed Induction motor drive

The input supply to the current source inverter is current source. The output current of the inverter is maintained constant irrespective of load on the inverter and the output voltage is forced to change. The firing pulses are provided to the inverter from the firing circuit and control. The firing instants are determined from the look up table. The look up table is created by using the Selective Harmonic elimination method of harmonic elimination. Based on the harmonics to be eliminated from the output of inverter the switching angles are calculated and stored in the look up table.

The advantage of current source inverter fed induction motor drives is that it gives constant torque operation of induction motor, since the torque of the motor depends on the supply current. Besides this the peak current of the power devices is limited, the commutation circuit for thyristors is simple etc.

1.2.1 Advantages and Disadvantages of CSI:

Advantages:

1. Four quadrant operation is possible as CSI employs fully controlled rectifiers at the input. During regeneration the voltage at the converter terminals become negative and energy will be fed back to source.
2. CSI has inherent short circuit protection as dc link reactor limits the rate of rise of current.
3. Due to inherent short circuit protection reliability increases.
4. Supply voltage variations immunity.
5. Uses less expensive converter grade thyristors.

Disadvantages of CSI:

1. Harmonic resonance.
2. Unstable operation at low speed ranges.
3. Torque pulsations.
4. Requires closed loop operation for maintaining the flux at nominal value.
5. Sluggish response due to DC link inductor.

1.2.2 Applications of CSI:

1. Superconducting magnet energy storage systems
2. Low speed and high power adjustable speed drives
3. Reactive power control systems to control STATCOM (static synchronous compensator).
4. A.C servo motors.

1.3 Literature Review:

Selective harmonic elimination for Current Source Inverter:

The concept of selectively eliminating harmonics was first given by F.G. Turnbull [1]. It proposed that by introducing the notches in the basic square wave output of the inverter, selected number of harmonics can be eliminated.

In reference [2] H.S Patel and R.G. Hoft has applied the SHE technique to the single phase half and full bridge inverters. A relationship between the number of chops and possible number of harmonics that can be eliminated has been derived. The chopping angles for eliminating 5^{th}, 7^{th}; and 5th, 7^{th}, 11^{th}, 13^{th}, 17^{th}; in VSI were determined using numerical techniques.

H.R. Karshenas, H.A. Kojori, and S.B. Dewan [3] had given generalized techniques of SHE and current control in CSI by using a combination of chops and short circuit pulses. It finds the chopping angles and also locates the shorting pulses by defining and solving a set of non linear equations to obtain the fundamental current control, besides eliminating the harmonics. The variation of the switching angles with the modulation index is also shown. The proposed approach is applicable only for eliminating the even number of harmonics.

J. R. Espinoza et al [4] had developed gating patterns for the she in CSI using a logic circuit which generates symmetrically distributed shorting pulses. These shorting pulses in combination with the gating patterns of the VSI generate the gating patterns for the CSI. This avoids the hassle of positioning the short circuit pulses and thereby no need of defining and solving a set of nonlinear equations dedicated to CSI. This approach has the advantage of eliminating both the odd or even arbitrary number of harmonics. It has been shown that the approach is applicable in both offline as well as online operating conditions.

Optimal PWM pattern:

A. Maheshwari and K. D. T. Ngo[5] has devised a method to synthesize line to line PWM waveforms with six-step symmetry for single phase and three phase inverters. The advantage of this method is that it eliminates both even and triplen harmonics.

P. N. Enjeti, P. D. Ziogas, and J.F. Lindsay [6] has evaluated different SHE-PWM patterns for synthesis of line to line voltages and line to neutral voltages in both single phase and three phase inverters and provided a framework on which to select a particular PWM pattern. Evaluation criteria include total harmonic distortion, harmonic loss factor, dominant harmonics etc…

C. Namuduri and P.C. Sen [7] have proposed the necessity of inverse mirror symmetry of the output current waveform before and after 30 degrees to ensure the continuity of the current from dc current source for CSI. This constraint also implies that no chopping is allowed in 60 deg. to 120 deg. interval of the output waveform. Thus switching angles for harmonic elimination is calculated within interval of 0 deg. to 30 deg.

H.R. Karshenas, H.A. Kojori, and S.B. Dewan [3] have used the concept of short circuit pulses in the CSI taking advantage of the fact that DC bus can be momentarily short circuited because of DC link inductor. The advantage of doing so is that the fundamental magnitude of output can be controlled and acceptable solutions for eliminating more number of harmonics (greater than 4 harmonics) are obtained. Reference [4] has developed a logic circuit which generates the symmetrically distributed short circuit pulses. This short circuit pulses in combination with gating patterns for VSI generates the gating pattern for the CSI.

S. R. Bowes and R.I Bullough [8] developed optimal PWM strategies that will improve ethe rotational motion of the drive at low speeds using microprocessor controlled CSI drives.

SHE CSI fed Induction motor:

P. N. Enjeti, P. D. Ziogas, and J.F. Lindsay [9] had applied the SHE method for the variable frequency operation of the CSI inverter with instantaneous current control capability. The instantaneous current control is obtained by varying the modulation index rather than varying input dc current via rectifier control. However in steady state the dc link current is adjusted to operate CSI in over modulation range so as to have the high utilization factor of dc current source.

A.R. Beig and V.T. Ranganathan [10] had developed a sensor less vector controlled CSI drive to fed an Induction motor by using a three-level inverter as an active filter across the motor terminals replacing the bulky ac capacitors. Kleinhans et al [11] had used a new simulation package CASED to implement the CSI field oriented controlled Induction Motor.

Selection of output capacitor bank:

P. N. Enjeti, P. D. Ziogas, and J.F. Lindsay[9] had given the necessary criteria which governs the design of the output capacitor. Important criteria are that the filter should offer high impedance to fundamental component and low impedance to the dominant current harmonic frequencies. Other criteria are that it should not provide phase shift between fundamental line current of CSI and the load current and also it should not be in resonance with the motor leakage reactance.

If a larger value of capacitance is used, the inverter current capacity will have to be increased [12]. The choice of the shunt capacitor across the motor, and the choice of the modulation ranges depends on a number of design criteria, eg... control of harmonic resonances, control of harmonic torques, avoidance of undue self excitation on loss of supply and limitation of inverter rating [12].

1.4 Scope of the work:

This dissertation work presents the implementation of SHE in CSI fed induction motor drive. Switching angles for the elimination of lower order harmonics in CSI output are calculated by solving a set of transcendental equations using NAG subroutine E04UCF. The variation of switching angles for the different modulation index (m) is plotted. The plots of switching angles vs. modulation index (m) for even number of harmonic elimination (5^{th}, 7th; 5th 7^{th} 11^{th} and 13^{th}; $5^{th,}$ 7^{th}, 11^{th}, 13^{th}, 17^{th}, 19^{th}; etc...) are obtained.

A SIMULINK model in MATLAB is developed to implement the SHE technique in CSI using the above calculated switching angles. A logic circuit was developed to generate the firing pulses sequences for the CSI to obtain the desired SHE output pattern.

A comparison of the harmonic spectrum of Six-pulse CSI and SHE CSI is made and their performances are evaluated.

Speed control of Induction motor fed with SHE CSI is simulated in the SIMULINK. The speed control is obtained using the slip speed control method.

1.5 Organization of the Dissertation:

This chapter gives an overview and brief discussion about SHE and CSI. It also deals with the literature review. Finally it gives a brief overview of work done in dissertation.

Second chapter deals with the basic principles of CSI and SHE techniques. The operation of the CSI and the commutation process of CSI for PWM mode is explained.

Third chapter deals with the SHE in CSI fed induction motor drive. It discusses the important aspects to be considered for implementation of speed control of induction motor using a current source. Additional aspects for SHE CSI fed induction motor drive are also discussed.

Fourth chapter gives the modeling of SHE technique in CSI in SIMULINK. First the plots of the switching angles vs. modulation index are obtained. The logic circuit which generates the firing pulses for CSI to implement the SHE is explained. It also evaluates the performance of Six-pulse CSI and SHE CSI based on the harmonic spectrum.

Fifth chapter gives the implementation of speed control of Induction motor fed with SHE CSI. Slip speed control method is used to control speed at constant flux and for faster dynamic response of the motor.

Second last chapter deals with conclusions and scope for future work. The closing chapter gives all the references, which are used to carry out the dissertation.

CHAPTER 2

CURRENT SOURCE INVERTER PRINCIPLE AND SELECTIVE HARMONIC ELIMINATION

CURRENT SOURCE INVERTER:

The CSI converts power between an adjustable current source and the single phase or three phase load. But power is usually supplied at constant voltage and constant frequency, so CSI mainly consists of two stages. At first a DC chopper or Rectifier unit converts the AC power at constant voltage to DC current. A DC link inductor is used to remove the ripples from the DC output. Then a CSI unit is used which converts DC current into AC current with variable output current and variable frequency.

2.1 BLOCK DIAGRAM OF PRACTICAL CSI:

The block diagram of practical CSI [13] when fed with three phase AC supply input is shown in fig 2.1.

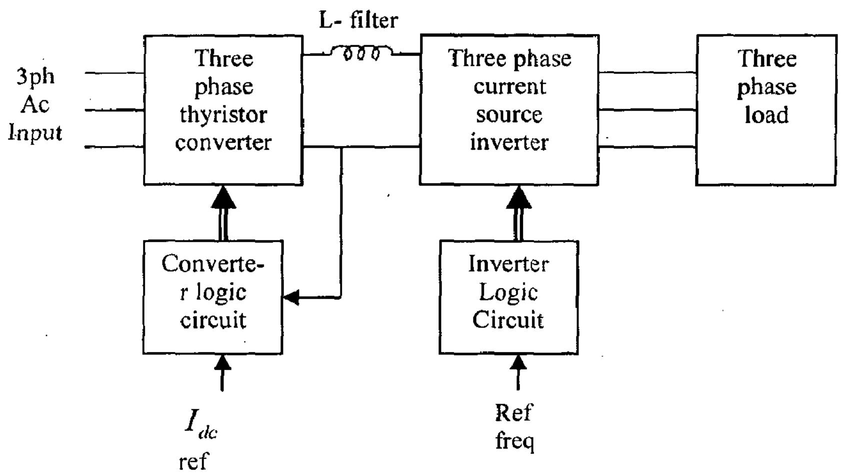


Fig. 2.1 Basic block diagram of practical CSI

The three phase supply at constant voltage and frequency is fed to the thyristors rectifier which converts it into DC voltage. The DC link filter (L-filter) performs two functions, first it smoothen the ripples in the output DC voltage of the converter and secondly it opposes the sudden changes in the current. So this combination acts as a constant DC current source. The DC current is fed to the CSI which converts it to the AC current at the desired frequency and desired magnitude. The inverter and rectifier logic circuit generates the gating pulses for the thyristors to obtain the required frequency and DC current output respectively.

The output current of the CSI can be controlled either by changing the modulation index (m) in CSI or by varying the input DC current i.e. by varying the firing angles of the rectifier converter. For instantaneous control of output current, modulation index (m) control technique is used and for the steady state control, the rectifier control is applied [9]. The steady state DC output current of rectifier is so set that the PWM CSI is operating at the maximum modulation index i.e. the fundamental component of PWM CSI is higher, for the given input DC current. This results in higher utilization factor of DC current.

2.2 Single phase and three phase Ideal CSI:

Single phase Ideal CSI:

The figure 2.2 shows the basic configuration of single phase CSI. The system consists of the ideal DC current source connected to single phase load through the ideal switches S_1, S_2, S_3 and S_4. A practical DC current source can be obtained by connecting a large inductor in series with the voltage source. The switch pairs S_1, S_3 and . S_2, S_4 are closed alternately at a constant frequency. The resulting output current is an ac square wave whose amplitude is equal to DC input current. The waveform of the load voltage depends upon the type of load, since the CSI supplies the load with the defined current waveform.

The input current I_{dc} is unidirectional. Thus the power flows from source to load when V_{in} is positive and it flows in reverse direction when V_{in} is negative. Thus regeneration of power is possible in CSI. Figure 2.3 shows the output waveform of ideal single phase CSI.

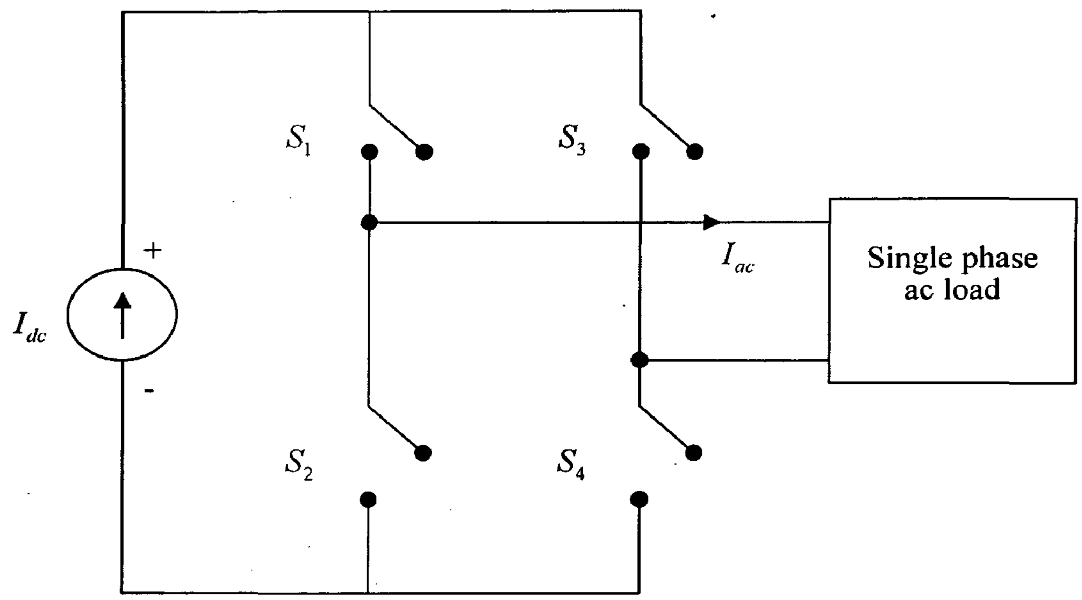


Fig 2.2 Single phase ideal CSI

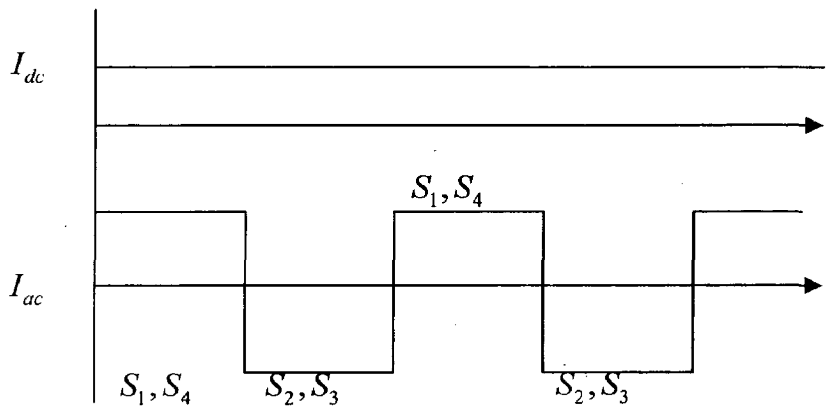


Fig 2.3 Output waveforms of the single phase CSI

Three phase Ideal CSI:

The figure 2.4 shows the three phase Ideal CSI. The switches S_1 to S_6 are closed periodically in the pairs. Each switch conducts for 120 degrees and is commutated when the next switch in the top (1, 3, 5) or bottom (4, 6, 2) group is turned on. The resulting three phase ouput current is a 120 degree wide square wave of amplitude *I*. The frequency of the output current is controlled by a separate logic circuit which closes and opens the switches in the required sequence.

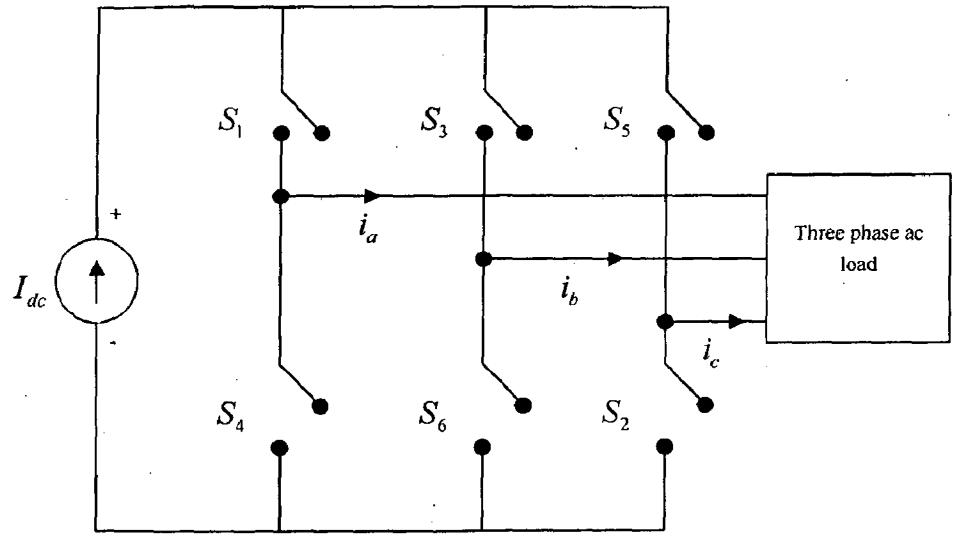


Fig. 2.4 Three phase ideal CSI

The output current waveform of the three phases and the switches which are conducting during each period is shown in figure 2.5.

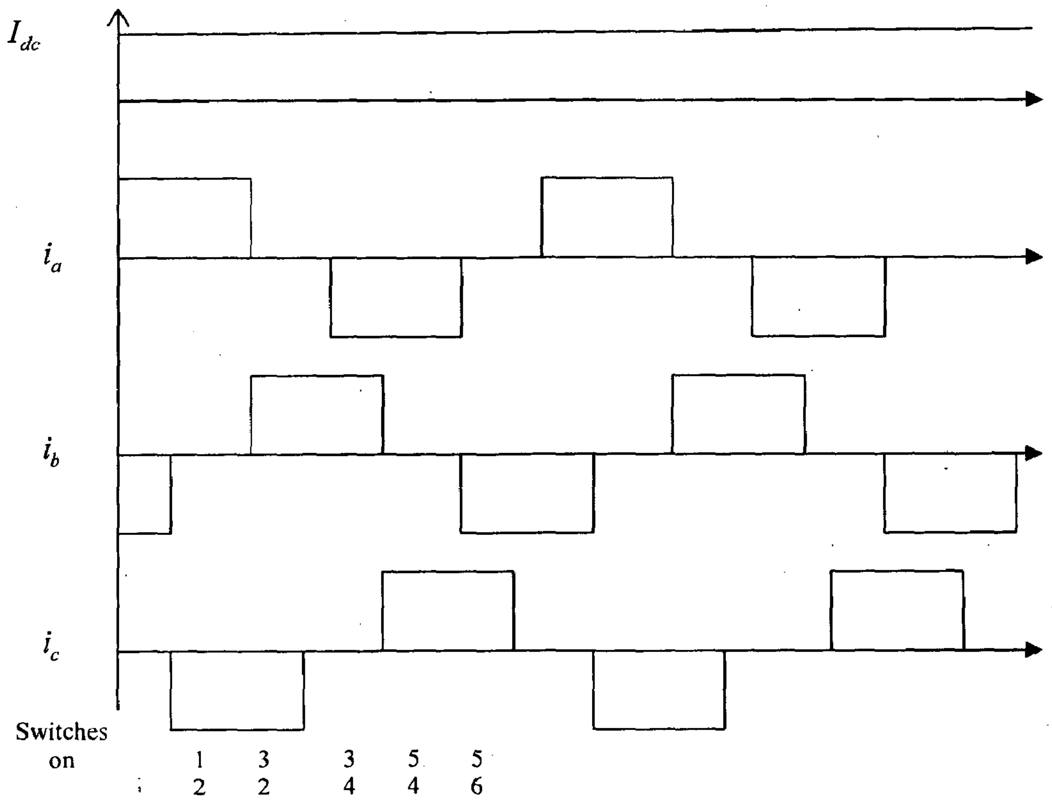


Fig. 2.5 Output currents of three phase CSI

2.3 Operation of SHE PWM CSI:

The circuit diagram of CSI fed to the inductive load is as shown in figure 2.6. The operation of CSI for SHE PWM is explained for the two cases based on the switching operation [14].

Case 1: When switching takes place without short circuit pulse.

Case 2: When switching takes place with the short circuit pulse.

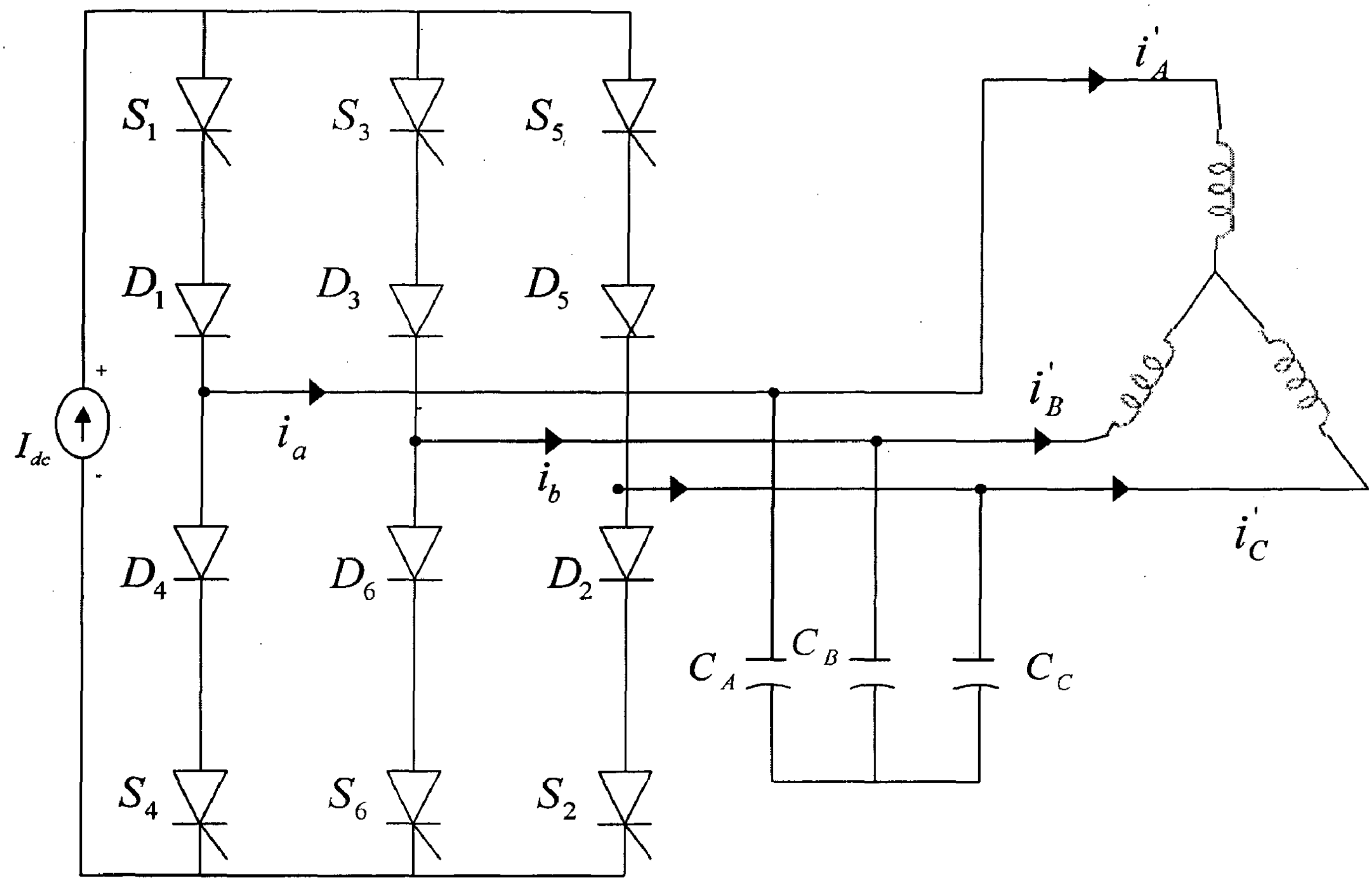


Fig. 2.6 Circuit diagram of CSI

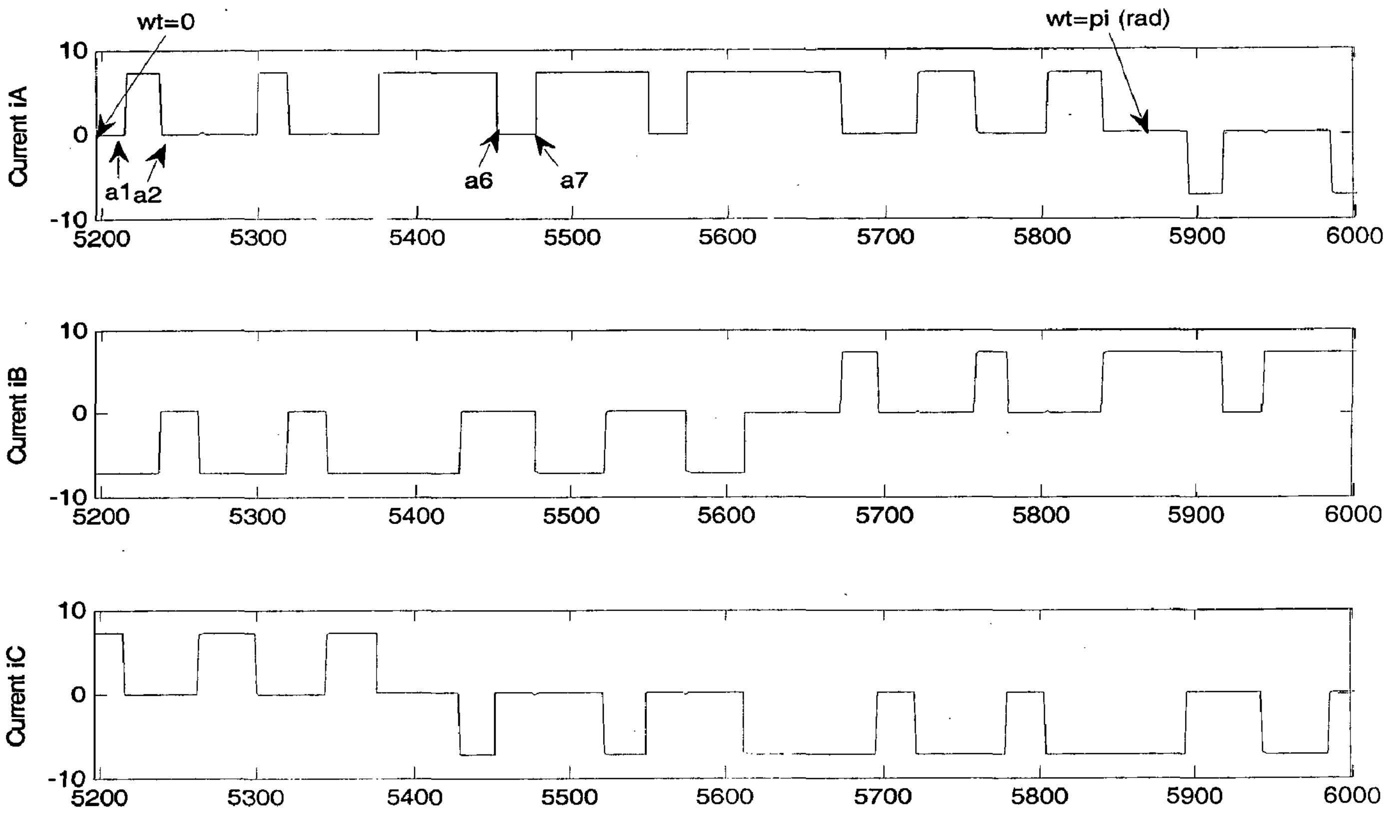


Fig. 2.7 Output currents showing the switching without short circuit pulse and with short circuit pulse

