A

Project Report

On

Selective Harmonic Elimination in a Three Phase Voltage/Current Source Inverter

DEPARTMENT OF ELECTRICAL ENGINEERING

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ABSTRACT

The prime domain of focus of this study is selective harmonic elimination (SHE) using pulse width modulation technique, SHE PWM. An attempt has been made to control single-phase and three-phase inverter's outputs with their corresponding loads, observe their results and estimate how far these methods can be implemented practically, and to observe the changes in Total Harmonic Distortion of current and voltage waveform as the conditions vary.This study enables us to calculate switching angles for any number (even or odd) of harmonics, elimination of which results in improvement of performance and detailed explanation has been given as to how these switching angles can eliminate the selected harmonics. With the proposed approach, along with eliminating the selected harmonic component the magnitude of the fundamental component is also controlled to the desired value.

Firing angles are evaluated for different cases and are implemented in that case and analysis of each case is presented.A system to control the speed of 3-phase Induction Motor by V/F control method using Pulse Width Modulation technique by eliminating the selected harmonics has also been designed. Voltage is controlled by changing Modulation Index. To maintain constant V/F ratio, frequency is varied proportionally with voltage. The above mentioned tasks are performed in MATLAB's Simulink. Results are studied and compared for various modulation indices.

INTRODUCTION

Motivation

An inverter is a power electronic device that changes direct current (DC) to alternating current (AC). Inverters are used in a variety of applications:

- As UPS-Uninterruptible power supplies.
- In solar power systems.
- Control of AC electric drives.
- For HVDC transmission. Power generated in AC is converted to DC using rectifier.

Applications of inverter are more likely to increase in future, as they are about to spread into daily household applications also.

Harmonics

The presence of harmonics in a network results in distortion of current and voltage and deviation from sinusoidal waveforms. Power electronic devices have become abundant today because of their precise process control and energy savings benefits. However, they also bring drawbacks to electrical distribution systems: harmonics.

Harmonic currents caused by nonlinear loads connected to the distribution system are flowing through the system impedances, and in turn distorts the supply voltage. Such loads are increasingly more abundant in all industrial, commercial, and residential installations and their percentage of the total load is growing steadily.

Harmonic currents increase the r.m.s. current in electrical systems and deteriorate the supply voltage quality. They stress the electrical network and potentially damage equipment. They may disrupt normal operation of devices and increase operating costs. They result in overheating of transformers, motors and cables, thermal tripping of protective devices and logic faults of digital devices. In addition, the life span of many devices is reduced by resulting elevated operating temperatures.

Capacitors are especially sensitive to harmonic components of the supply voltage as capacitive reactance decreases as the frequency increases. As a result, a relatively small percentage of harmonic voltage can cause a significant current to flow in the capacitor circuit.

Objective

The main objective of this thesis is to reduce the harmonic content in Voltage and Current Source Inverters by eliminating the selected harmonics by using Selective Harmonic Elimination with Pulse Width Modulation technique. Selective Harmonic Elimination can be done by giving firing angles in certain pattern. This pattern of gating pulses for certain conditions is determined by using Numerical Iterative Methods.

Besides eliminating selected harmonic component, Fundamental component magnitude is also controlled by using the proposed technique. The firing angle patterns for the different conditions are determined and are implemented and results are analyzed to estimate how far these methods can successfully be implemented practically, and to observe the changes in Total Harmonic Distortion and harmonic component in Voltage and Current Waveform as Modulation Index varies.

Organization of the Project

Detailed explanation has been presented in the next sections about the formation of harmonic components and their elimination using firing angle patterns for every individual case. Newton Raphson Method also explained in detail which is used in finding of switching angles by iterative methods.

This Project is divided into five use cases:

(i) Single Phase Voltage Source Inverter with series RL Load.

(ii) Single Phase Current Source Inverter with parallel RC Load.

(iii) Three Phase Voltage Source Inverter with series RL Load.

(iv) Three Phase Current Source Inverter with parallel RC Load.

(v) Speed Control of Three Phase Induction Motor with V/F Method.

FORMULATION OF THE SHE PROBLEM

Let us assume the following nomenclature for the switches.

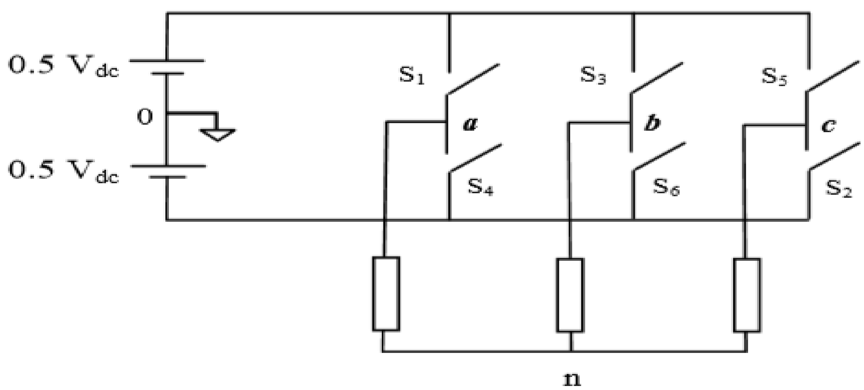

Fig. 1: Power circuit of a three-phase VSI.