Case 1: Switching without short circuit pulse:

Initial conditions at ωt =0 :

At ωt =0 as the output current i_C is positive and i_B is negative, the switches S_5, S_6 are ON and the source current I_d is flowing through a path consisting of S_5, phase C, phase B and S_6 as shown figure 2.8. Let this path be designated as loop 1. The machine phase current i_A', which is sinusoidal and lags behind i_A, is still negative. Hence, another small current is flowing through loop 2 formed by phase A, capacitor C_A, capacitor C_B, and phase B.

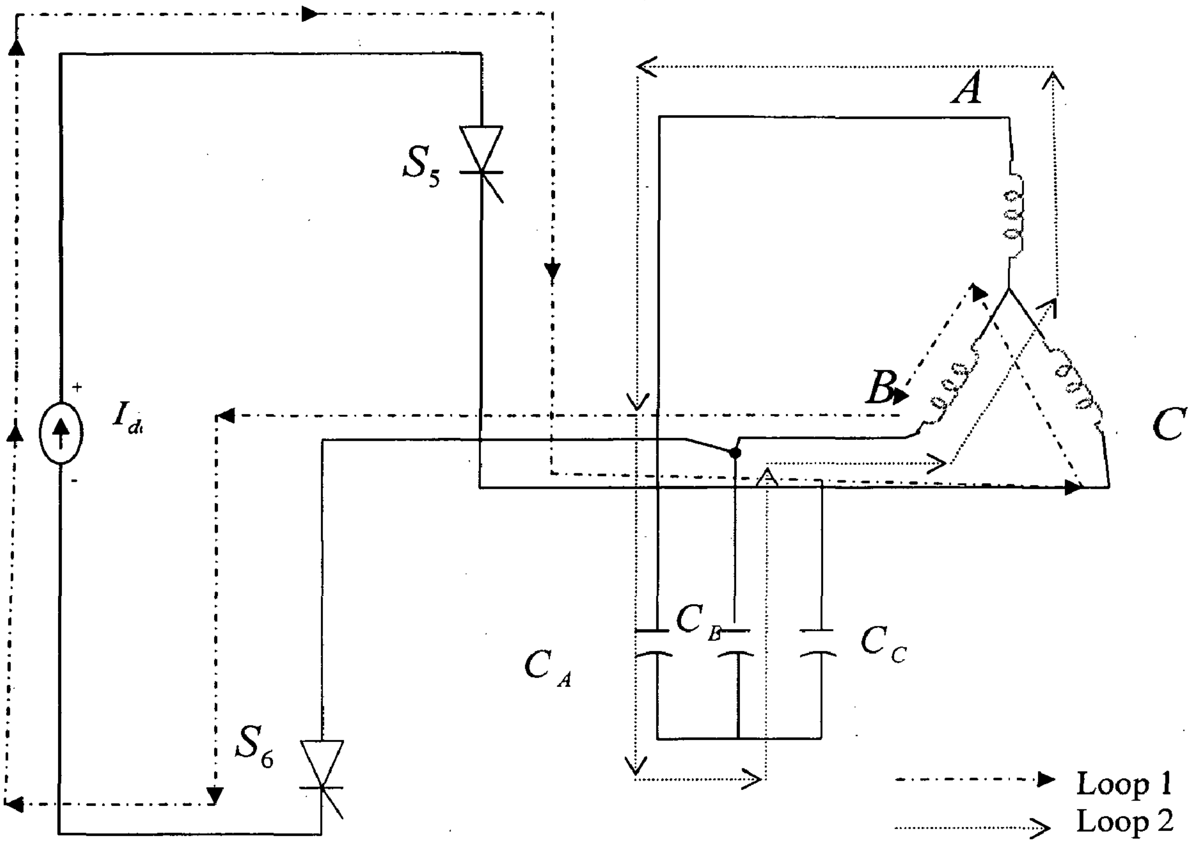


Fig. 2.8 CSI operation at wt =0

At angle α_1 :

When S_1 is turned on at angle α_1 , I_d is transferred from line C to line A, by turning off S_5 and turning on S_1. Since the machine phase current i_A' is still negative, the source current, I_d, flows through a loop say loop 3, comprised of S_1, capacitor C_A, capacitor C_C, phase C, phase B, and S_6,as shown in figure 2.9. The current though loop 2 continues to flow as before. Now C_A is charged both by the source current I_d and the loop 2 current, and its voltage shoots up. Loop 2 current charges the capacitor C_B in the negative direction. The voltage V_{AB}, which is the sum of voltages across capacitors C_A and C_B also shoots up.

The build up of voltage V_{AB} continues as long as the machine's phase current i_A' remains negative. After i_A' reverses, the loop 2 current flows to discharge capacitors C_A and C_B, while the loop 3 current continues to charge them. At a certain value of i_A' the build up of the capacitor voltage stops and thereby V_{AB} decreases after attaining the maximum value which occurs soon after the reversal of machine current i_A'. Since the circuit works symmetrically, identical spikes will be produced at the reversal of currents i_B'and i_C'.

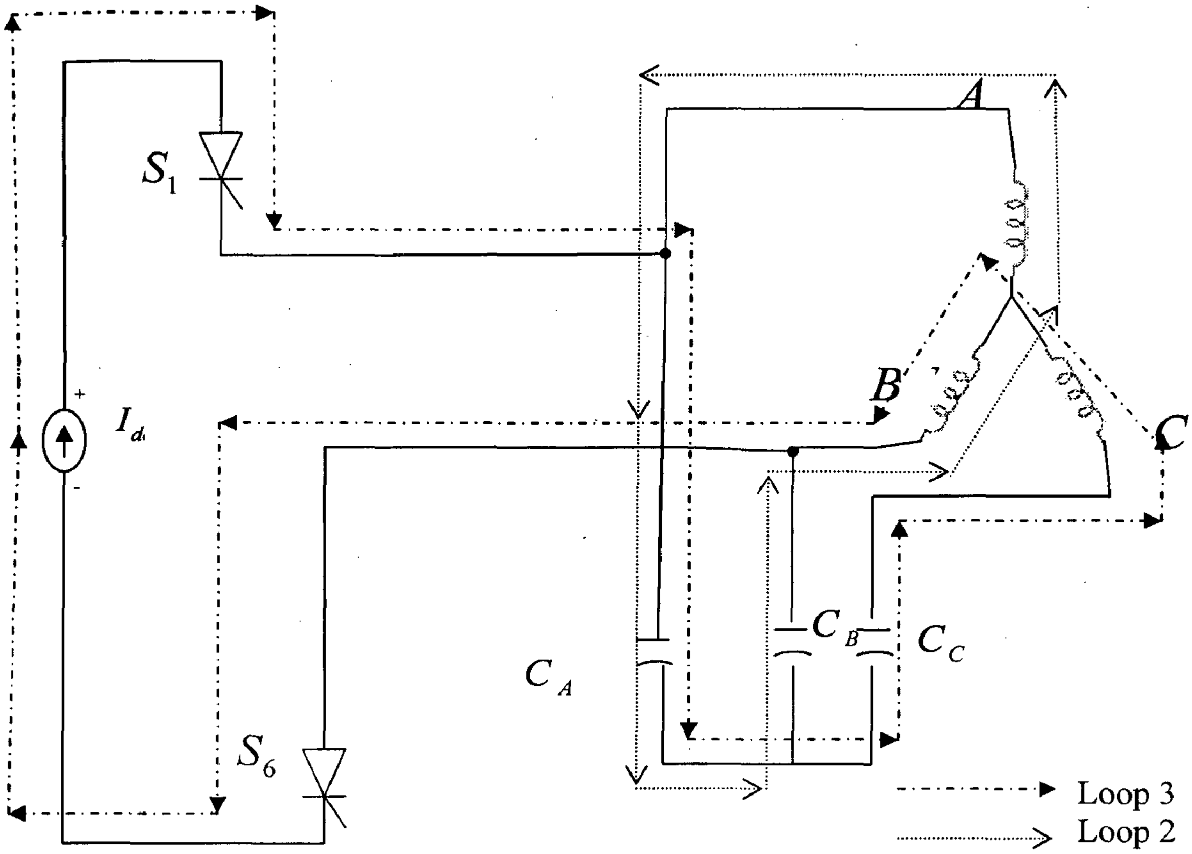


Fig. 2.9 CSI operation at instant α_1

CASE 2: Switching with short circuit pulses:

Advantage of switching with short ciruit pulses:

In switching without short circuit pulses, as explained above the voltage spikes are produced in the output voltage at each switching instant. It is also observed that as the pulse duration increases, the period of charging of capacitor increases which results in an increase in the voltage spike even though the charging current (I_d - I_A') is low.

The voltage spikes are produced as the capacitors are being charged by the source current. In the above case spikes are produced due to the charging of C_A by the source current when it flows through loop 3. Thus the voltage spike can be reduced if the source current can be diverted away from loop 3 for some time. In CSI the GTO's in the same leg can be allowed to conduct for a short duration. Hence, the source current can be diverted away from loop 3 by tuning on S_1 and S_4.

Operation with short ciruit pulse:

At wt=0, S_5 and S_6 conduct and operation is described by figure 2.8. The source current I_d flows through loop 1 consisting of S_5, phase C, phase B, S_6 and the source. Another small current flows through loop 2 consisting of phase A, capacitor C_A, capacitor C_B, and phase B. At angle say α_1 (not shown in figure) S_1 and S_4 are turned on. The source current flows through the short circuited path of S_1 and S_4. The loop 2 current flows as before. The phase C current now flows through loop 4 formed by phase C, phase B, capacitor C_B and capacitor C_C. Because of the diversion of the source current, capacitor C_A is prevented from being overcharged for some time. Also loop 2 current charges capacitor C_A in a direction to increase V_{AB}. But the loop 4 current, which is higher than the loop 2 current, charges C_B to reduce voltage V_{AB}. At α_2, S_4 is turned off and S_6 is turned on. S_1 is already on. The inverter operation is governed by the equivalent circuit of figure 2.10. The source current flows through loop 3 and the phase A current continues to flow through loop 2. A switching of the G.T.O with the short circuit pulse takes place at an angle α_6 in the figure 2.7

In the SHE PWM implemented the shorting pulses are placed in the interval of non chopping period so as to reduce the duration of the charging of capacitor. Thus the overcharging of the capacitor, by the source current is prevented which in turn reduces the voltage spike magnitude. It also has the advantage that lower values of capacitor can be used for limiting the spike voltage. The advantage of using lower value capacitor is that the delay in the transfer of current from one inverter leg to other reduces, so the CSI can be operated at higher switching frequency.

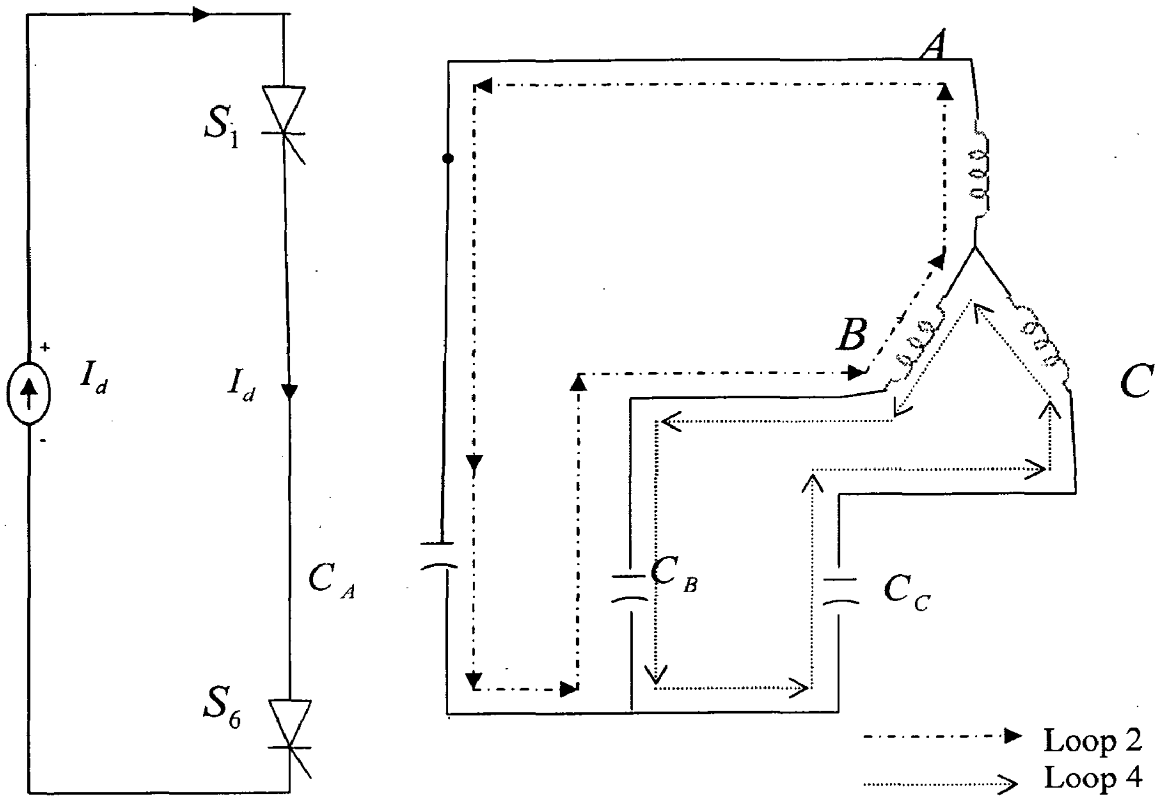


Fig. 2.10 CSI operation during short pulse period

2.4 Selective Harmonic elimination:

Various PWM techniques exist for the control of the inverter to provide variable frequency and variable voltage. They can be classified as programmed PWM techniques and carrier modulated PWM techniques. Programmed PWM techniques optimize a particular objective function such as minimum losses, reduced torque pulsations, THD minimization etc, and therefore are the most effective means of obtaining high-performance results [6].

SHE is one such programmed PWM techniques optimized for the minimization of THD. The advantage of the minimization of THD is that the lower order harmonics from the output are eliminated. The higher order harmonics can be easily eliminated using filters and also as the order of harmonics increases, the impedance offered by the motor increases resulting in automatic filtering action. The absence of the lower order harmonics reduces the torque pulsations, minimizes ripple in current, reduced harmonic losses in the motor etc. Thus the overall performance of drive is improved by using the SHE technique.

2.4.1 Basic Principle of SHE:

The basic principle of SHE is to chop the square wave output of the inverter at the appropriate instants so as to eliminate the desired harmonics. These appropriate instants are called as chopping angles or switching angles. The chopping angles are calculated by equating the corresponding harmonic equation (obtained by Fourier series expansion) to zero.

2.4.2 SHE applied to CSI:

SHE is most suitable for the CSI than other PWM techniques as

- To avoid possible resonance between the input/output filter and motor leakages at low order harmonic frequency. SHE eliminates low order harmonics.
- Carrier based PWM techniques cannot be applied to CSI due to limitation of switching frequency in CSI due to slow response of commutation capacitor (ASCI) or filter capacitor (GTO CSI).
- The DC bus in CSI can be shorted momentarily because of the DC link inductor. Thus by using the combination of chops and short circuit pulses more number of lower order harmonics can be eliminated [3].
- The use of short circuit pulses also reduces the rating of commutation capacitor which in turn increases the operating frequency range of CSI (as the commutation capacitor charges and discharges quickly).
- CSI fed Induction motor are generally operated at low frequency applications, so SHE with different objective function optimization based on application can be implemented. Since several solutions for switching angles are possible at low frequency.

SHE can be applied to both CSI and VSI, but there is a difference in the SHE PWM pattern for VSI and CSI. The main difference are given below

a) Shorting of the inverter leg:

There is a restriction that for the VSI PWM pattern in that the upper and lower switches in one arm should never be closed simultaneously, since it leads to a DC bus short circuit. But in CSI the DC bus can be shorted momentarily because of the DC link inductor.

b) Symmetry conditions in the output waveform:

In VSI to eliminate even order harmonics and triplen harmonics the output voltage waveform should satisfy half-wave and quarter-wave symmetry. But in CSI apart from the half-wave symmetry and quarter-wave symmetry, the waveform before and after $\pi/6$ in a PWM SHE should be an inverse mirror image to always ensure continuity of the current for CSI [7]. Besides this, no chop is allowed in $\pi/3$ to $2\pi/3$ interval.

c) Independent switching angles interval:

In VSI the independent switching angles can be varied between 0 to $\pi/2$ because of quarter-wave symmetry, but due to constraint of continuity of current in CSI the independent switching angles can be varied only between 0 to $\pi/6$.

d) Minimum pulsewidth requirements:

In CSI there is a restriction that a minimum angular pulsewidth must be maintained due to delay introduced by the capacitor in transfer of current between inverter legs. The delay in transfer of current is done so as to reduce the switching voltage spikes [13]. Higher the value of the capacitor, greater is the delay and which in turn increases the minimum angular pulse width (for constant frequency).

2.4.3 Advantages and Disadvantages of Selective Harmonic Elimination:

Advantages:

1. There is reduction in inverter switching frequency compared to carrier- modulated sine PWM techniques.
2. The reduction in the switching frequency causes reduction in the switching losses and also permits the use of GTO switches for high power inverters.
3. The ripple in dc link current is small due to high quality of the output voltage and current. Thereby the size of the dc link filter reduces.
4. The use of precalculated optimized programmed PWM switching patterns avoids on line computations and provides straightforward implementation of a high performance technique.

5. The SHE with magnitude control i.e. by varying the modulation index, can be used to obtain the fast dynamic response of the CSI. [9]
6. As the lower harmonics are eliminated torque pulsations, copper/core losses, acoustic noise etc also reduces.

Disadvantages of SHE:

1. The main drawback of SHE is that it relies heavily on off-line computing power since it involves solving nonlinear transcendental equations, which is difficult to solve on-line by a microprocessor- based controller.
2. Implementation of SHE is based on look-up table and interpolation between look up tables and hence requires large storage memory.
3. SHE technique cannot be implemented for high frequency operation of the CSI motor due to requirements of minimum angular pulse width.

SIMULATION OF SHE IN CSI:

3.1 Block diagram of Implementattion of SHE in CSI:

The basic block diagram of implementation of SHE in CSI is shown below. The CSI takes Input DC current and converts into an AC current at variable frequency and variable fundamental current. Look up table stores the switching angles for eliminating the desired harmonics at the desired fundamental output current i.e. modulation index (m). The firing circuit generates the firing pulses for CSI to generate the desired SHE PWM pattern.

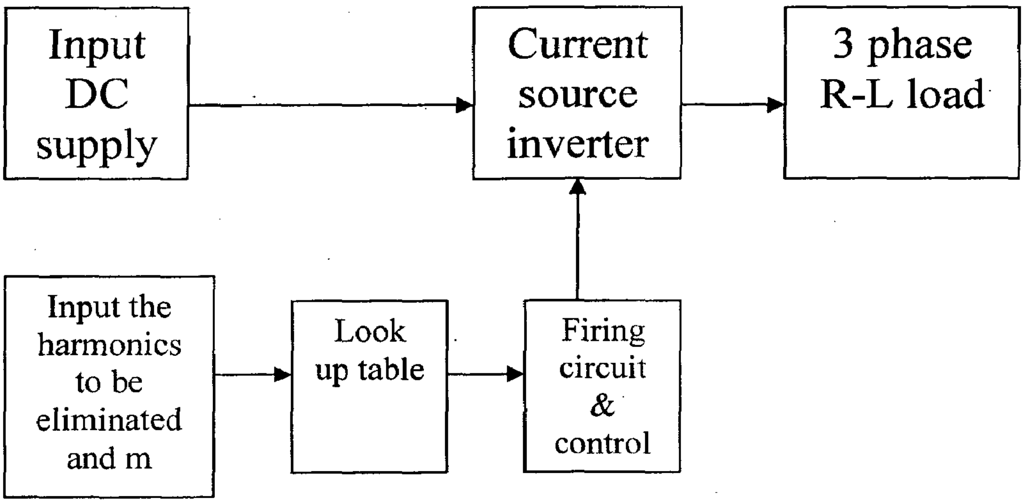


Fig. 3.1 Implementation of SHE in CSI

The implementation of SHE in CSI is done in two stages.

1. Look up table of switching angles vs. modulation index (m) is created for eliminating the low order harmonics. The LUT is obtained by solving the transcendental equations of corresponding current harmonics.

2. Using the look up table firing pulses are generated by a logic circuit and given to CSI. The CSI generates the SHE PWM pattern of output current which is free from the undesired harmonics.

3.2 Formulation of look up tables:

The output of the CSI should satisfy half wave symmetry, quarter wave symmetry and folded symmetry at 30 deg and 150 deg so that the even and triplen harmonics are eliminated and also to ensure continuity of the current. Thus SHE PWM pattern are developed which has the above mentioned symmetries [3]. This SHE PWM pattern consists of notches and short circuited pulses distributed in such a way that not only desired lower order harmonics are eliminated but also it provides fundamental magnitude control of the output current.

The width, number and location of short circuit pulses and chops can be changed to make different SHE-PWM patterns. Basically all the SHE- PWM patterns follow one of the four basic patterns identified as Type 0, Type1, Type 2, and Type 3 [3]. These four different types are required to account for different PWM pattern shapes around $\pi/6$.

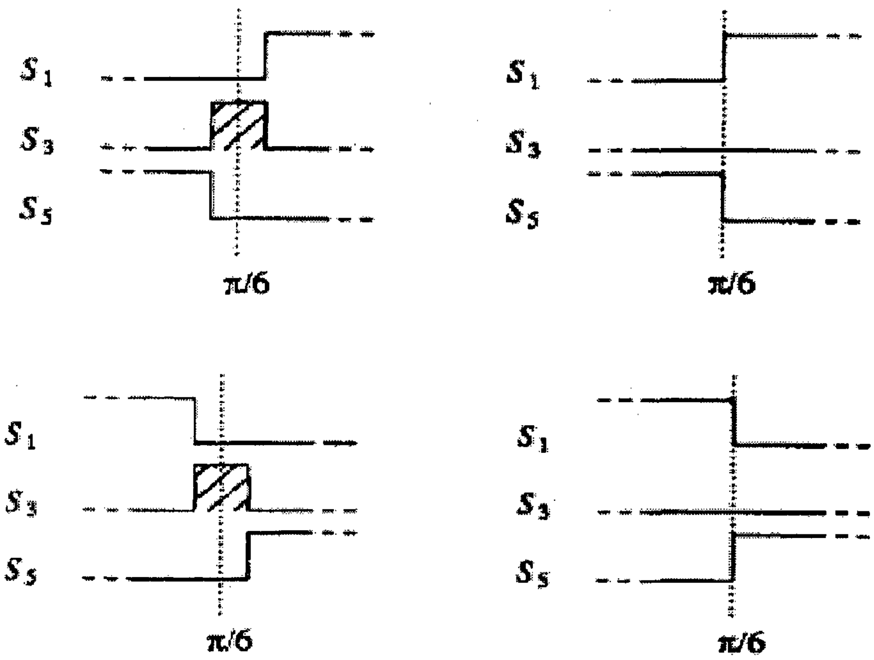


Fig. 3.2 Different PWM patterns around $\pi/6$ [3]

Type 0: Magnitude control:

This PWM pattern does not eliminate the harmonics but only controls the fundamental amplitude of the output current. To control the fundamental component of the output current a short circuit pulse is created at the center of the conventional Six-step waveform. By varying width of short circuit pulse magnitude of fundamental can be controlled.

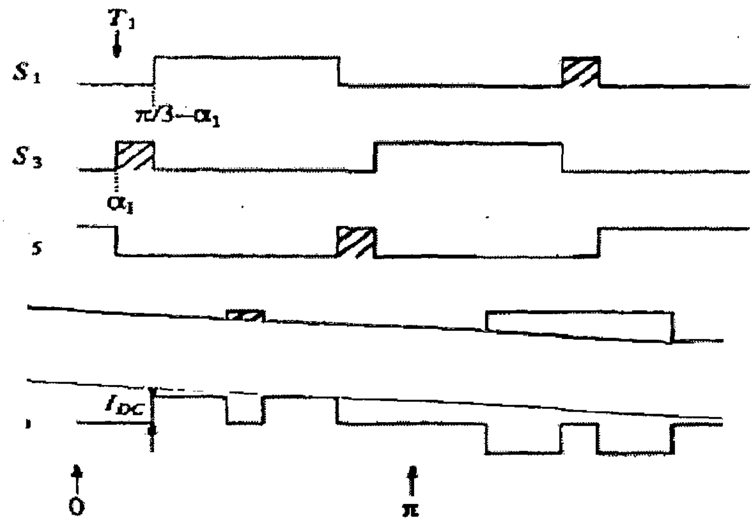


Fig. 3.3 Firing pulses pattern for CSI and the output current i_a for type 0 SHE PWM

The Fourier series expansion of the output current [3] i_a for n^{th} harmonic is given by

$$I_{a,n} = \frac{4I_{DC}}{n\pi}\left[\cos n(\frac{\pi}{3}-\alpha_1)-\cos n(\frac{\pi}{3}+\alpha_1)\right] \qquad 0 \le \alpha_1 \le \frac{\pi}{6}$$

The magnitude of the fundamental AC current is usually expressed as the Modulation index (m)

$$\mathrm{m} = \frac{\hat{I}_1}{I_{DC}} \qquad 0 \le m \le m_{max}$$

where, $\hat{I}_1$ is the peak fundamental AC current

I_{DC} is the magnitude of DC link current

m_{max} is the maximum possible modulation index.

Thus the fundamental current equation (n=1) in terms of modulation index (m) can be written as

$$m = \frac{4}{\pi}\left[\cos(\frac{\pi}{3} - \alpha_1) - \cos(\frac{\pi}{3} + \alpha_1)\right]$$

The number of variables that can be controlled is equal to the number of independent switching angles. So here only the fundamental magnitude control is possible as α_1 is the only independent switching angle. The switching angle for different values of m can be obtained by solving the above transcendental equation. A computer program to solve the above transcendental equation using the NAG subroutine E04UCF is given in the Appendix –I. The plot of variation of switching angles for different values of m is obtained as shown in figure 3.4.

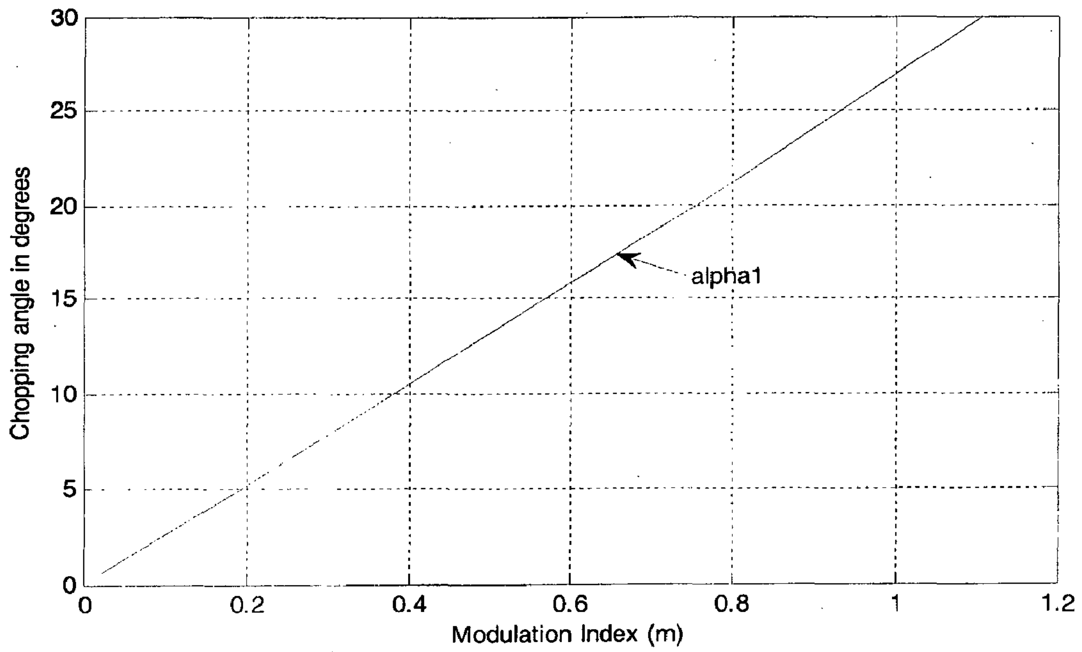


Fig. 3.4 Switching angles Vs. Modulation index for type 0 SHE PWM

The maximum modulation index is obtained at m=1.1 and the switching angle corresponding to it is 30 deg. Actually the inverter is operating in the Six-step mode at m_{max} because the width of short circuit pulse is reduced to zero.

Typical Type 1: Eliminating 5th and 7th harmonics:

Based on the above mentioned constraints of CSI the SHE PWM pattern for eliminating the 5th and 7th harmonic is developed. In Type 1 pattern there is no short circuit pulse around $\pi/6$.

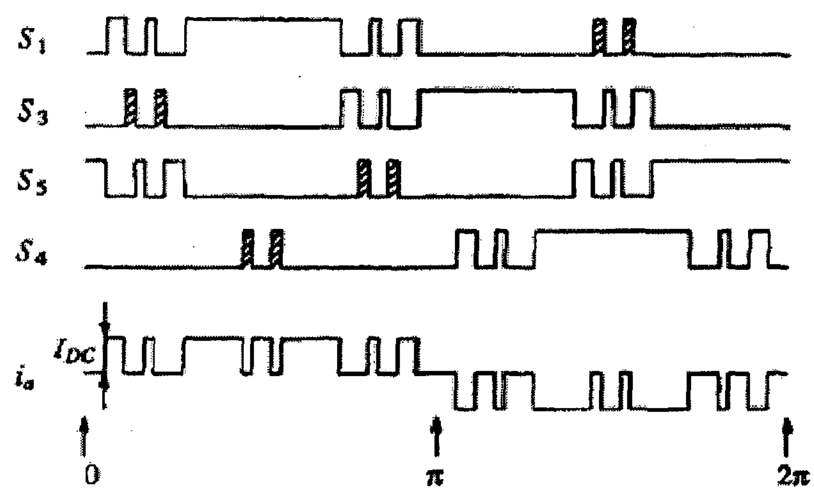


Fig. 3.5 Firing pulses pattern for CSI and the output current i_a for type 1 SHE PWM [3]

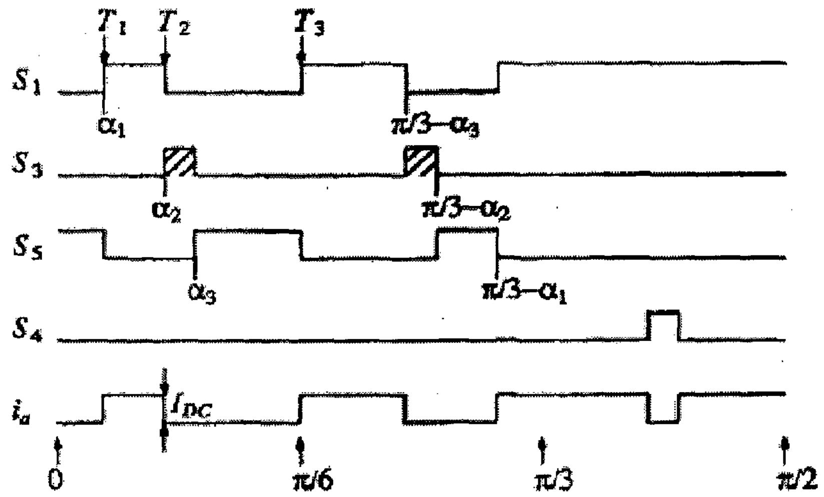


Fig. 3.6 Expansion of fig in the 0 to $\pi/2$ region [3]

The expression of the output current i_a [3] for the n^{th} harmonic is given by

$$I_{a,n} = \frac{4I_{DC}}{n\pi}\left[\cos n\alpha_1 - \cos n\alpha_2 + \cos\frac{n\pi}{6} - \cos n(\frac{\pi}{3}-\alpha_3) + \cos n(\frac{\pi}{3}-\alpha_1) - \cos n(\frac{\pi}{3}+\alpha_2) + \cos n(\frac{\pi}{3}+\alpha_3) - \cos\frac{n\pi}{2}\right]$$

Where $\alpha_1, \alpha_2 and \alpha_3$ vary in the range 0 to $\pi/6$

As there are three independent switching angles the three variables can be controlled. So one is used to fundamental magnitude control and other two to eliminate the two different

$$m = \frac{4}{\pi}\left[\cos(\frac{\pi}{3}-\alpha_1)-\cos(\frac{\pi}{3}+\alpha_1)\right]$$

The number of variables that can be controlled is equal to the number of independent switching angles. So here only the fundamental magnitude control is possible as α_1 is the only independent switching angle. The switching angle for different values of m can be obtained by solving the above transcendental equation. A computer program to solve the above transcendental equation using the NAG subroutine E04UCF is given in the Appendix –I. The plot of variation of switching angles for different values of m is obtained as shown in figure 3.4.

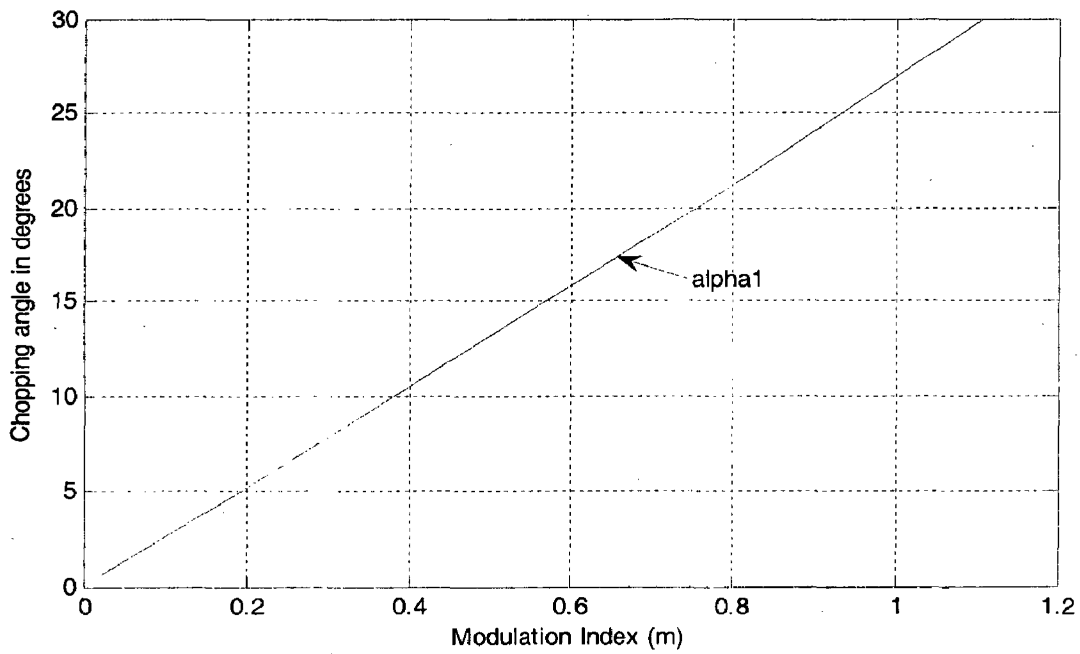


Fig. 3.4 Switching angles Vs. Modulation index for type 0 SHE PWM

The maximum modulation index is obtained at m=1.1 and the switching angle corresponding to it is 30 deg. Actually the inverter is operating in the Six-step mode at m_{max} because the width of short circuit pulse is reduced to zero.

Typical Type 1: Eliminating 5th and 7th harmonics:

Based on the above mentioned constraints of CSI the SHE PWM pattern for eliminating the 5th and 7th harmonic is developed. In Type 1 pattern there is no short circuit pulse around $\pi/6$.

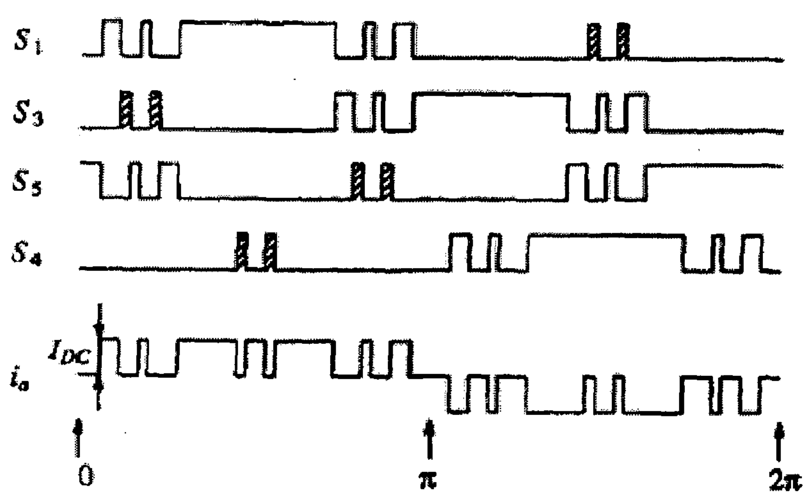


Fig. 3.5 Firing pulses pattern for CSI and the output current i_a for type 1 SHE PWM [3]

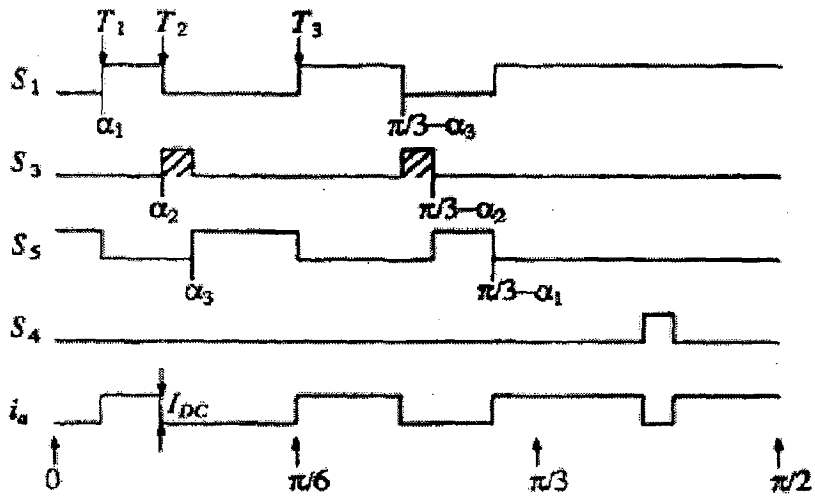


Fig. 3.6 Expansion of fig in the 0 to $\pi/2$ region [3]

The expression of the output current i_a [3] for the n^{th} harmonic is given by

$$I_{a,n} = \frac{4I_{DC}}{n\pi}\left[\cos n\alpha_1 - \cos n\alpha_2 + \cos\frac{n\pi}{6} - \cos n(\frac{\pi}{3} - \alpha_3) + \cos n(\frac{\pi}{3} - \alpha_1)\right.$$

$$\left. - \cos n(\frac{\pi}{3} + \alpha_2) + \cos n(\frac{\pi}{3} + \alpha_3) - \cos\frac{n\pi}{2}\right]$$

Where $\alpha_1, \alpha_2 and \alpha_3$ vary in the range 0 to $\pi/6$

As there are three independent switching angles the three variables can be controlled. So one is used to fundamental magnitude control and other two to eliminate the two different harmonics (in the present case 5th and 7th harmonics). The three transcendental equations that are required to be solved are

$$m = \frac{4}{\pi}\left[\cos\alpha_1 - \cos\alpha_2 + \cos\frac{\pi}{6} - \cos(\frac{\pi}{3} - \alpha_3) + \cos(\frac{\pi}{3} - \alpha_1)\right.$$

$$\left. - \cos(\frac{\pi}{3} + \alpha_2) + \cos(\frac{\pi}{3} + \alpha_3) - \cos\frac{\pi}{2}\right] \qquad (1)$$

$$I_{a,5} = \frac{4I_{DC}}{5\pi}\left[\cos 5\alpha_1 - \cos 5\alpha_2 + \cos\frac{5\pi}{6} - \cos 5(\frac{\pi}{3} - \alpha_3) + \cos 5(\frac{\pi}{3} - \alpha_1)\right.$$

$$\left. - \cos 5(\frac{\pi}{3} + \alpha_2) + \cos 5(\frac{\pi}{3} + \alpha_3) - \cos\frac{5\pi}{2}\right] = 0 \qquad (2)$$

$$I_{a,7} = \frac{4I_{DC}}{7\pi}\left[\cos 7\alpha_1 - \cos 7\alpha_2 + \cos\frac{7\pi}{6} - \cos 7(\frac{\pi}{3} - \alpha_3) + \cos 7(\frac{\pi}{3} - \alpha_1)\right.$$

$$\left. - \cos 7(\frac{\pi}{3} + \alpha_2) + \cos 7(\frac{\pi}{3} + \alpha_3) - \cos\frac{7\pi}{2}\right] = 0 \qquad (3)$$

The above three transcendental equations are solved and the variation of switching angles for the different values of the modulation index is plotted as shown in figure 3.7.

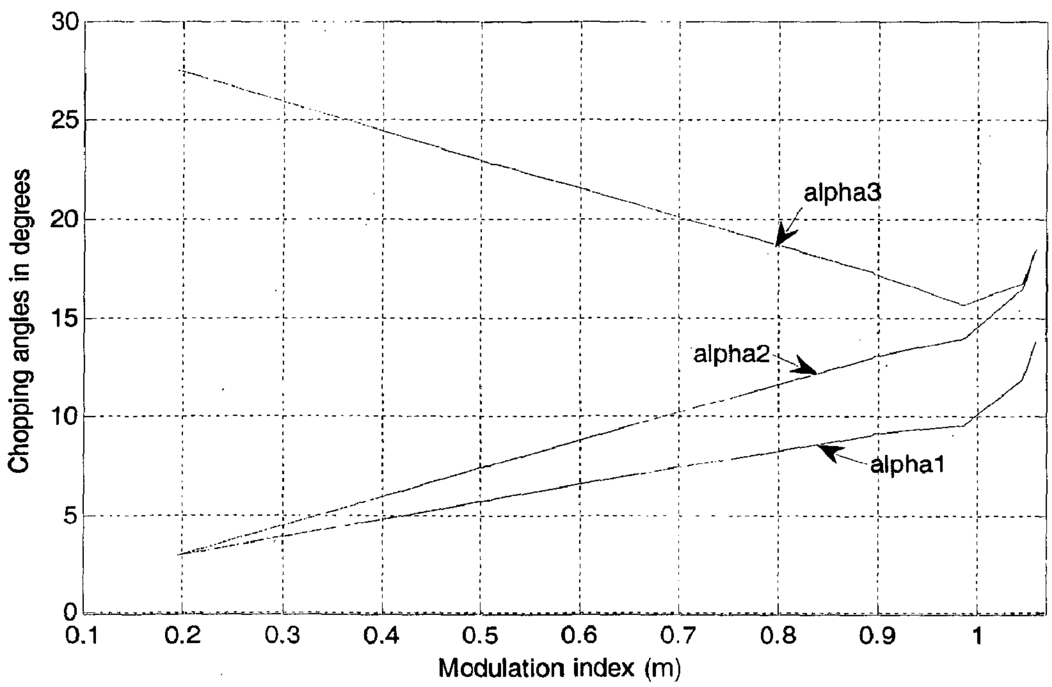


Fig. 3.7 Switching angles Vs. Modulation index for type 1 SHE PWM

From the graph it can be easily observed that for low values of m, the width of short circuit pulse $(\alpha_3 - \alpha_2)$ is large and as m decreases the width of the short circuit pulse increases. Thus it can be said that the fundamental magnitude control is possible because of the short circuit pulse.

Typical Type 2: Eliminating 5th, 7th, 11th and 13th harmonics:

A typical Type 2 SHE PWM pattern for eliminating the four harmonics, besides the control of fundamental component of current is as shown below.

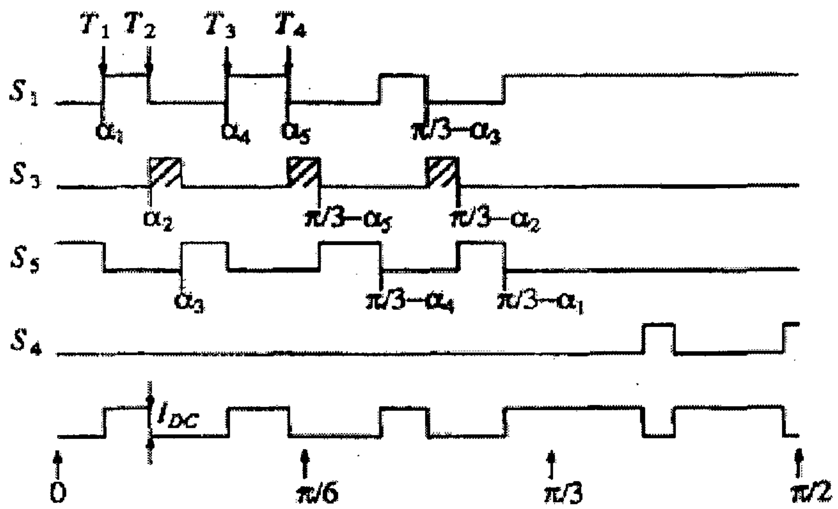


Fig. 3.8 Firing pulses pattern for CSI and the output current i_a for type 2 SHE PWM [3]

The gating pattern for the region 0 to 2π can be easily obtained from the region 0 to $\pi/2$ based on the quarter wave symmetry conditions. It can be observed that there is a short circuit pulse around $\pi/6$ similar to Type 0 SHE PWM pattern but the gating patterns for $S_1, S_3 and S_5$ are mirror images to Type 0 SHE PWM pattern with respect to $\pi/6$.