Under the SHE switching technique, the normalized phase voltage Va0 with respect to the fictitious dc center tap has a generalized waveform, as shown in Fig. 2 The output voltage is assumed to have nine pulses per half-cycle, with symmetrical switching angles around π /2. In VSI care must be taken while giving the firing angles to the switches, the switches S1 and S4, S3 and S6, S5 and S2 shouldn't be simultaneously triggered.

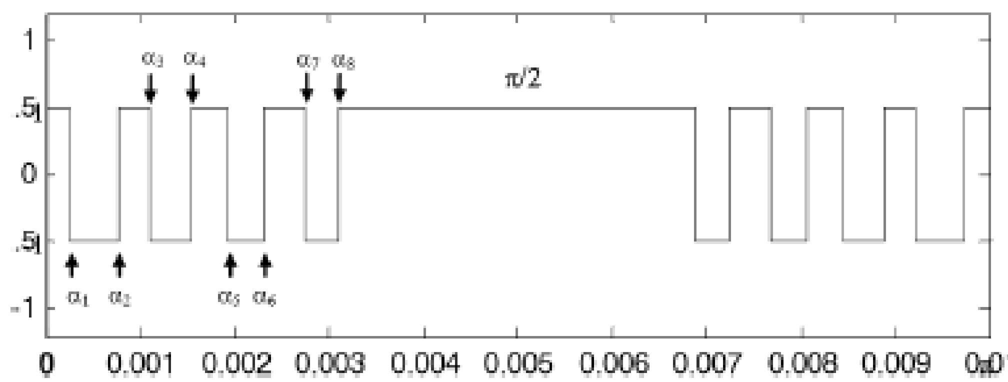

Fig. 2: Normalized inverter output voltage Va0.

The waveform has quarter wave symmetry. The general formula of Fourier series of above waveform gives

$$b_k = \frac{4}{T}\int_0^{T/2} f(t)\sin(k\omega t)\,dt$$

$$a_k = \frac{4}{T}\int_0^{T/2} f(t)\cos(k\omega t)\,dt$$

Here T =π

As the wave has quarter wave symmetry it contains only odd terms, therefore

$$a_k = 0,$$

The normalized voltage Va0 can be expressed as a Fourier series by

$$V_{ao} = \sum_{n=1}^{\infty} (B_n \sin(\text{nwt}))$$

The Fourier coefficients of the Va0 are computed by the following equation:

$$B_n = \frac{4}{n\pi}\left[1 + 2\sum_{i=1}^{k}(-1)^i \cos(n\alpha_i)\right]$$

If the waveform contains (*K*+1) pulses per half cycle, (*K*) harmonics can be controlled.

In this case, study *K* is equal to 8, where n has only odd values. For *K* = 8, Eq. (1.26) has 8 variables (α_1 to α_8).As the 3rd harmonic and other triple-n harmonics do not exist when the neutral point is isolated, *n* takes the odd values 5, 7, 11, 13, 17, 19, and 23.Thus, the following equations should be solved simultaneously to obtain the proper switching angles.To control the magnitude of 1st harmonic ($M \in [0, 0.9]$ is the Modulation Index):

$$\frac{4}{\pi}\left[1 + 2\sum_{i=1}^{8}(-1)^i \cos(\alpha_i)\right] - M = 0$$

To eliminate the undesired low-order odd harmonics:

$$\frac{4}{n\pi}\left[1 + 2\sum_{i=1}^{8}(-1)^i \cos(n\alpha_i)\right] = 0$$

To solve these switching angles, the **Newton Raphson** method is applied and the followingmatrices (for a sample of five harmonics elimination) are implemented

1)The switching angle matrix,

$$\alpha^j = [\alpha_1{}^j, \alpha_2{}^j, \alpha_3{}^j, \alpha_4{}^j, \alpha_5{}^j]^T$$