The Fourier series expansion of the output current is as shown below [3]

$$I_{a,n} = \frac{4I_{DC}}{n\pi}\left[\cos n\alpha_1 - \cos n\alpha_2 + \cos n\alpha_4 - \cos n\alpha_5 + \cos n(\frac{\pi}{3} - \alpha_4) - \cos n(\frac{\pi}{3} - \alpha_3)\right.$$

$$\left. + \cos n(\frac{\pi}{3} - \alpha_1) - \cos n(\frac{\pi}{3} + \alpha_2) + \cos n(\frac{\pi}{3} + \alpha_3) - \cos n(\frac{\pi}{3} + \alpha_5)\right]$$

Where $\alpha_1, \alpha_2, \alpha_3, \alpha_4, and \alpha_5$ vary in the range 0 to $\pi/6$.

To calculate the chopping angles for controlling the modulation index (m) and canceling the specified harmonics in the SHE method, I_1 should be set to m and corresponding $I_{a,n}$ to zero. Thus a system of non linear transcendental equations are obtained which are solved by using the NAG subroutine E04UCF, and the variation of switching angles for different values of modulation index is plotted.

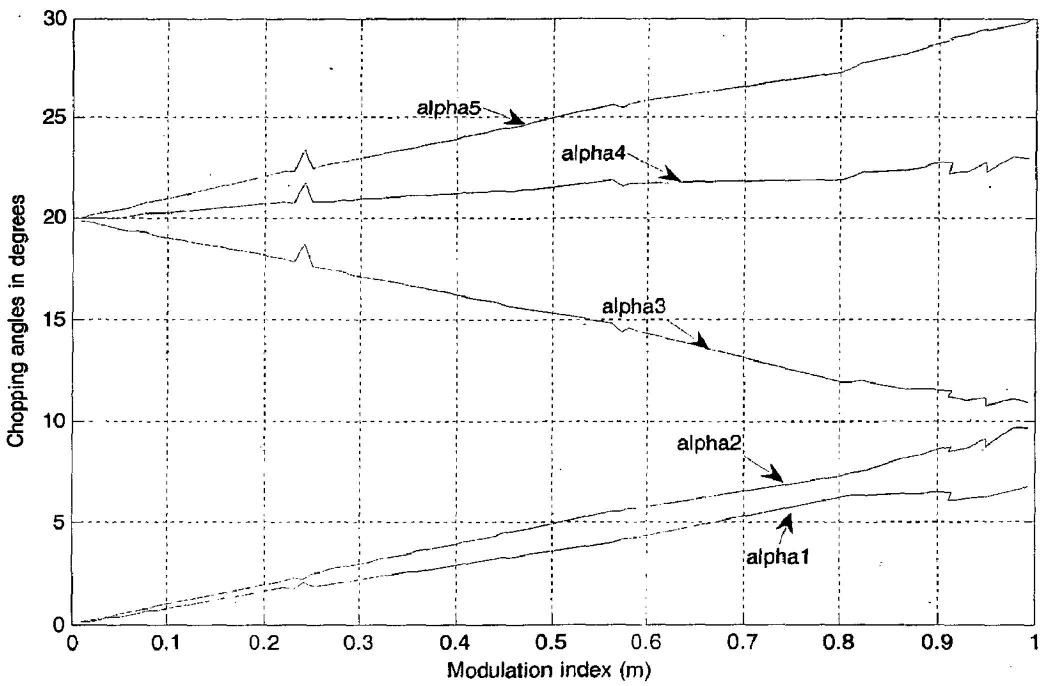


Fig. 3.9 Switching angles Vs. Modulation index for type 2 SHE PWM

Again it can be easily observed that the variation in the width of the short ciruit pulses is mainly responsible for the variation in the modulation index, thereby controlling the fundamental component of the output current. The other notches contribute to the elimination of the specified harmonics.

Typical Type 3: Eliminating 5th, 7th, 11th, 13th, 17th and 19th harmonics:

The SHE PWM pattern has no short circuit pulse around $\pi/6$ simlar to Type 1 system, but the gating patterns for $S_1, S_3 and S_5$ are mirror images to Type 1 SHE PWM pattern with respect to $\pi/6$. The SHE PWM pattern for the typical Type 3 system is shown figure 3.10.

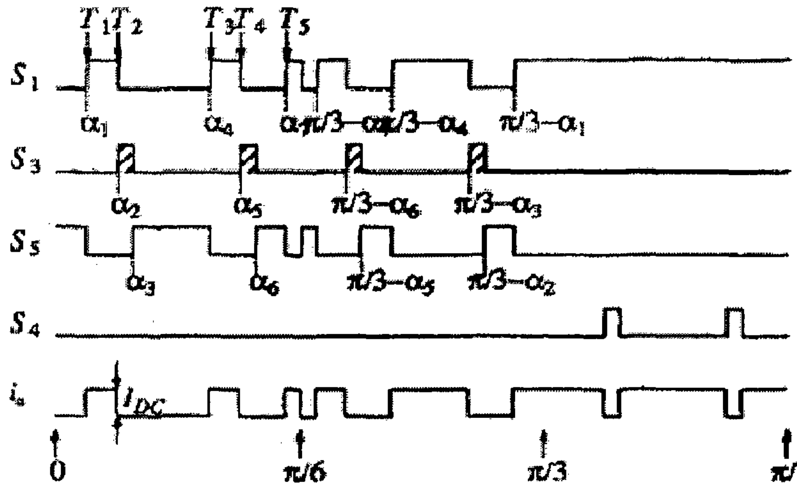


Fig. 3.10 Firing pulses pattern for CSI and the output current i_a for type 3 SHE PWM [3]

The expression of the output current i_a [3] for the n^{th} harmonic is given by

$$I_{a,n} = \frac{4I_{DC}}{n\pi}\Bigg[\cos n\alpha_1 - \cos n\alpha_2 + \cos n\alpha_4 - \cos n\alpha_5 + \cos n\alpha_7 - \cos\frac{n\pi}{6}$$

$$+\cos n(\frac{\pi}{3}-\alpha_7) - \cos n(\frac{\pi}{3}-\alpha_6) + \cos n(\frac{\pi}{3}-\alpha_4) - \cos n(\frac{\pi}{3}-\alpha_3)$$

$$+\cos n(\frac{\pi}{3}-\alpha_1) - \cos n(\frac{\pi}{3}+\alpha_2) + \cos n(\frac{\pi}{3}+\alpha_3) - \cos n(\frac{\pi}{3}+\alpha_5) + \cos n(\frac{\pi}{3}+\alpha_6) - \cos\frac{n\pi}{2}\Bigg]$$

There are seven independent switching angles so six harmonics can be eliminated, besides the fundamental current control. The transcendental equations are solved and the plot of switching angles vs. modulation index (m) is shown in figure 3.11.

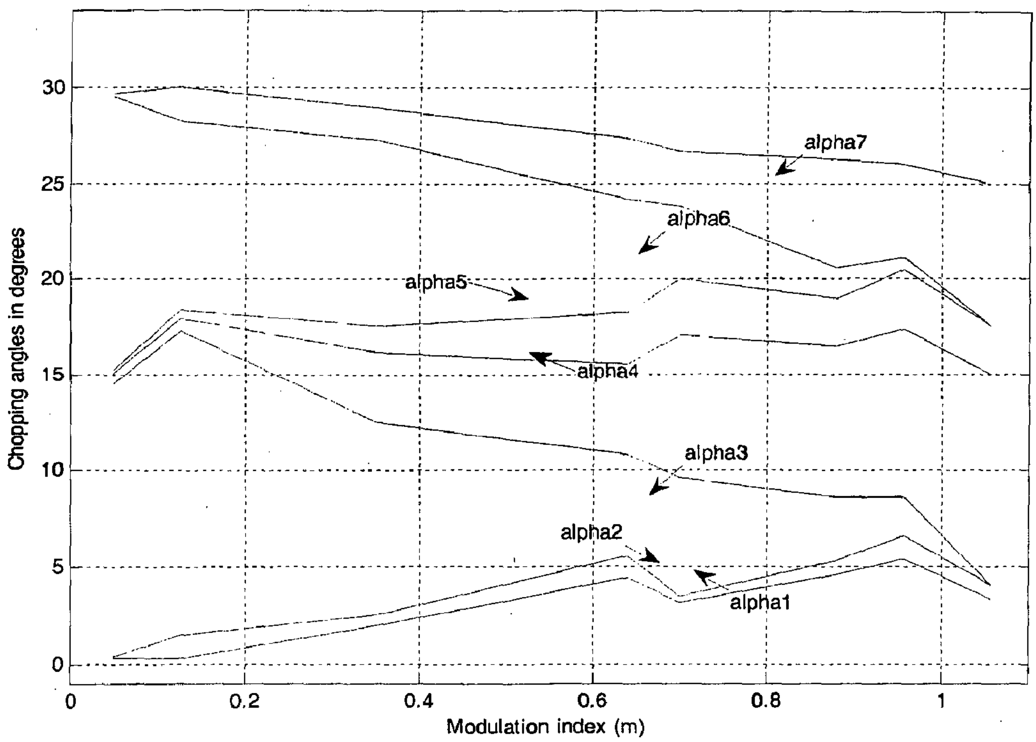


Fig. 3.11 Switching angles Vs. Modulation index for type 3 SHE PWM

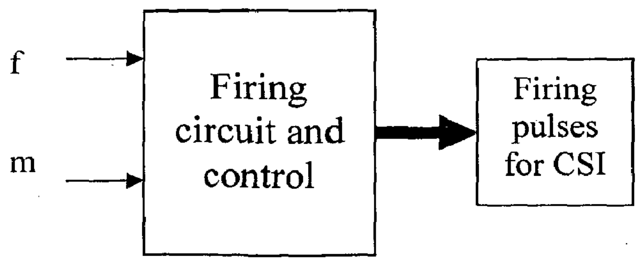
From the plot it can be easily observed that the short circuit pulses contributes major role in providing fundamental current control. Besides this the other notches eliminate the specified harmonics.

Creation of LUT's:

From the plots of switching angles Vs. modulation index, the look up tables are created which store the switching angles for the given modulation index. The creation of LUT is useful for the offline application of the SHE in CSI.

3.3 Logic circuit design for implementation of SHE in CSI :

A logic circuit is developed which gives firing pulses to CSI switches so as to have the desired SHE PWM pattern.



CSI are used to feed the induction motor and for speed control of it, requires variable frequency and variable output current. The LUT's stores the switching angles in degrees for different modulation index. Thus the SHE PWM pattern is independent of frequency The basic block diagram of the firing circuit and control is as shown in figure 3.12

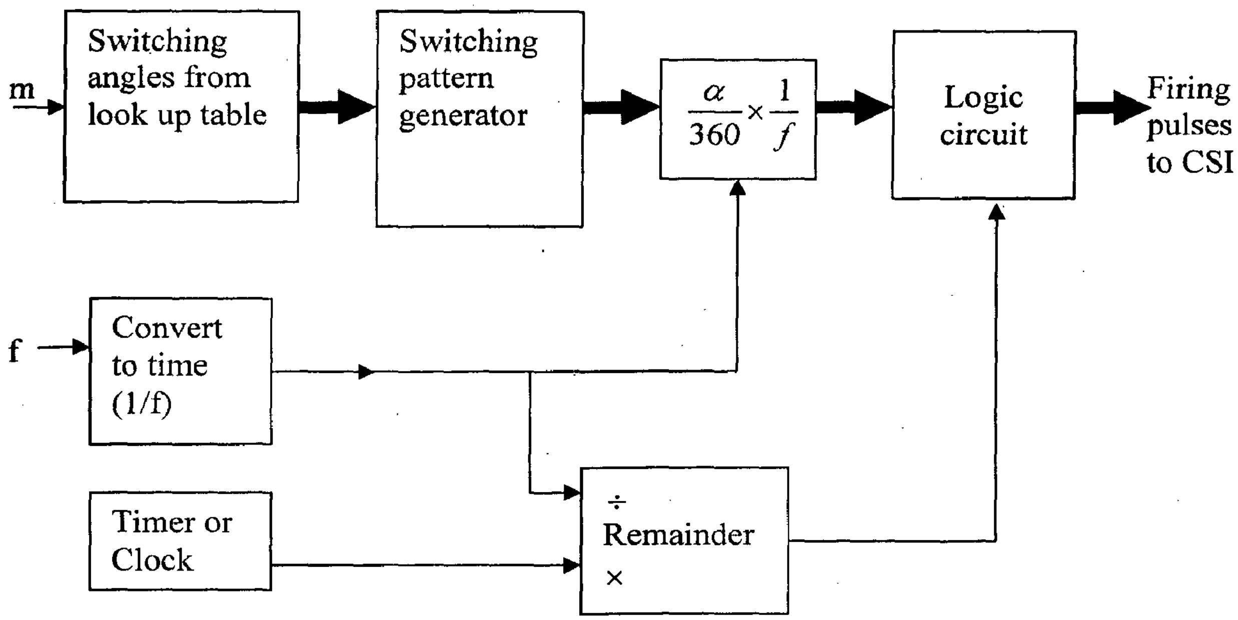


Fig. 3.12 Block diagram of Firing pulse generator

The modulation index (m) and frequency (f) are given to the firing circuit. Based on m value, switching angles from the look up table are selected. The switching angles are then given to pattern generator circuit which develops the necessary switching pattern of firing pulses to the CSI. The pattern generator gives all the switching angles of firing pulses. These switching angles are then converted to timing instants by multiplying each angle by the factor $\frac{\alpha}{360} \times \frac{1}{f}$. The logic circuit consisting of comparators, AND, OR gates generates the necessary firing pulses for the CSI.

The logic circuit operation can be explained with the help of an example. The switching angles can be obtained based on m value from look up table. Let $\alpha_1 = 5^\circ$ $\alpha_2 = 10^\circ, \alpha_3 = 15^\circ$ and the required firing pattern are two pulses of width say

1st pulse width = $(\alpha_2^\circ - \alpha_1^\circ)$ starting at α_1°

2^{nd} pulse width = $((30^\circ - \alpha_1^\circ) - \alpha_3^\circ)$ starting at α_3°

Let the frequency be 25Hz.

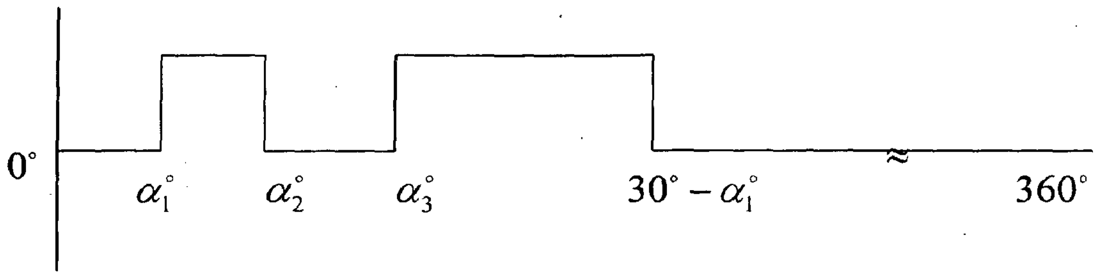


Fig. 3.13 Pulses with different pulse widths

Multiplying the switching instants (in degrees) which will be obtained from the switching pattern generator by $\frac{\alpha}{360} \times \frac{1}{f}$ gives the switching instants in terms of time for a particular frequency f. For our example

Switching instants say T_1 = 5.5e-4, T_2 = 11.11e-4, T_3 = 16.67e-4 and T_4 = 16.67e-4

The remainder function divides the clock time with the $1/f$ and gives the remainder. So we get a clock which is running from 0 to $1/f$. Let us denote the instantaneous time which is varying from 0 to $1/f$ as't'. The logic circuit using the comparator and AND, OR gates is as shown below generates the required switching pulses.

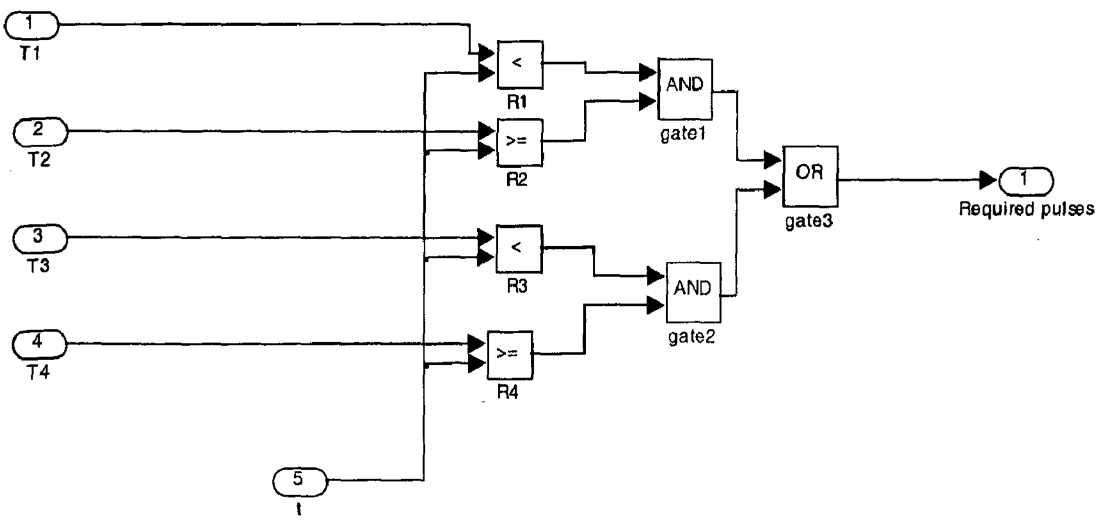


Fig. 3.14 Logic circuit for firing circuit

The R1, R2, R3 and R4 are comparators which compare the signal 't' with the switching instants and generate the output as 1 if true.

Table 3.1: Truth table showing how the logic circuit is working

Time interval	R1	R2	R3	R4	Gate1	Gate2	Gate3
0 to T1	0	1	0	1	0	0	0
T1 to T2	1	1	0	1	1	0	1
T2 t0 T3	1	0	1	1	0	1	1
T3 to T4	1	0	1	0	0	0	0
T4 to $1/f$	1	0	1	0	0	0	0

Thus the required pulses are obtained by using the logic circuit. This logic circuit can be implemented using digital logic circuits. Based on the above technique the firing pulses for the CSI are generated. The firing pulses for eliminating 5th and 7th harmonic using the above technique is as shown in figure 3.15

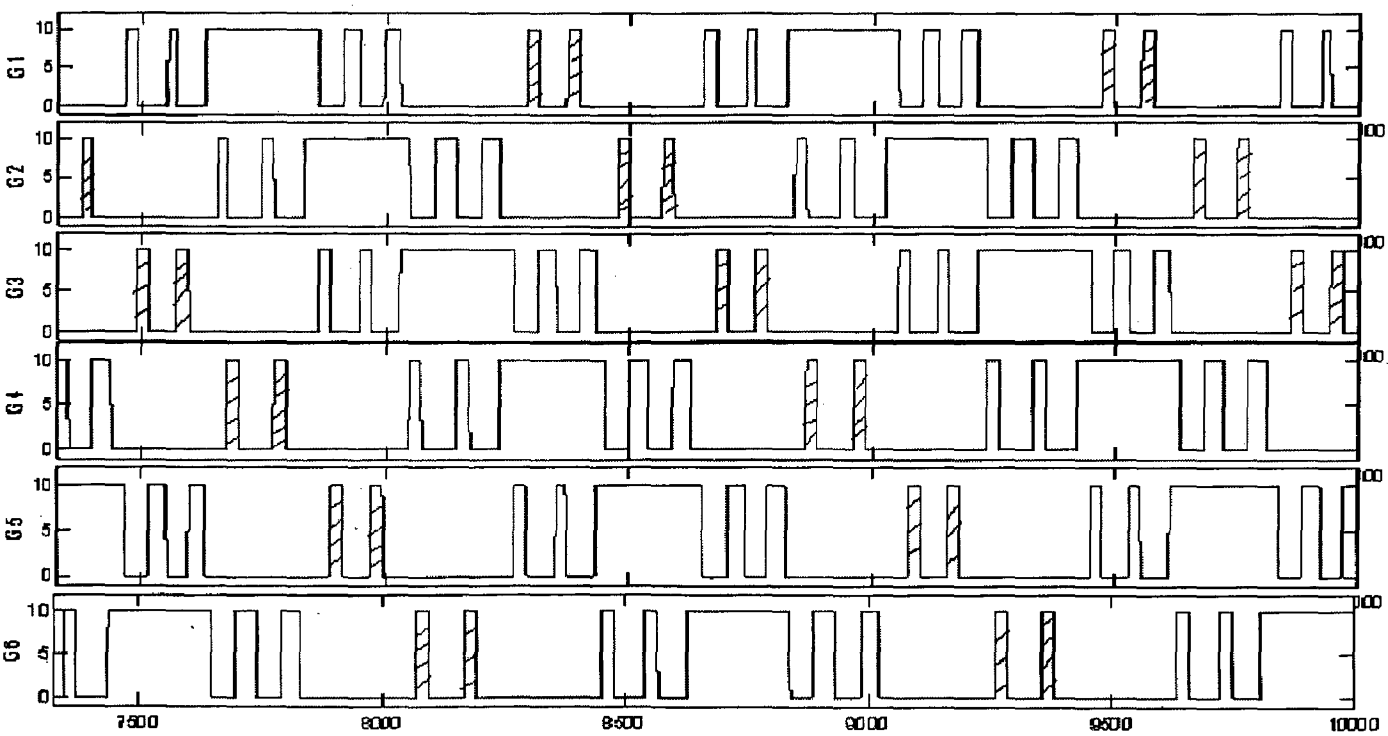


FIG. 3.15 Firing pulses for the switches S_1 to S_6

CHAPTER 4

PERFORMANCE ESTIMATION OF SHE PWM TECHNIQUE IN CSI

The AC output current of SHE CSI is fed to the 3 phase load and their harmonic spectrums are plotted for different types of SHE PWM pattern. The basic circuit diagram for the implementation of CSI is as shown below.

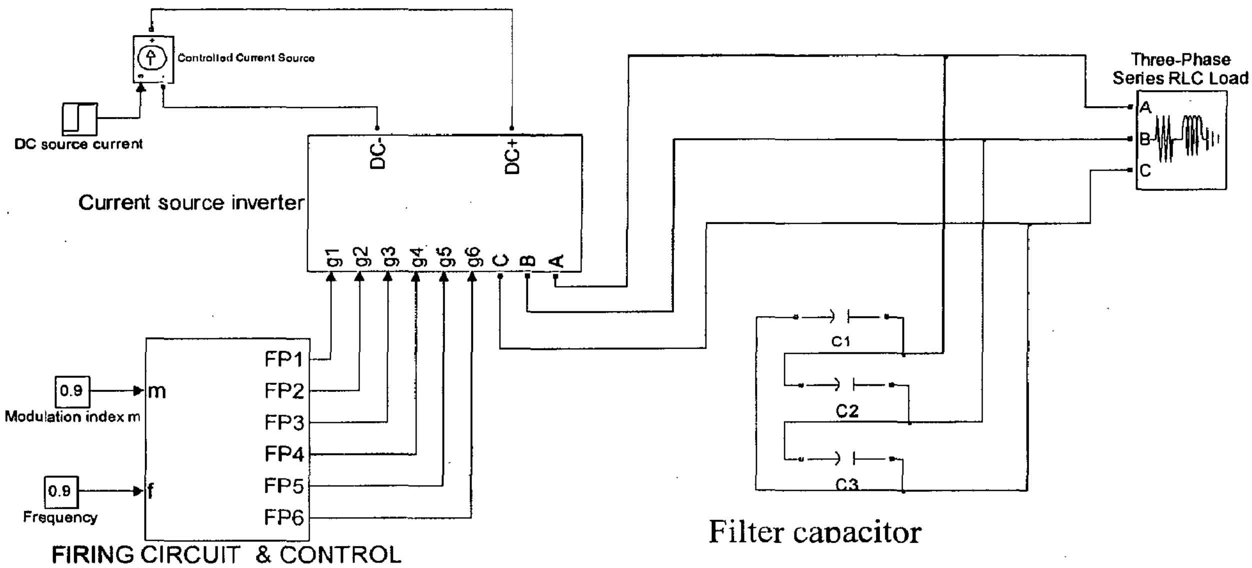


Fig. 4.1 Basic CSI implementation in Matlab with R- L load

Parameters:

Three phase R- L load: Active power = 4 K.W and Reactive Power = 3 KVAR, power factor = 0.8 lag.

DC current source: 7.2 A

Filter capacitor: 10 μF

Modulation index m: 0.9

Fundamental frequency: 50 Hz

The harmonic spectrum of the output voltage, output current and the output current of CSI are obtained for different Types of SHE PWM patterns are obtained as shown below.

4.1 SIX PULSE CSI

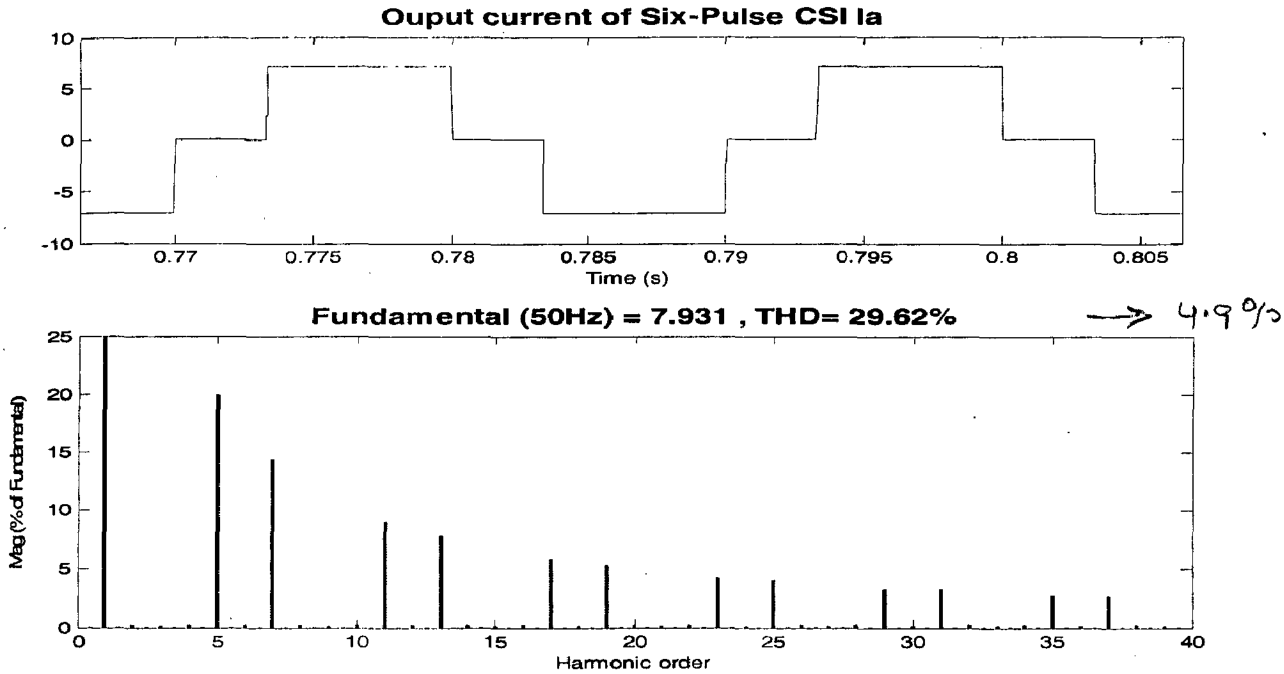


Fig. 4.2

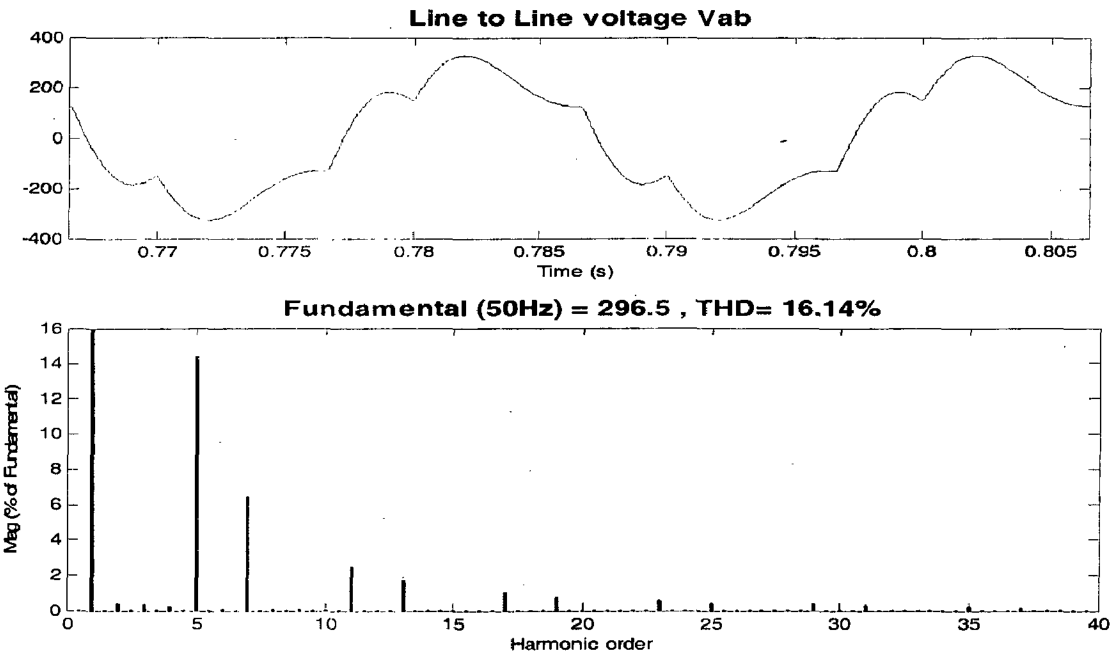


Fig. 4.3

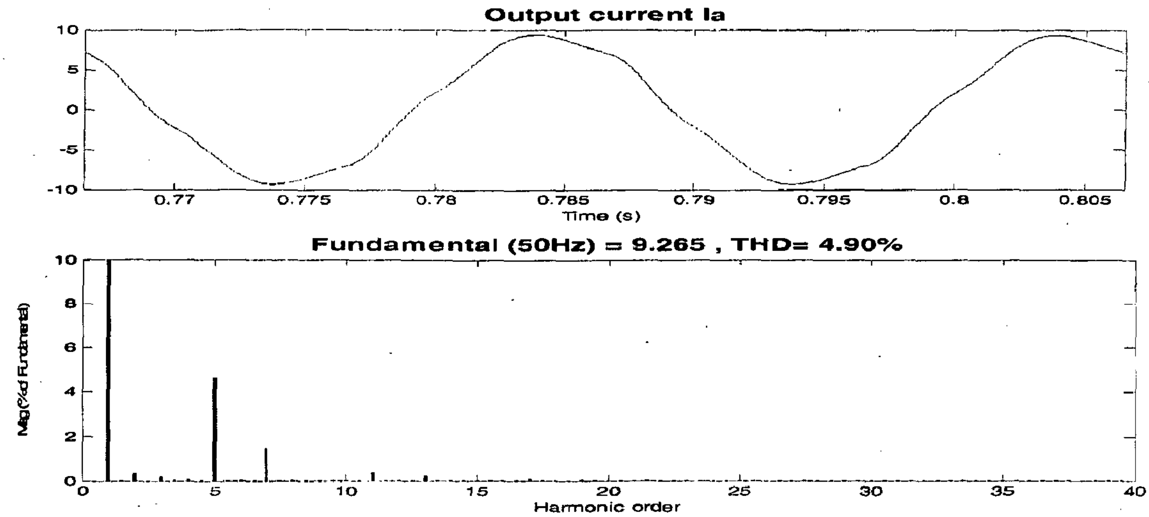


Fig. 4.4

For the six pulse CSI the THD of load current is around 4.9% and it contains the 5th and 7th harmonic of considerable magnitude. Thus even though the THD is less, but because of presence of 5th and 7th harmonics, the performance of the motor is poor.

4.2 Typical Type 0 SHE PWM:

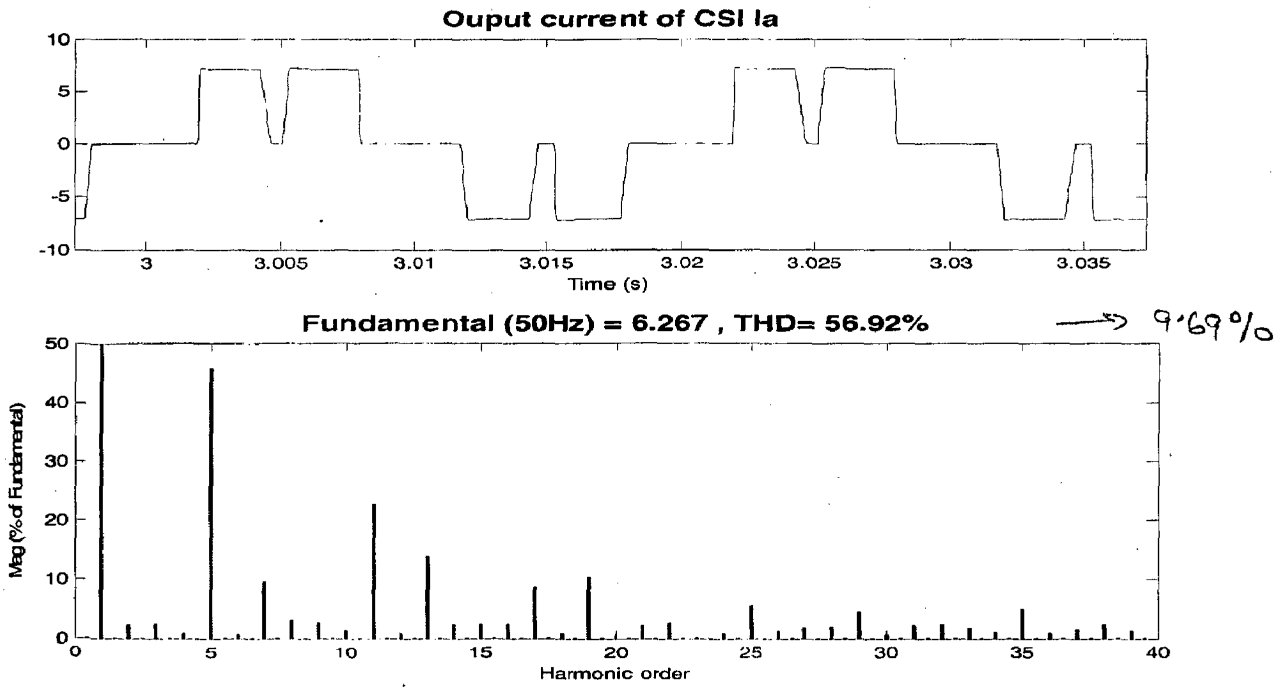


Fig. 4.5

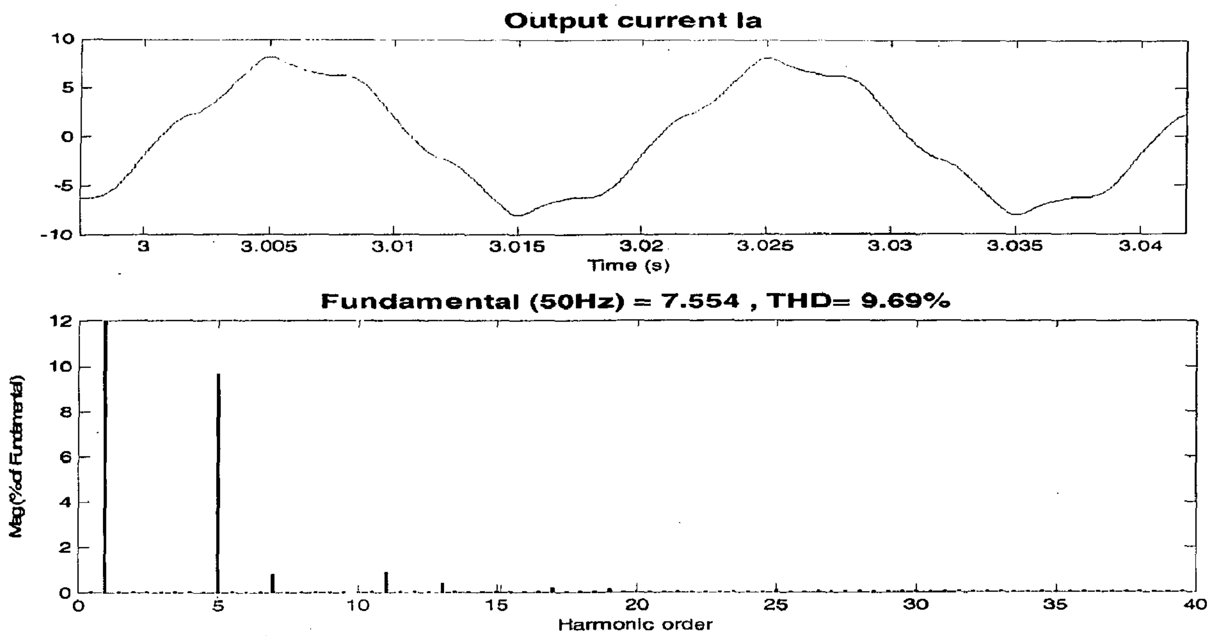


Fig. 4.6

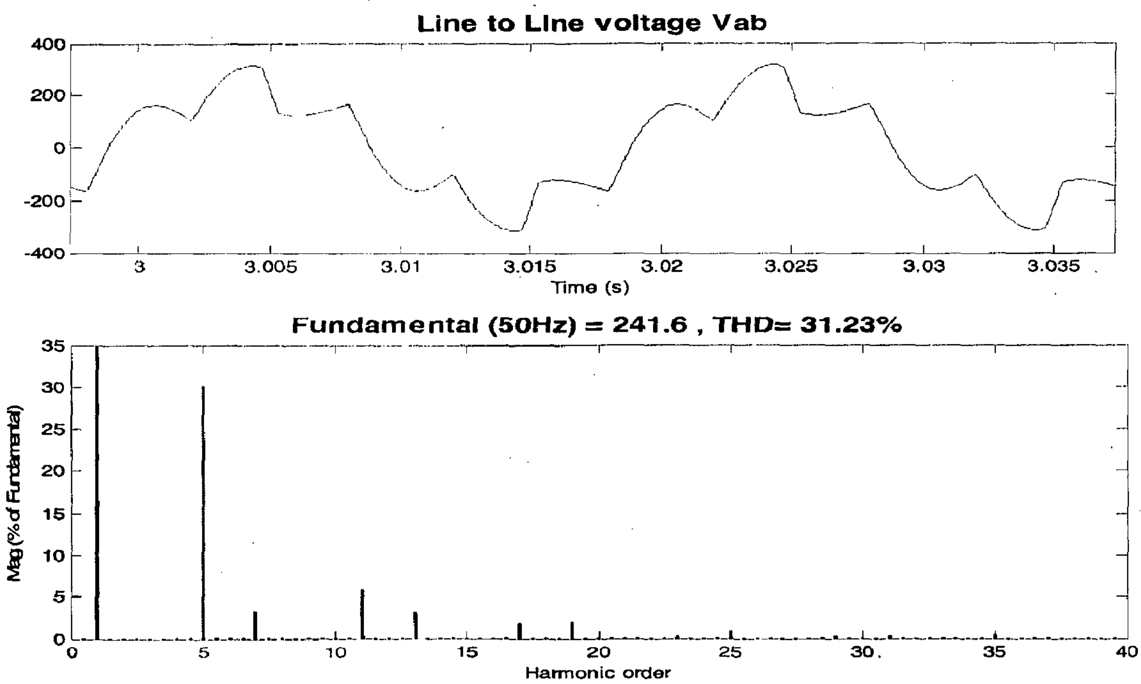


Fig. 4.7

In case of Type 0 system the THD (=9.69%) of load current is quite high as compared to the Six pulse CSI (THD = 4.9%). This is due to the reason that the output of the Type 0 system is square wave in shape with a short circuit pulse and here no harmonic is being eliminated.

4.3 Typical Type 1 SHE PWM:

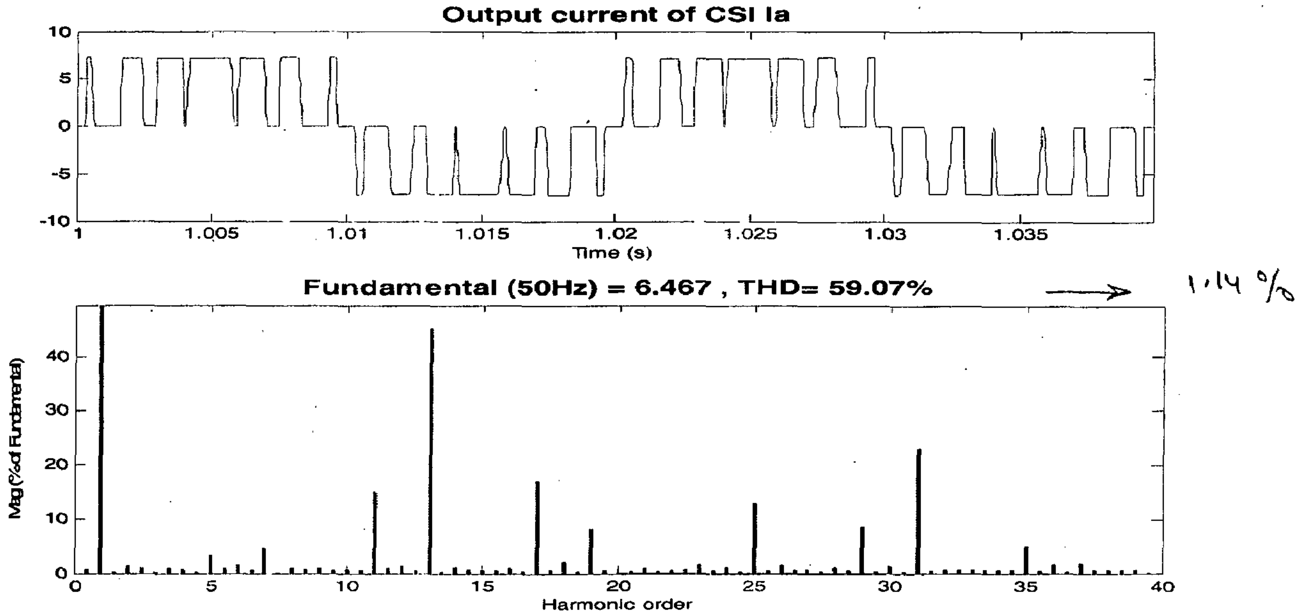


Fig. 4.8

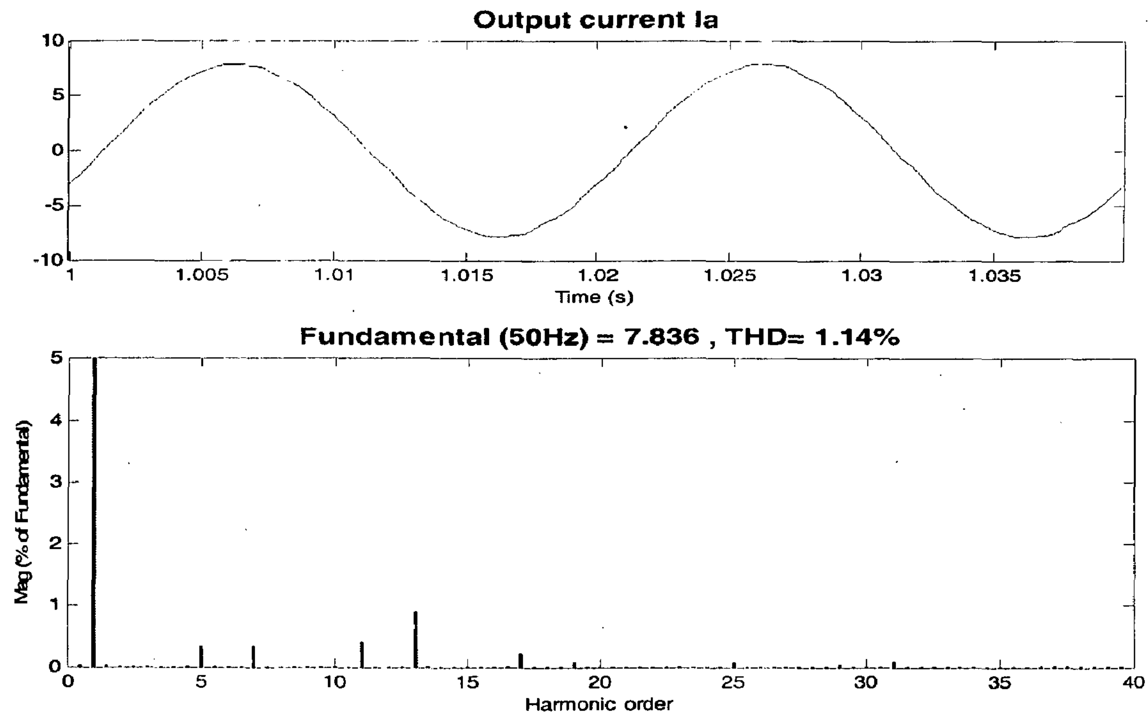


Fig. 4.9

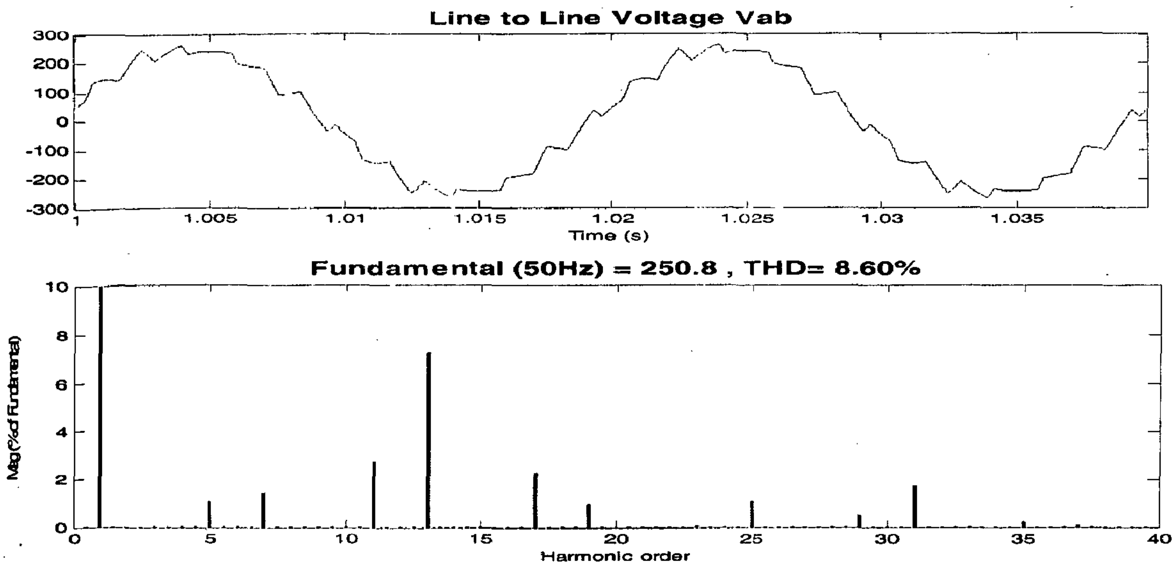


Fig. 4.10

In Type 1 system the 5th and 7th harmonic are eliminated, the THD of the load current reduces drastically to 1.14% when compared to the THD of Six pulse CSI of 4.91% and of Type 0 system of 9.39%. This conveys that the effect of higher order harmonics is very less in case of the inductive loads. In other words that the automatic filter action takes place by the inductor and higher order harmonics are filtered off.

For Typical Type 2 SHE PWM:

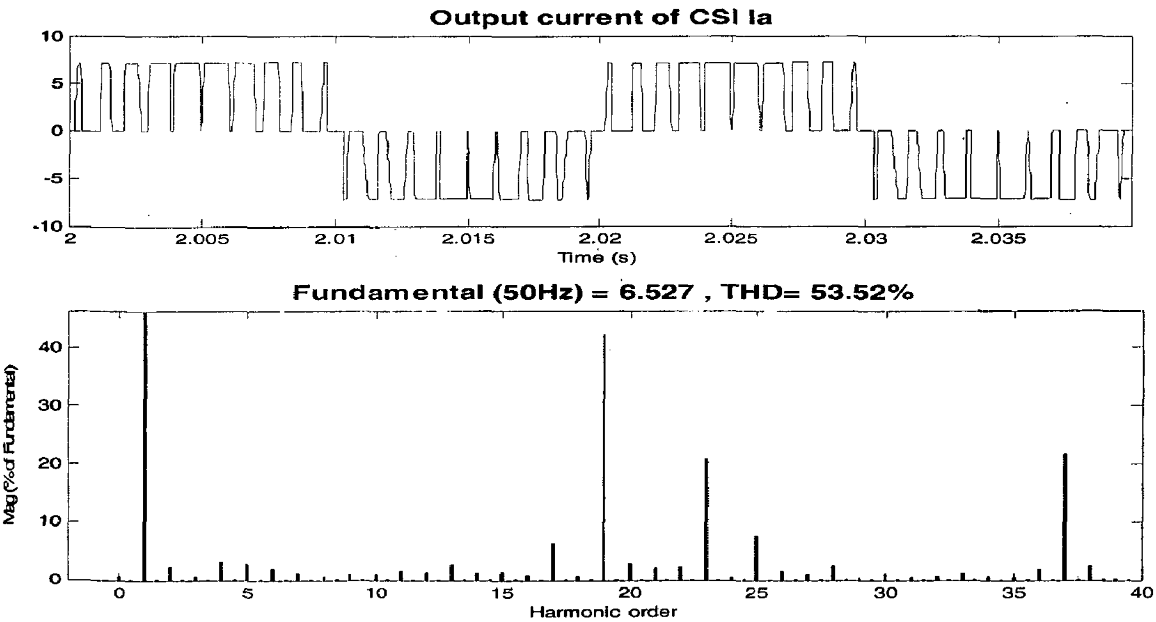


Fig. 4.11

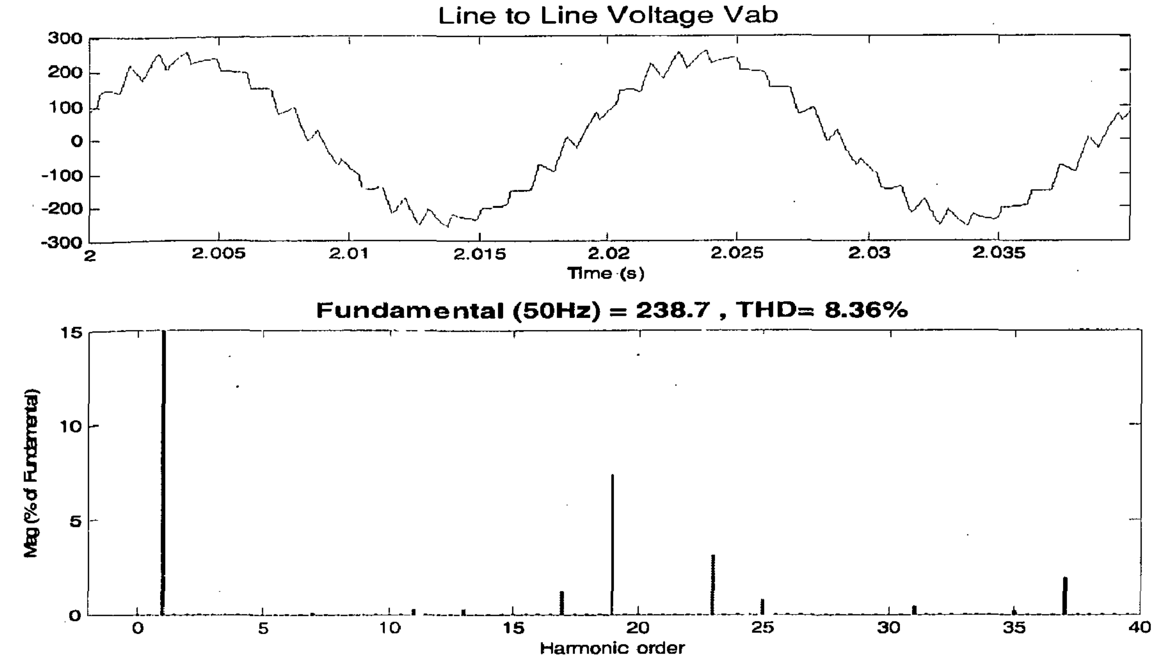


Fig. 4.12

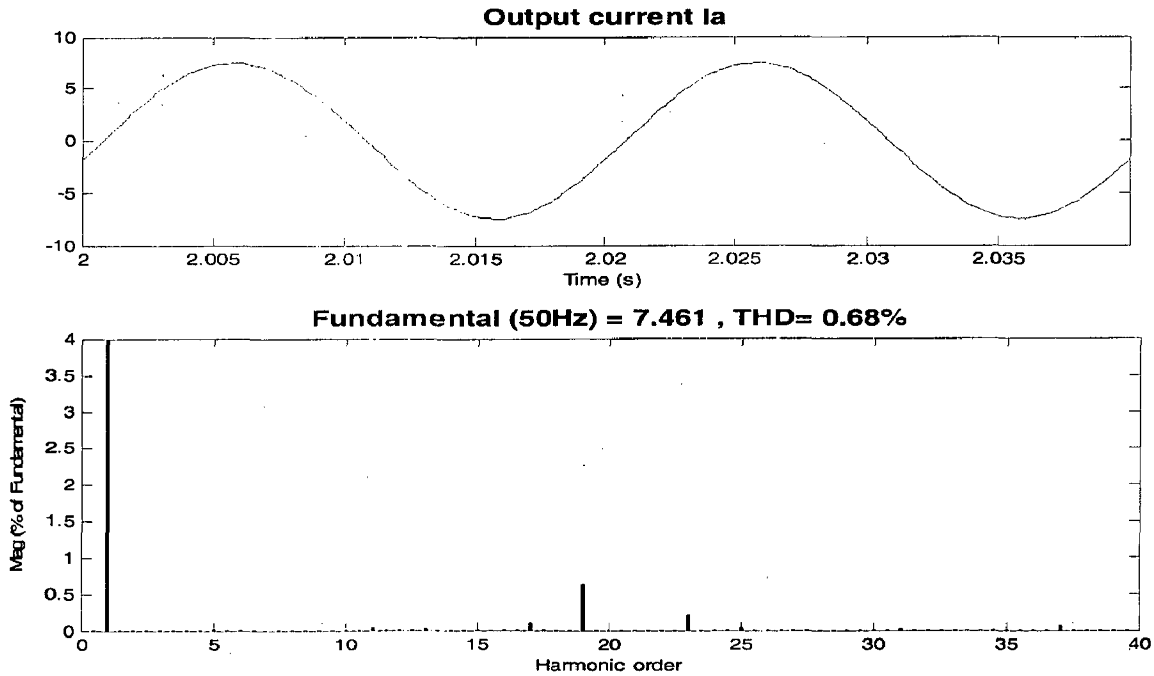


Fig. 4.13

In case of Type 2 system harmonics 5^{th} ,7^{th}, 11^{th} and 13^{th} are eliminated. The THD of the load current is decreased slightly from 1.14% of Type 1 system to 0.68%. Thus it shows that the higher order harmonics have less influence on the THD in case of inductive load.

For Typical Type 3 SHE PWM:

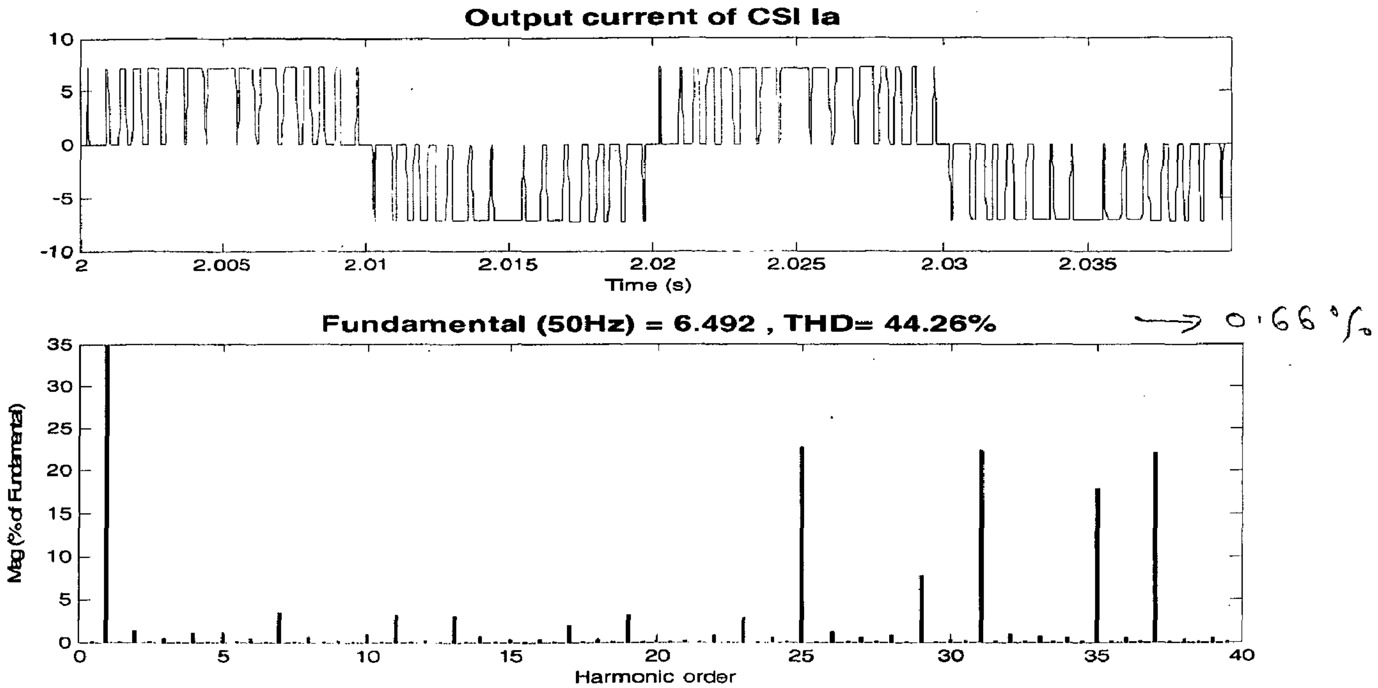


Fig. 4.14

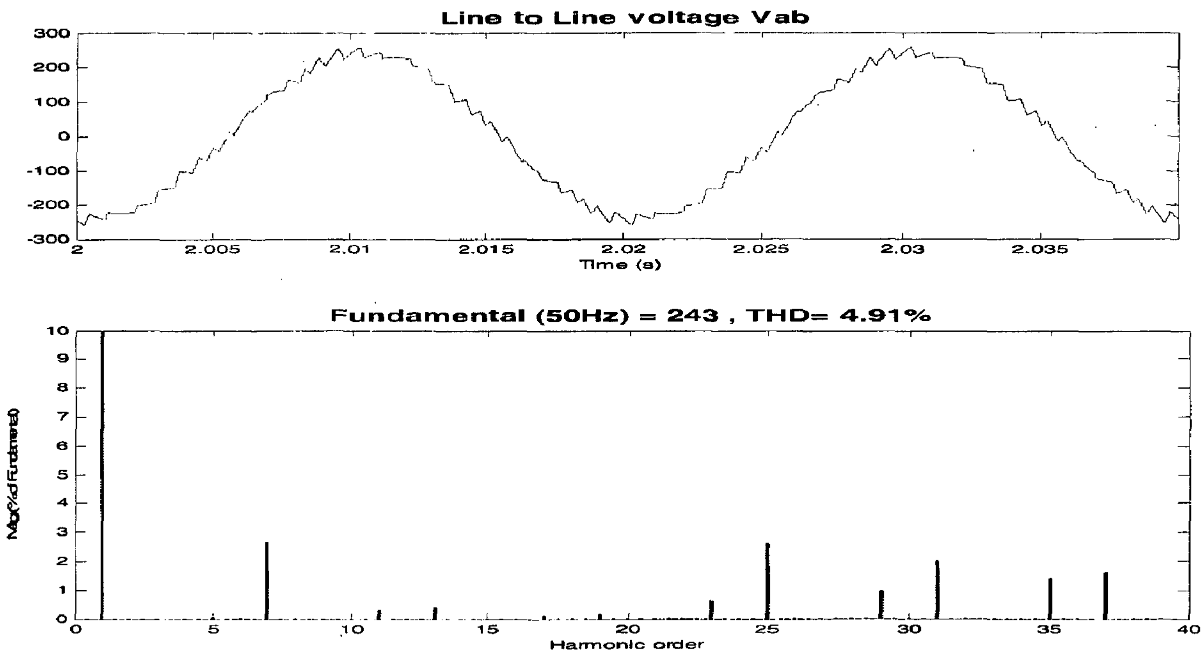


Fig. 4.15

For Typical Type 3 SHE PWM:

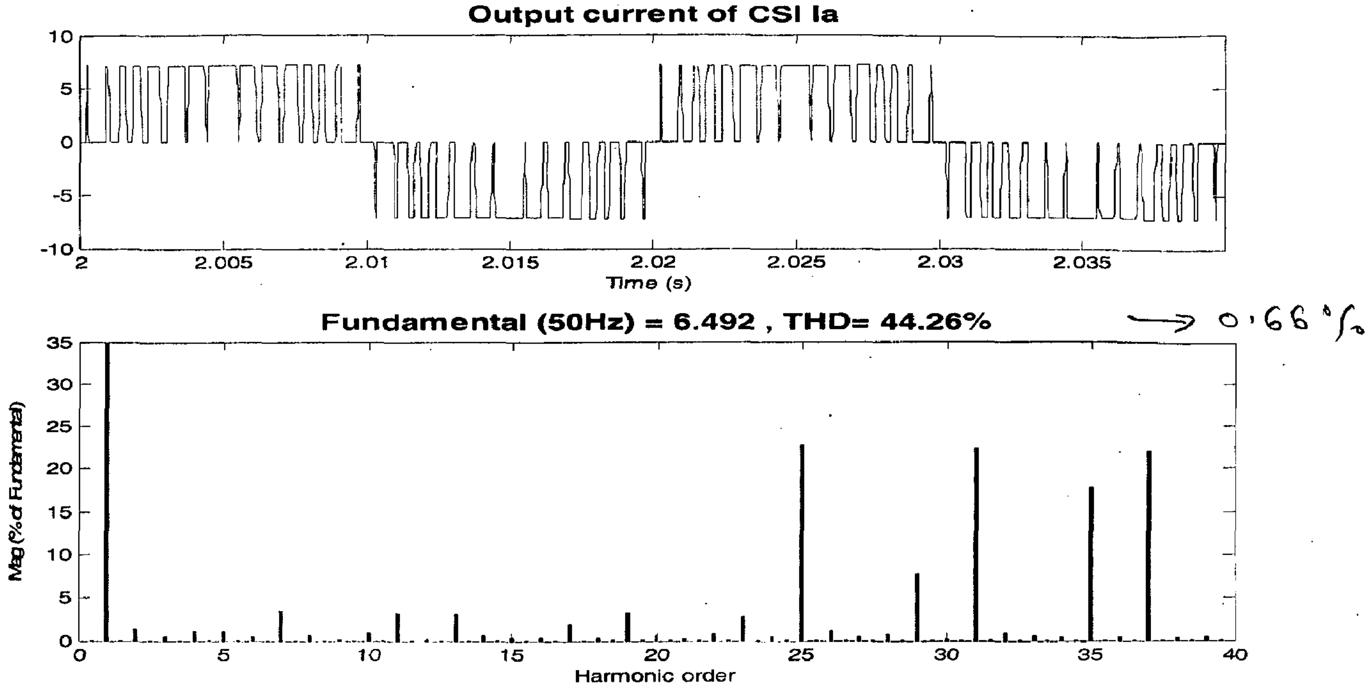


Fig. 4.14

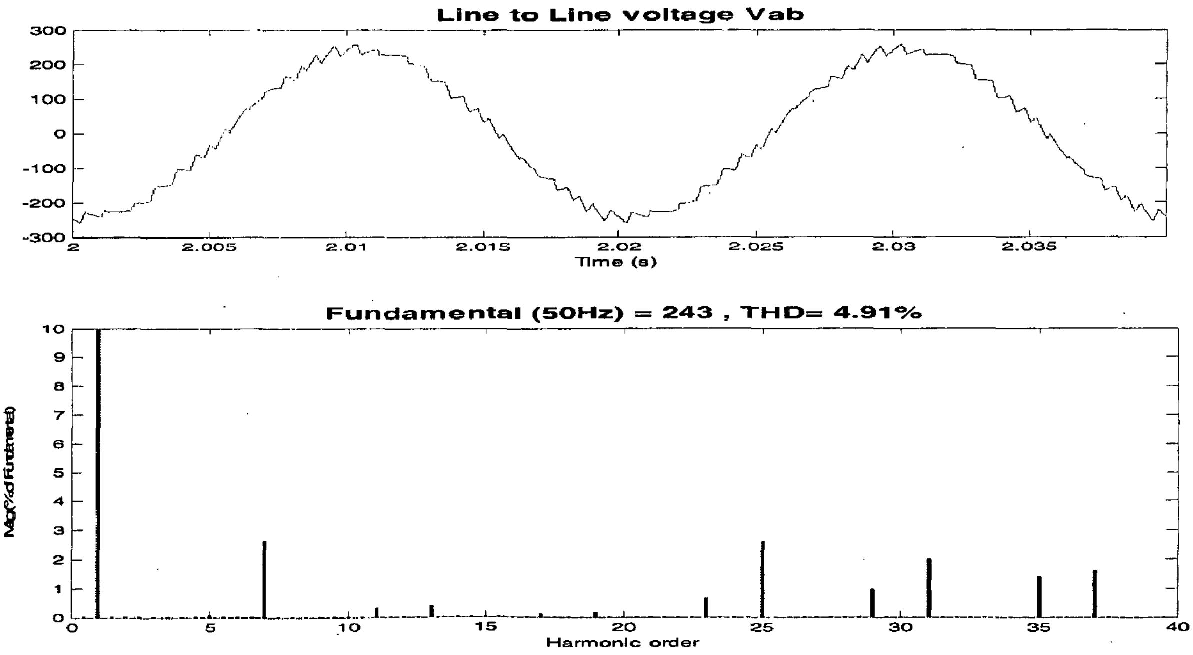


Fig. 4.15

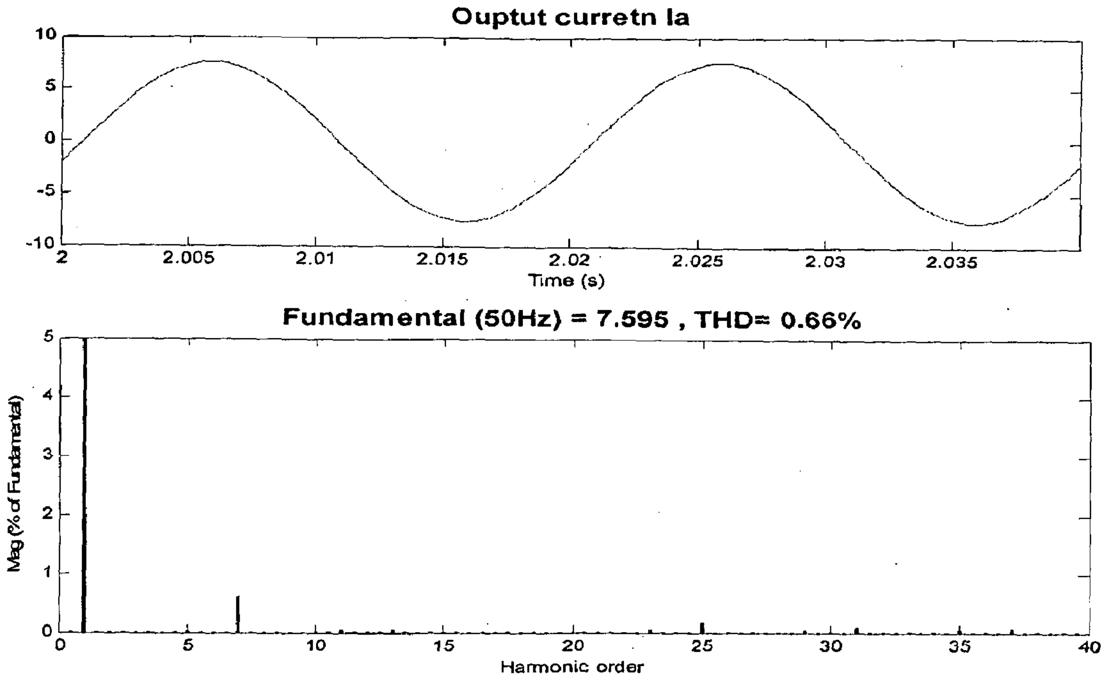


Fig. 4.16

4.6 CONCLUSION:

The plot of the THD vs. modulation index for different types of switching patterns is plotted for output load current as shown in figure 4.17. From the plot it can be easily said as the more number of harmonics are eliminated the THD reduces accordingly. Similarly in case of THD of output voltage as shown in figure 4.18, the THD of Type 1 system is slightly more than the type 2 system. From the harmonic spectrum of output current of CSI and the output load current, it can be observed that there is a large difference in the magnitudes of higher order harmonics. This is due to the reason that the as the order of the harmonics increases the impedance offered by the inductance of the load is very high and thus it can be concluded that the effect of higher order harmonics is very less. This implies that it is sufficient if lower order harmonics are eliminated because higher order harmonics are filtered by the reactance of the load.

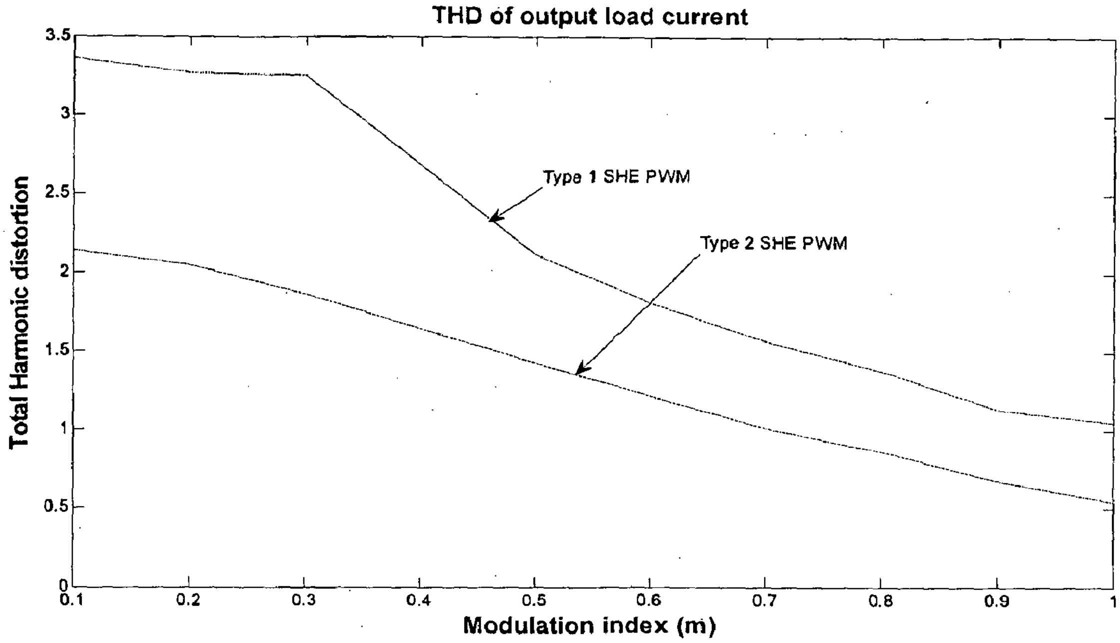


Fig. 4.17 THD of output load current vs Modulation index for Type 1 and Type 2 system

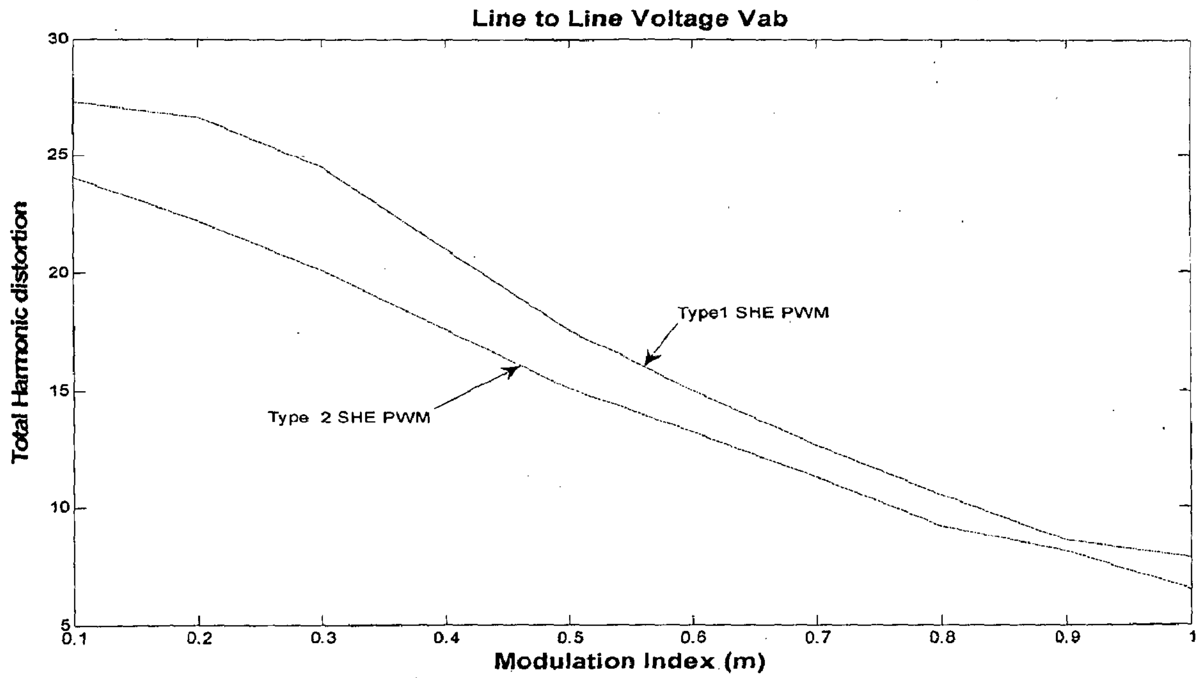


Fig. 4.18 THD of Line to Line voltage vs Modulation index for Type 1 and Type 2 system.

CHAPTER 5

SHE in CSI FED INDUCTION MOTOR:

Induction motor operation when fed with current source.

CSI are used to feed the induction motor and for speed control of it, requires variable frequency and variable output current. The variable output current can be obtain either by varying the modulation index or by controlling the DC link current I_d. The modulation index method of control has the advantage of instantaneous current control [9] but it results in lesser utilization of DC link current I_d. On the other hand DC link current control can be obtained by varying the firing angle of the thyristors rectifier. But such a control of current leads to slow dynamic response due to DC link inductor. An ideal control strategy will be to use the instantaneous current control method for quick response and in steady state the DC link current control is implemented. This has the advantage of faster dynamic response in transient period and improved utilization of DC link current in steady state.

The SHE PWM is used to eliminate the lower order harmonics from the output waveform of CSI. The elimination of lower order harmonics is necessary in CSI to avoid the possible resonance between the input/output filter and motor leakages at low order harmonic frequency. It also reduces the THD of the output current which in turn will reduce the harmonic losses.

5.1 Salient features of speed control of CSI fed Induction motor drives:

1. Need of capacitor bank:

In CSI the output current suddenly changes from 0 to I_d as the switching takes place. This forces the corresponding phase current of the motor to jump instantaneously from 0 to I_d. In the absence of capacitor bank C, the machine phase current will also jump instantaneously. Due to large rate of change of phase current, the machine leakage inductance wil produce a sharp positive spike in phase volatage V_{AN}. Similarly when the switch is turned off, a sharp negative spike is produced in the phase voltage. The capacitor bank, by providing alternative paths for current flow, reduces change of machine phase currents and therefore the voltage spikes are reduced. This also prevents excessive increase in the voltage rating of the switches.

2. Low leakage inductance motor is preferred:

As motor leakage increases, the magnitude of voltage spike increases. And thus a large value of capacitor is then required to limit the spikes in the voltage. Consequently, the time required for current transfer from one phase to other increases, decreasing the frequency range of inverter. This requirement is contrary to VSI requirement of high leakage inductance.

3. Effect of harmonics:

The harmonic currents flow mostly through rotor since X_m offers very high reactance to harmonic currents. Thus the flux produced and induced emf are sinsusoidal of fundamental, if stator drop is neglected then stator voltage is also sinusoidal with spikes at the switching instants superimposed. Because of sinusoidal flux, only fundamental component of current contributes to developed torque and power. The harmonics increases copper and core losses, produces pulsating torques which cause jerky motion at low speeds and cogging during reversal.

4. Load commutation:

The thyristors can be made to commutate naturally, if capacitors are chosen such that the capacitor motor combination has a leading power factor. The leading power factor at all operating conditions and frequency can be obtained by using variable capacitor (static leading VAR generator).

5. Regenerative Braking capability:

In closed loop control, the rectifier current automatically adjusts the firing angle and keeps the dc link current constant. When operation shifts from motoring to generation, V_d becomes negative, the rectifier firing angle automatically changes to make its output voltage negative. Therefore the rectifier works as an inverter transferring power from DC link to AC supply and regenerative braking is achieved. Thus to have regenerative action one has to simply reduced the inverter frequency to make the synchronous speed less than the rotor speed.

6. Four Quadrant operation:

For a given phase sequence, drive operates in the first and second quadrant. When motor is at standstill, the phase sequence is reversed simply by interchanging the control signals between any two legs of inverter, causing motor run in reverse direction and therefore the motor operates in the third and fourth quadrant. Thus four quadrant operations can be achieved using the CSI.

5.2 Speed control of Induction motor fed with SHE CSI using the slip speed control method:

Operation of Induction motor fed with Current source:

Induction motor when fed with the current source in the open loop mode operates in the region of saturation. From the equivalent circuit of induction motor [14]

$$I_s = I_r + I_m$$

At low values of slip's', I_r' is small and so

$$I_m \cong I_s.$$

But I_s is much higher than normal I_m, so motor operates under saturation at low values of slip. Also the starting torque is low due to low values of flux (as I_m is low) and rotor current compared to their values at rated voltage. The torque increases with speed due to increase in flux. But because of saturation, the increase in terminal voltage and torque is much lower than what could be predicted if saturation is neglected. The induction motor can be made to operate in the constant flux mode by using the closed loop control. Due to above mentioned reasons the induction motor when fed with current source is always operated in the closed loop mode to make the machine operate at constant flux.

Block diagram of SHE CSI fed induction motor using slip control method:

In closed loop operation of the CSI fed Induction motor the main aim is to keep the flux constant at nominal value irrespective of the changes in the load and frequency. When the operation is constrained to occur at a constant flux, saturation does not occur. The motor will operate at nominal flux if I_m is maintained constant at the nominal value.

Operation at fixed frequency:

From the equivalent circuit of Induction motor the I_m for the rated stator current can be obtained from the expression [14]

$$\bar{I}_m = \left[\frac{\frac{R_r'}{s} + jX_r'}{\left(\frac{R_r'}{s}\right) + j\left(X_r' + X_m\right)} \right] \bar{I}_s \quad \text{or}$$

$$I_m^2 = \left[\frac{\left(\frac{R_r'}{s}\right)^2 + X_r'^2}{\left(\frac{R_r'}{s}\right)^2 + \left(X_r' + X_m\right)^2} \right] I_s^2$$

Using the above expression nominal value of I_m at rated stator current and rated slip is calculated.

Now keeping the I_m constant at nominal value, slip corresponding to different values of I_s is calculated. Since I_d is proportional to I_s corresponding values for the slip vs. I_d are obtained. Slip speed is calculated for the respective slip's' values. A plot of Slip speed vs. the I_d is obtained. Thus constant flux operation can be achieved if I_d is varied according to the slip speed.

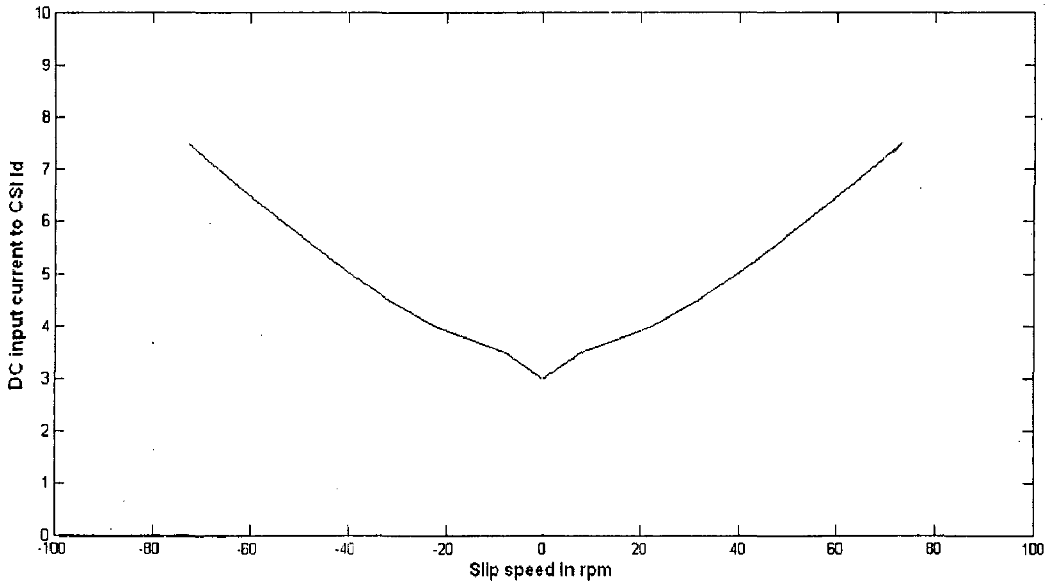


Fig. 5.1 Slip speed vs. I_d current to implement constant flux control

The relation between I_d and I_s for CSI is $m = \frac{I_s}{I_d}$ Therefore for m =1, $I_d = I_s$

The slip regulator regulates the slip speed within this range by limiting the slip speed. The slip limits of the slip regulator are set to higher values than obtained in the graph and the current for those slip speeds is maintained constant at highest rated value i.e 7.5 in above case. This is done so as to increase the effectiveness of the controller. Thus the operation of induction machine at constant flux is achieved.

Operation at and below rated frequency:

In reference [14] it has been proved that the slip speed which provides motor operation at nominal flux at rated frequency also gives operation at nominal flux at all frequencies. Hence, the relationship obtained between I_d and ω_{sl} at rated frequency for the operation at nominal flux is valid for all frequencies.

Operation above the rated frequency:

The motor terminal voltage becomes rated value at rated frequency. At speeds above the base speed, the machine terminal voltage is held constant at the rated value. The operation at the maximum permissible current gives operation at constant maximum power. To get the constant terminal voltage, the machine impedance must be held constant as frequency is increased. This is achieved by increasing the slip speed to compensate for an increase in reactance. To operate the drive up to the rated inverter current, the slip speed limit of the slip speed regulator must increase linearly with frequency. This is achieved by adding to the slip speed regulator output an additional slip speed signal proportional to frequency and of appropriate sign.

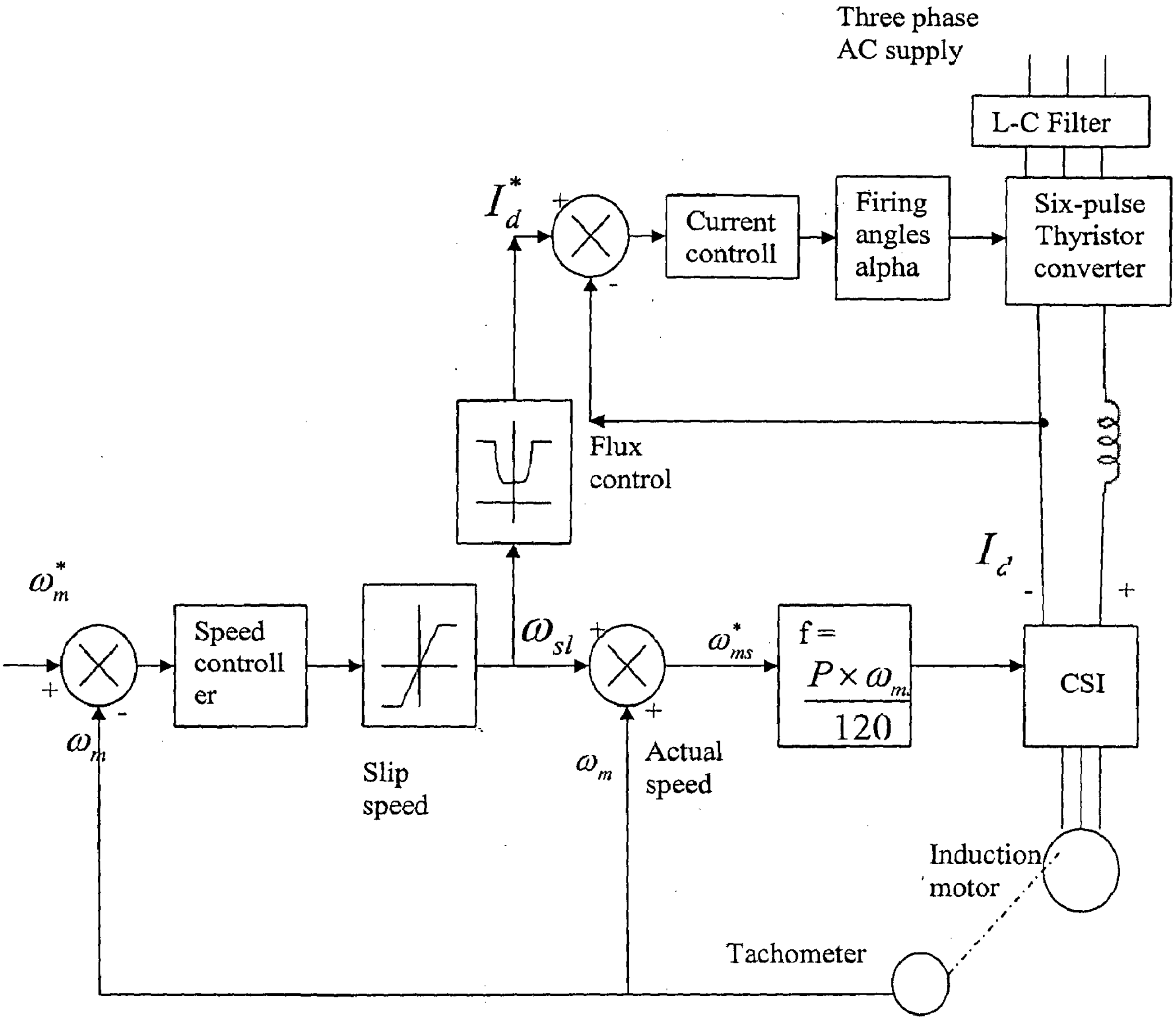


Fig. 5.2 Block diagram of Slip speed control CSI fed Induction motor drive

A closed loop CSI drive is shown in the above circuit diagram. The speed error signal after being processed through the speed controller, is given to the slip speed regulator, which controls slip speed ω_{sl}. The sum of rotor speed ω_m and slip speed ω_{sl} gives synchronous speed, which determines the inverter frequency. Based on the value of the slip speed, the flux controller provides a reference signal I_d^*, to the current controlled current source, which changes its output immediately to I_d so as to maintain constant flux. The speed controller employs a PI controller to get good steady-state accuracy and fast dynamic response.

When the speed error is positive, slip speed is also positive and the drive accelerates under motoring to the required speed. When speed error is negative, slip speed is also negative, giving a synchronous speed less than motor speed. Hence the drive decelerates under braking to the desired speed. The limit imposed on the output of the slip regulator limits the I_d at the inverter rating. Thus, the transient operation of the drive, below base speed, both in motoring and braking, is carried out at the rated inverter current. Since flux is constant, the drive operates at maximum available torque. This results in fast transient operation.

5.3 Simulation of slip speed control in SHE CSI fed Induction motor drive:

The model of slip speed control in SHE CSI fed induction motor drives is simulated in the SIMULINK/MATLAB. The basic diagram is as shown in figure

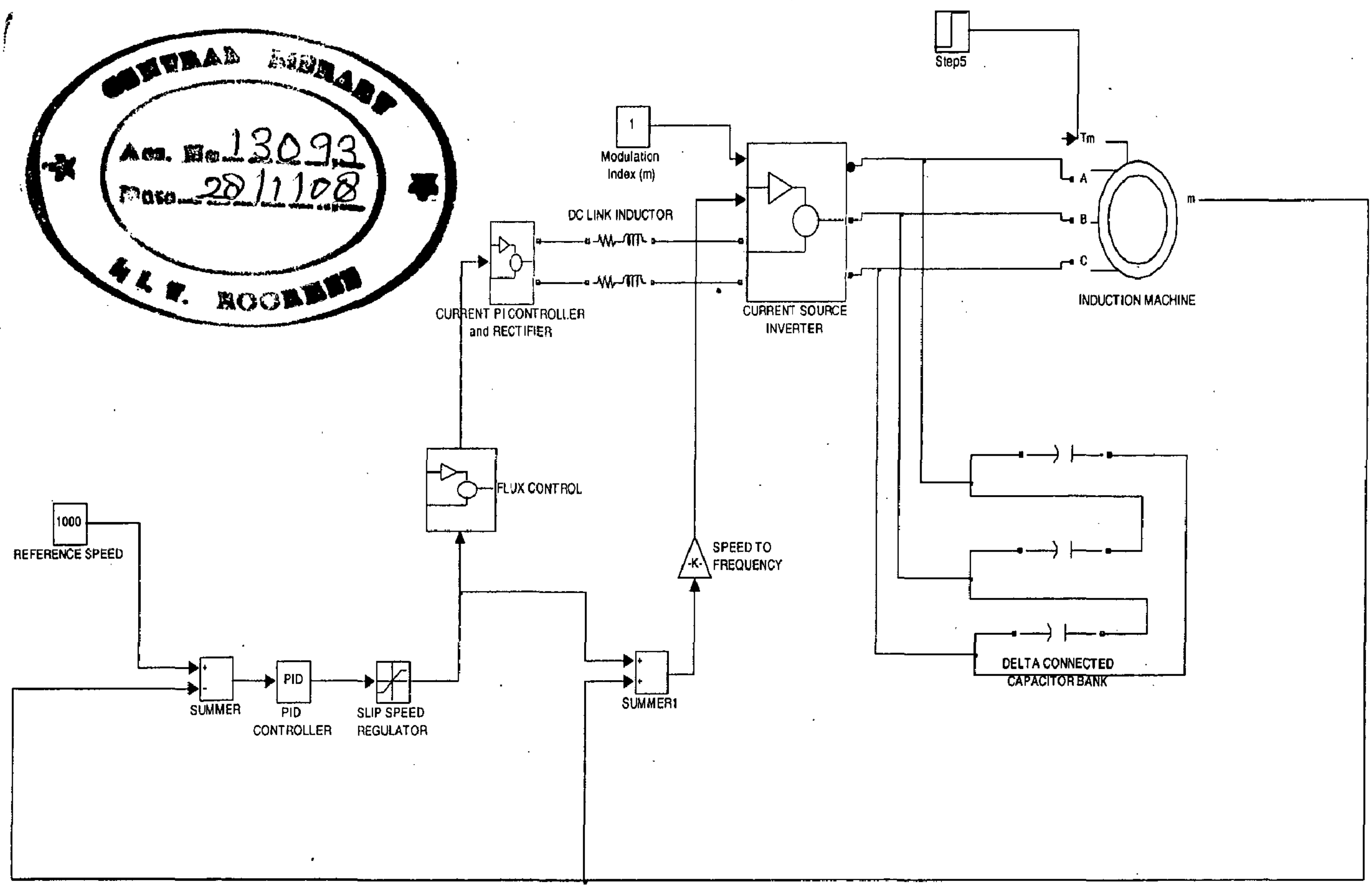


Fig. 5.3 Simulation model of Slip speed control in SHE CSI fed Induction motor

The speed control is implemented using the model shown in figure 5.3. The reference speed is set to 1000 RPM and the waveforms of speed, stator current Ia, torque, capacitor voltage, capacitor current ,line current etc are as shown below.

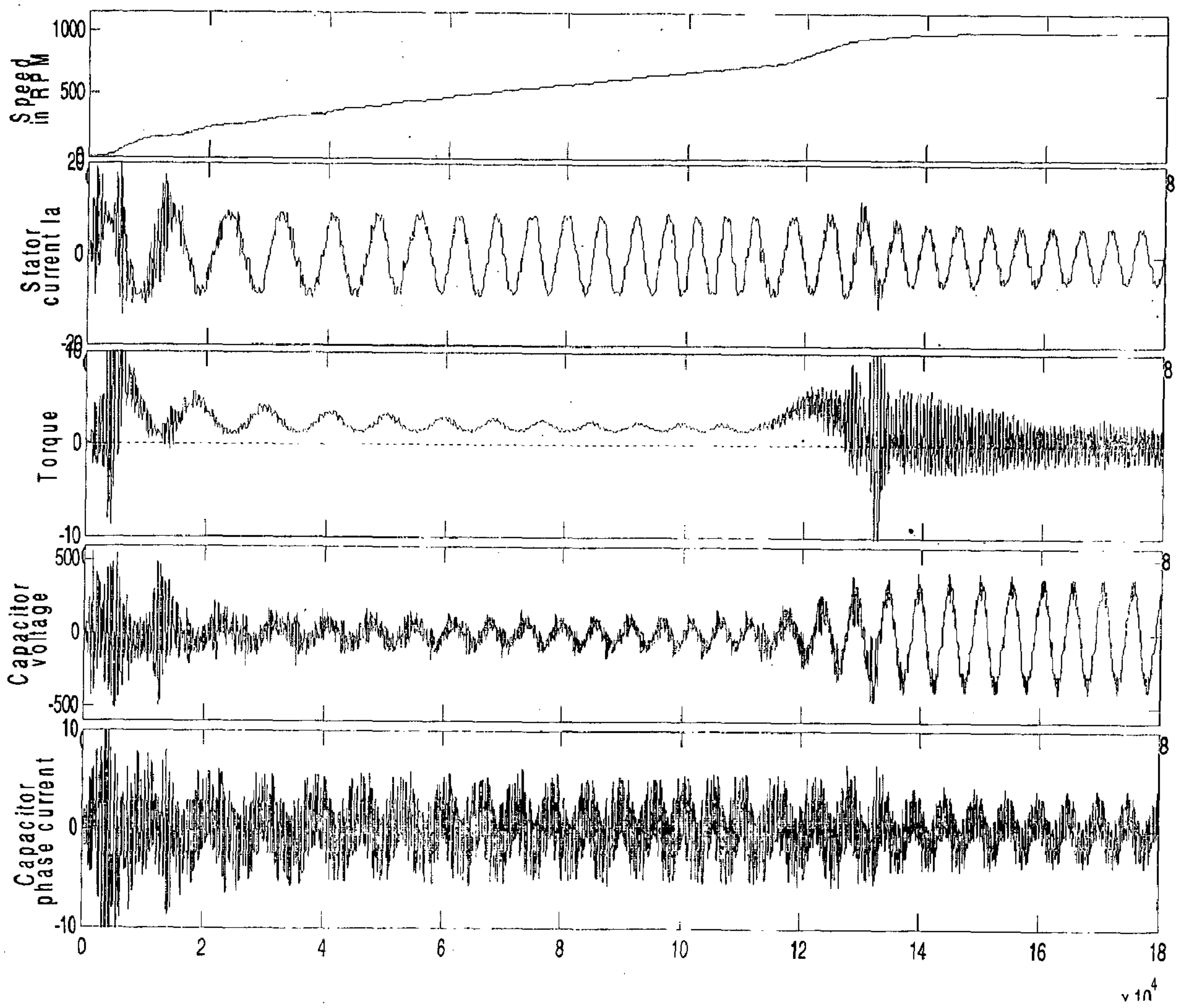


Fig. 5.4 Plot of different parameters of motor and capacitor as speed is set to 1000 RPM

In steady state the output waveforms are as shown in figure 5.5

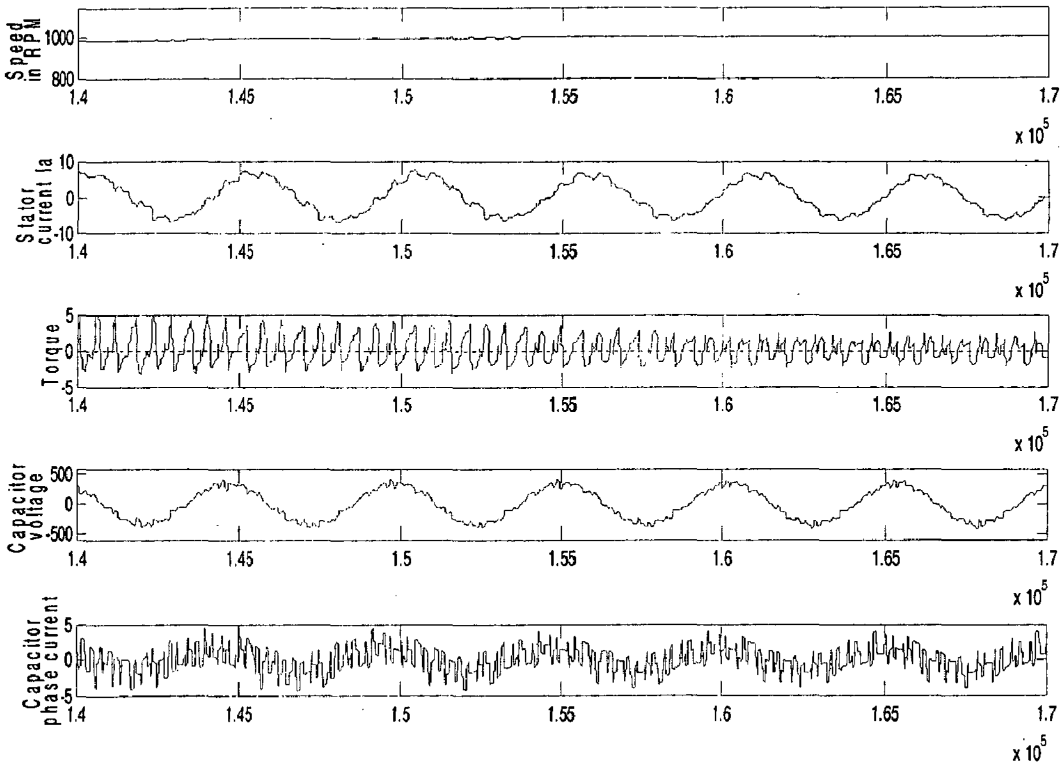


Fig. 5.5 The steady state waveforms of motor and capacitor

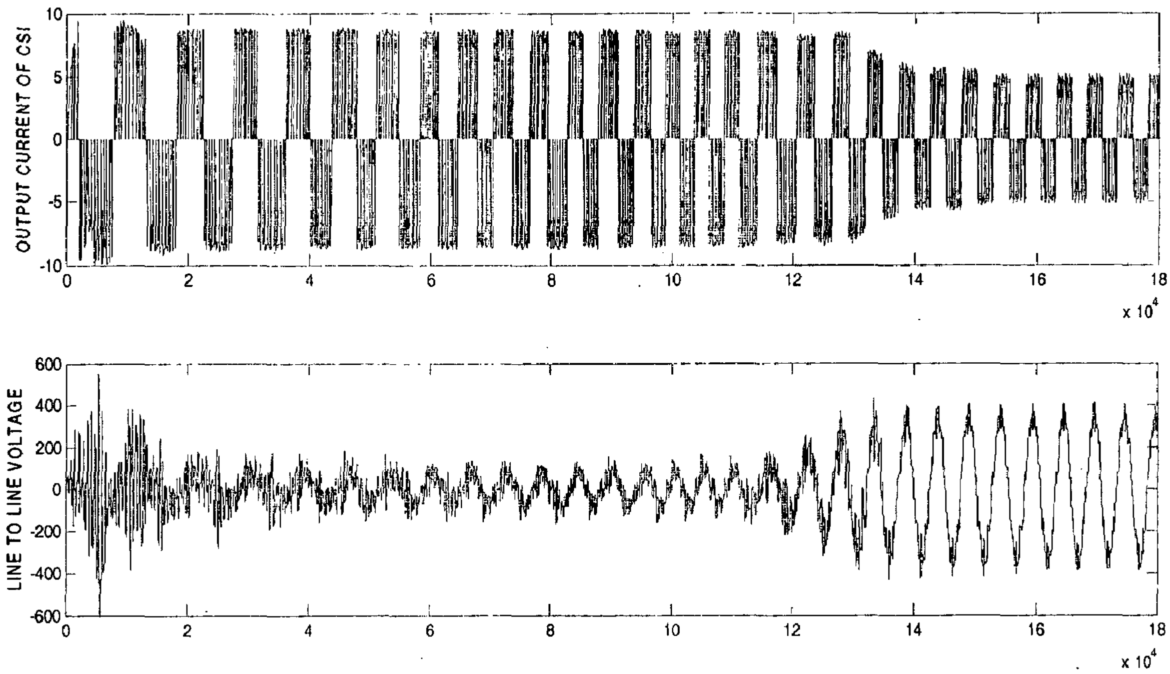


Fig.5.6 Output Voltage and current of CSI

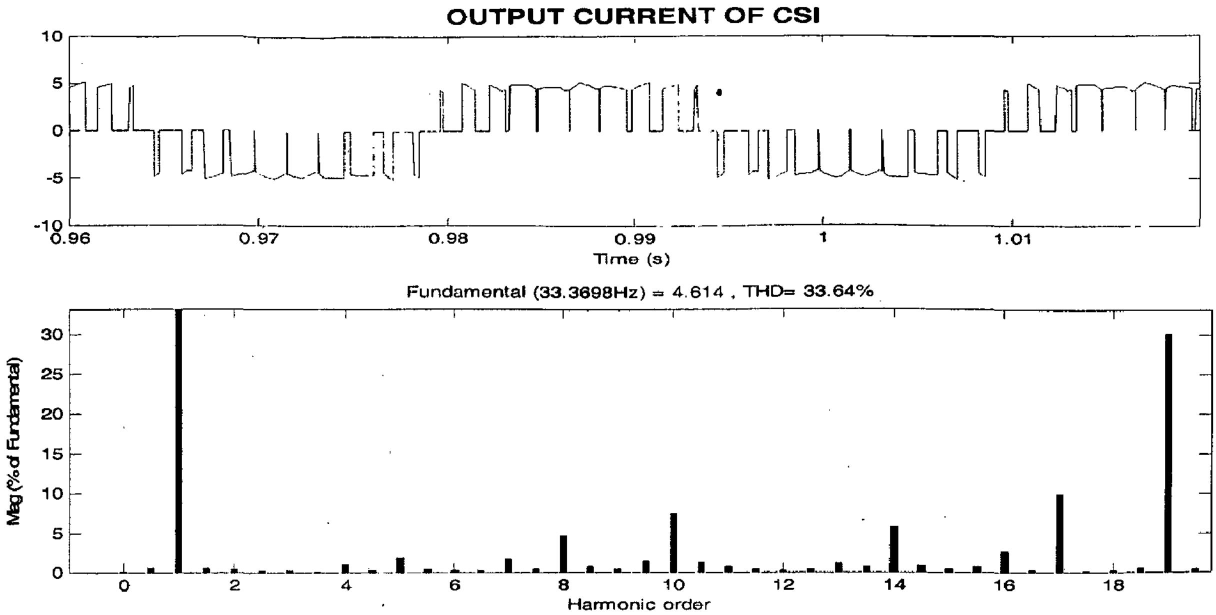


Fig 5.7 Harmonic spectrum of CSI output current

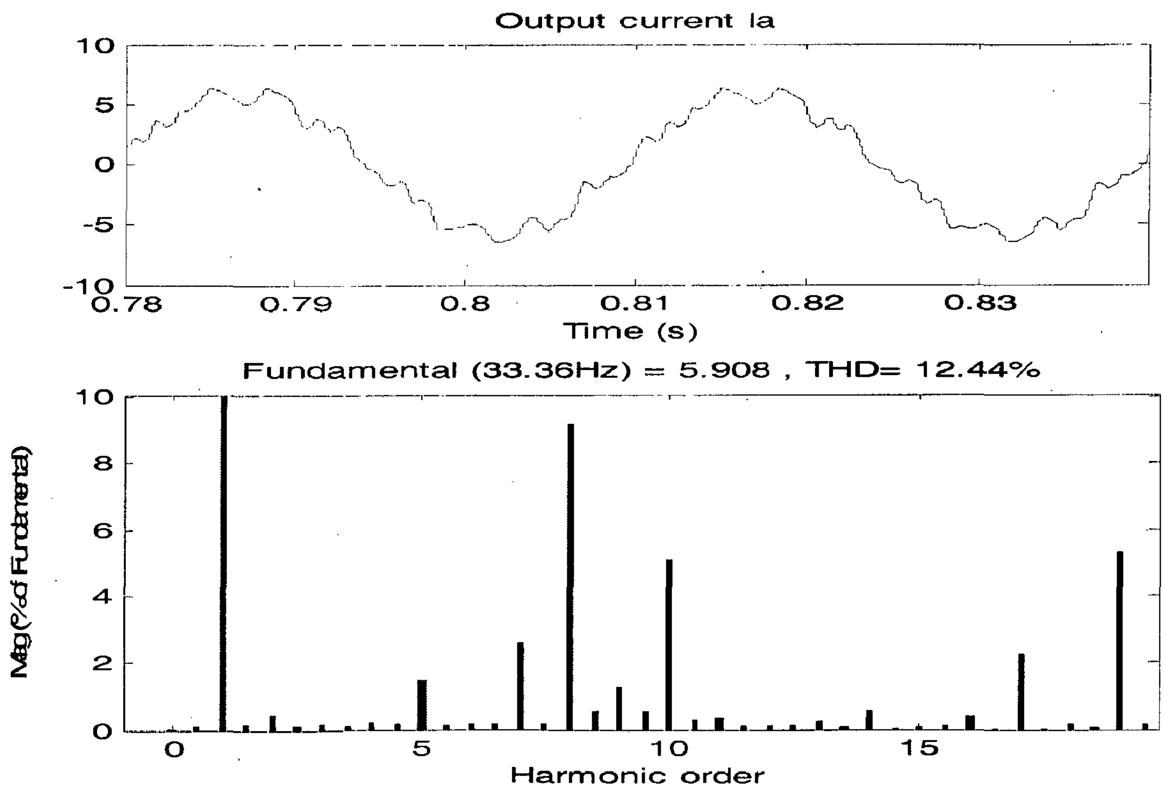


Fig 5.7 Harmonic spectrum of output current I_a

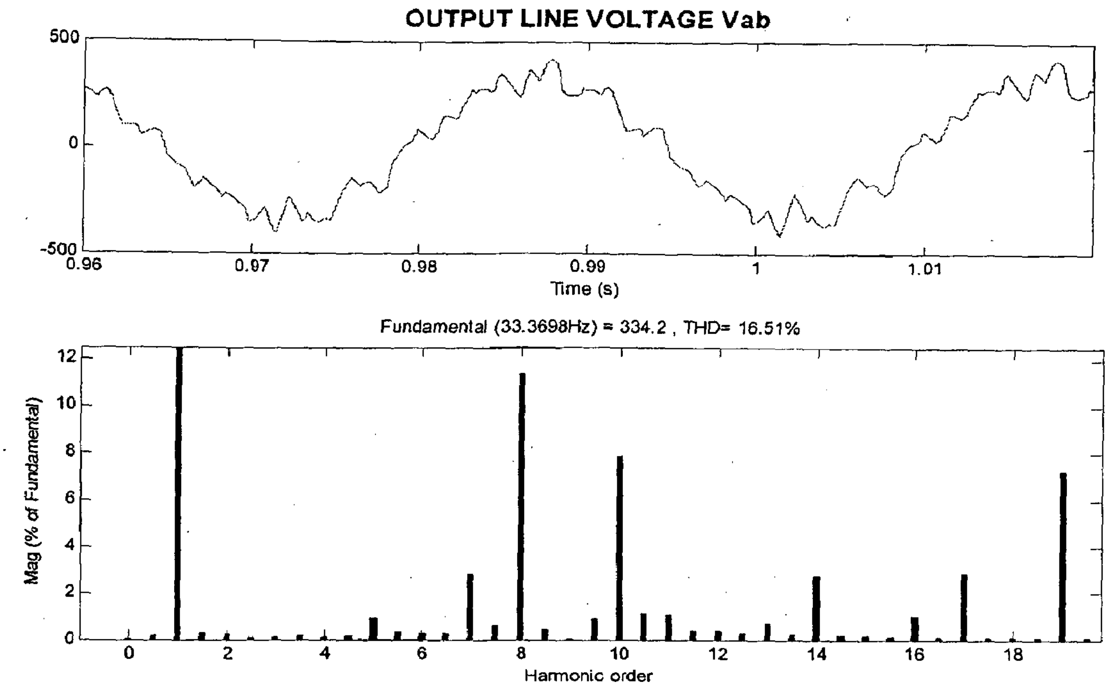


Fig 5.8 Harmonic spectrum of output line to line voltage V_{ab}

Conclusion:

The speed control of induction motor fed with SHE CSI is implemented using the slip speed control method. Various output waveforms of the motor and capacitor are plotted. Harmonic spectrum of the output load current and output line voltage of CSI are studied. From the harmonic spectrum it is studied that 5^{th}, 7th, 11^{th} and 13^{th} harmonics are eliminated but due to temporary presence of even harmonics the THD is very high. The even harmonics are present as there is unbalance in the positive and negative cycle of output waveform. The unbalance is due to the continuous change in the rectifier output current.

CHAPTER 6

CONCLUSION and FUTURE SCOPE:

For high power motors, CSI could be used as a means to provide variable frequency current to induction motor for speed control. The controlled current operation of the inverter protects the power components and machine from over currents. Beside the above mentioned advantages CSI has natural regeneration capability which makes its use more viable for high power motors.

In this dissertation, SHE PWM technique is applied to CSI. A new logic circuit was developed to generate the firing pulses sequences for the CSI to obtain the desired SHE output pattern. The plots of switching angles with the modulation index (m) are obtained using NAG subroutine E04UCF. It is observed that THD of the load current decreases as more number of harmonics is eliminated. From the harmonic spectrum of load current, as the order of the harmonics increases the impedance offered by the inductance of the load is very high and thus it can be concluded that the effect of higher order harmonics is very less.

A model implementing the Slip speed control method using SHE CSI fed Induction motor drive is simulated using the SIMULINK software of MATLAB. Speed control with fast dynamic response is achieved using the Slip speed control method in SHE CSI fed induction motor. In slip speed control method the motor is constrained to operate at constant flux, thus the speed torque characteristics of CSI fed induction motor drive are similar to the VSI fed induction motor drive.

FUTURE SCOPE:

CSI fed induction motor drives has the advantages of inherent regenerative capability, load commutation of thyristors is possible at leading power factors, requires cheap converter grade thyristors, and also it has inherent short circuit protection. Thus the CSI fed induction motor drive may be used in high power application where the short circuit protection is quite essential and where load is of leading power factor nature.

In slip speed control of SHE CSI fed induction machine, the reasons for low accelerating torque development are to be investigated and techniques must be developed so as to improve the torque characteristics of the drive.

One of the novel applications of SHE CSI or rather CSC would be in the wind power generation systems. Induction generator is used in wind power generation which generates power at the variable voltage. Because of the characteristic of CSI of immunity to supply voltage variation, it could be used to convert power from variable voltage AC source to power at fixed AC voltage.

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APPENDIX – I

Program for Switching angles calculation using NAG sub routine E04UCF:

Main Program:

A program for calculating the switching angles to eliminate the 5th, 7th ,11th and 13th harmonics is written in MATLAB m-file editor using the NAG subroutine E04UCF to solve the transcendental equations.

```
i=1;
itr=57;
mam=zeros(1,itr)    %Different variables for plotting
for m=0.0:0.01:1.1  %modulation index varied in steps of 0.01 from 0 to
1

n=5                 %No. of unknown switching angles
nclin=4;            %No. of Linear constraints
ncnln=5;            %No. of non linear constraints
for k=1:nclin       %initiaize the linear constraint coefficents
  for j=1:n
         a(k,j)=0;
  end
end
for k=1:nclin       %Linear constraint on switching angles so that
                     x1<x2<x3<x4<x5
   a(k,k)=-1.0;
   a(k,k+1)=1.0;
end
bl=[0.0 0.001 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0 0 0 0 m]; %lower bounds
bu=[0.186  0.286  0.3736 0.4436 0.5236 0.5236 0.5236 0.5236 0.5236...
   0 0 0 0 m];          % Upper bounds
x=[0.0 0.01 0.2 0.3 0.3]; % initial guess values of x1,x2,x3,x4;x5
confun='thdfunalen5';     %calling subroutine of constraint function
objfun='thdfunaen5';      %calling subroutine of objective function
string = ' Infinite Bound Size = 1.0e25 ';
e04uef(string);
string = ' Print Level = 1 ';
e04uef(string);
string = ' Verify Level =-1 ';
e04uef(string);
string = ' Major Iteration Limit = 15 ';
e04uef(string);
string = ' Minor Iteration Limit = 20 ';
e04uef(string);                 % initialization for calling E04UCF
subroutine
```

```
[iter,c,objf,objgrd,x,cjac,istate,clamda,r,ifail] =
e04ucf(bl,bu,confun,...
 objfun,x,ncnln,a);           %calling the nag subroutine E04UCF

  if(ifail~=3 && ifail~=1)  %eliminating cases which not satisfy
constraints
ma=c(5);
mam(i)=ma;
x=x*(180/pi)                  %converting from radians to degrees
x1(i)=x(1);x2(i)=x(2);x3(i)=x(3);x4(i)=x(4);x5(i)=x(5);
thd(i)=objf;                  %storing for plotting the waveforms
i=i+1;
   end


end
itr=itr
i=i
x1=x1(1:itr)
x2=x2(1:itr)
x3=x3(1:itr)
x4=x4(1:itr)
x5=x5(1:itr)
mam=mam(1:itr)
thd=thd(1:itr)


plot(mam,x1)     %plot the switching angles vs modulation index
hold on
plot(mam,x2)
hold on
plot(mam,x3)
hold on
plot(mam,x4)
hold on
plot(mam,x5)
hold off
```

Constraint function subroutine:

```
function [mode,c,cjac] =
thdfunalen5(mode,ncnln,n,nrowj,needc,x,c,cjac,nstate) %constraint
function subroutine with input and output arguments
 if nstate==1
  cjac=zeros(ncnln,n);      %initializing the jacobian matrix of
constraints
 end
```

```
   if needc(1)>0
     if mode == 0 | mode ==2
   c(1)= ((25.5/5)*(cos(5*x(1))-cos(5*x(2))+cos(5*x(4))-cos(5*x(5)) ...
          +cos(5*(1.05-x(4)))-cos(5*(1.05-x(3)))+cos(5*(1.05-x(1)))...
          -cos(5*(1.05+x(2)))+cos(5*(1.05+x(3)))-cos(5*(1.05+x(5)))));;
     end                        %constraint for eliminating 5th harmonic
end
if mode==1 | mode==2
   cjac(1,1) = (25.5)*(-1)*(sin(5*x(1))-sin(5*(1.05-x(1))));
   cjac(1,2) = (25.5)*(sin(5*x(2))+sin(5*(1.05+x(2))));
   cjac(1,3) = (25.5)*(-1)*(sin(5*(1.05-x(3)))+sin(5*(1.05+x(3))));
   cjac(1,4) = (25.5)*(-1)*(sin(5*x(4))-sin(5*(1.05-x(4))));
   cjac(1,5) = (25.5)*(sin(5*x(5))+sin(5*(1.05+x(5))));
end


 if needc(2)>0
     if mode == 0 | mode ==2
   c(2)= ((25.5/7)*(cos(7*x(1))-cos(7*x(2))+cos(7*x(4))-cos(7*x(5)) ...
          +cos(7*(1.05-x(4)))-cos(7*(1.05-x(3)))+cos(7*(1.05-x(1)))...
          -cos(7*(1.05+x(2)))+cos(7*(1.05+x(3)))-cos(7*(1.05+x(5)))));;
     end
 end                             %constraint for eliminating 7th harmonic
if mode==1 | mode==2
   cjac(2,1) = (25.5)*(-1)*(sin(7*x(1))-sin(7*(1.05-x(1))));
   cjac(2,2) = (25.5)*(sin(7*x(2))+sin(7*(1.05+x(2))));
   cjac(2,3) = (25.5)*(-1)*(sin(7*(1.05-x(3)))+sin(7*(1.05+x(3))));
   cjac(2,4) = (25.5)*(-1)*(sin(7*x(4))-sin(7*(1.05-x(4))));
   cjac(2,5) = (25.5)*(sin(7*x(5))+sin(7*(1.05+x(5))));
end

 if needc(3)>0
     if mode == 0 | mode ==2
   c(3)= ((25.5/11)*(cos(11*x(1))-cos(11*x(2))+cos(11*x(4))-cos(11*x(5))
...
          +cos(11*(1.05-x(4)))-cos(11*(1.05-x(3)))+cos(11*(1.05-x(1)))...
          -cos(11*(1.05+x(2)))+cos(11*(1.05+x(3)))-
cos(11*(1.05+x(5)))));;
     end                        %constraint for eliminating 11th harmonic
end
if mode==1 | mode==2
   cjac(3,1) = (25.5)*(-1)*(sin(11*x(1))-sin(11*(1.05-x(1))));
   cjac(3,2) = (25.5)*(sin(11*x(2))+sin(11*(1.05+x(2))));
   cjac(3,3) = (25.5)*(-1)*(sin(11*(1.05-x(3)))+sin(11*(1.05+x(3))));
   cjac(3,4) = (25.5)*(-1)*(sin(11*x(4))-sin(11*(1.05-x(4))));
   cjac(3,5) = (25.5)*(sin(11*x(5))+sin(11*(1.05+x(5))));
end

 if needc(4)>0
     if mode == 0 | mode ==2
   c(4)= ((25.5/13)*(cos(13*x(1))-cos(13*x(2))+cos(13*x(4))-cos(13*x(5))
...
          +cos(13*(1.05-x(4)))-cos(13*(1.05-x(3)))+cos(13*(1.05-x(1)))...
          -cos(13*(1.05+x(2)))+cos(13*(1.05+x(3)))-
cos(13*(1.05+x(5)))));;
```

```
    end
 end                            %constraint for eliminating 13th harmonic
if mode==1 | mode==2
  cjac(4,1) = (25.5)*(-1)*(sin(13*x(1))-sin(13*(1.05-x(1))));
  cjac(4,2) = (25.5)*(sin(13*x(2))+sin(13*(1.05+x(2))));
  cjac(4,3) = (25.5)*(-1)*(sin(13*(1.05-x(3)))+sin(13*(1.05+x(3))));
  cjac(4,4) = (25.5)*(-1)*(sin(13*x(4))-sin(13*(1.05-x(4))));
  cjac(4,5) = (25.5)*(sin(13*x(5))+sin(13*(1.05+x(5))));
end
if needc(5)>0          %constraint for fundamental magnitude control i.e
                         fundamental =m
    if mode == 0 | mode ==2
  c(5)= ((4/3.14)*(cos(x(1))-cos(x(2))+cos(x(4))-cos(x(5)) ...
        +cos((1.05-x(4)))-cos((1.05-x(3)))+cos((1.05-x(1)))...
        -cos((1.05+x(2)))+cos((1.05+x(3)))-cos((1.05+x(5)))));;
    end
end
if mode==1 | mode==2
  cjac(5,1) = (4/3.14)*(-1)*(sin(x(1))-sin(1.05-x(1)));
  cjac(5,2) = (4/3.14)*(sin(x(2))+sin(1.05+x(2)));
  cjac(5,3) = (4/3.14)*(-1)*(sin(1.05-x(3))+sin(1.05+x(3)));
  cjac(5,4) = (4/3.14)*(-1)*(sin(x(4))-sin(1.05-x(4)));
  cjac(5,5) = (4/3.14)*(sin(x(5))+sin(1.05+x(5)));
end
```

Objective function subroutine:

```
function [mode,objf,objgrd] = thdfunaen5(mode,n,x,objf,objgrd,nstate)
Idc = 20;
for i = 1:2:(5*n)
    I(i) = (Idc) * (4/(i*(3.14))) * ((cos(i*x(1))-
cos(i*x(2))+cos(i*x(4))-cos(i*x(5)) ...
        +cos(i*(1.05-x(4)))-cos(i*(1.05-x(3)))+cos(i*(1.05-x(1)))...
        -cos(i*(1.05+x(2)))+cos(i*(1.05+x(3)))-cos(i*(1.05+x(5)))));
end              %Calculating all the harmonic components

  temp = 0;

        for j = 3:2:(5*n)
        temp =  temp + (I(j))^2;
        end
        temp = sqrt(temp);
        objf = 100*temp/(I(1)); %calculating THD
```

APPENDIX –II

Specifications of the system elements

1. Induction motor specifications

Voltage	:	400
Connection	:	Star
Power	:	4 K.W
Phase	:	3
Current	:	7.2A
Frequency	:	50 Hz
R.P.M	:	1430

2. Capacitor bank specifications

Connection	:	Delta
Capacitance	:	10 μf