2) Calculate the value of $\boldsymbol{F^j}$ $\boldsymbol{F^j} = \boldsymbol{F}(\boldsymbol{\alpha^j})$

$$F^j = \begin{bmatrix} \cos(\alpha_1{}^j) - \cos(\alpha_2{}^j) + \cos(\alpha_3{}^j) - \cos(\alpha_4{}^j) + \cos(\alpha_5{}^j) \\ \cos(3\alpha_1{}^j) - \cos(3\alpha_2{}^j) + \cos(3\alpha_3{}^j) - \cos(3\alpha_4{}^j) + \cos(3\alpha_5{}^j) \\ \cos(5\alpha_1{}^j) - \cos(5\alpha_2{}^j) + \cos(5\alpha_3{}^j) - \cos(5\alpha_4{}^j) + \cos(5\alpha_5{}^j) \\ \cos(7\alpha_1{}^j) - \cos(7\alpha_2{}^j) + \cos(7\alpha_3{}^j) - \cos(7\alpha_4{}^j) + \cos(7\alpha_5{}^j) \\ \cos(9\alpha_1{}^j) - \cos(9\alpha_2{}^j) + \cos(9\alpha_3{}^j) - \cos(9\alpha_4{}^j) + \cos(9\alpha_5{}^j) \end{bmatrix}$$

3) 4) **J** is the Jacobian matrix. The partial derivative of the above matrix results in,

$$\boldsymbol{J^j} = \begin{bmatrix} -\sin(\alpha_1{}^j) & +\sin(\alpha_2{}^j) & -\sin(\alpha_3{}^j) & +\sin(\alpha_4{}^j) & -\sin(\alpha_5{}^j) \\ -3\sin(3\alpha_1{}^j) & +3\sin(3\alpha_2{}^j) & -3\sin(3\alpha_3{}^j) & +3\sin(3\alpha_4{}^j) & -3\sin(3\alpha_5{}^j) \\ -5\sin(5\alpha_1{}^j) & +5\sin(5\alpha_2{}^j) & -5\sin(5\alpha_3{}^j) & +5\sin(5\alpha_4{}^j) & -5\sin(5\alpha_5{}^j) \\ -7\sin(7\alpha_1{}^j) & +7\sin(7\alpha_2{}^j) & -7\sin(7\alpha_3{}^j) & +7\sin(7\alpha_4{}^j) & -7\sin(7\alpha_5{}^j) \\ -9\sin(9\alpha_1{}^j) & +9\sin(9\alpha_2{}^j) & -9\sin(9\alpha_3{}^j) & +9\sin(9\alpha_4{}^j) & -9\sin(9\alpha_5{}^j) \end{bmatrix}$$

4) The corresponding harmonic amplitude matrix,

$$T = \begin{bmatrix} \frac{(0.85)\pi}{4} & 0 & 0 & 0 & 0 \end{bmatrix}^T$$

5) Error in firing angles can be calculated as,

$$\boldsymbol{F^j} + \boldsymbol{J^j} \times \boldsymbol{d\alpha^j} = \boldsymbol{T}$$

$$\boldsymbol{d\alpha^j} = [\boldsymbol{J^j}]^{-1} \times (\boldsymbol{T} - \boldsymbol{F^j})$$

$$\mathbf{d}\boldsymbol{\alpha^j} = [\boldsymbol{d\alpha_1}^{\mathbf{j}}\ \mathbf{d}\boldsymbol{\alpha_2}^{\mathbf{j}} \boldsymbol{d\alpha_3}^{\mathbf{j}}\ \boldsymbol{d\alpha_4}^{\mathbf{j}}\ \ \boldsymbol{d\alpha_5}^{\mathbf{j}}]^{\mathbf{T}}$$

$$\alpha^{j+1} = \alpha^j + d\alpha^j$$

6) Repeat the above process until the required convergence criteria is achieved.

These iterations were done using a MTALB program where the tolerance value was. These values were then given to the simulation diagram to fire the switches (as gate pulses). The FFT(Fast Fourier Transform) analysis was done to find out the magnitudes of the harmonics.

Such iterations were also done for CSI with suitable adjustments.

CASE STUDIES WITH SIMULATION RESULTS

Simulation-1: Simulation of Single Phase VSI for Series RL Load

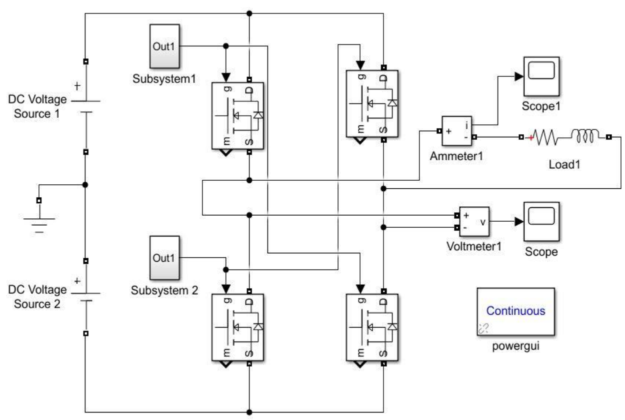

Fig. 3: Block diagram of Single Phase VSI for Series RL Load with PWM Technique

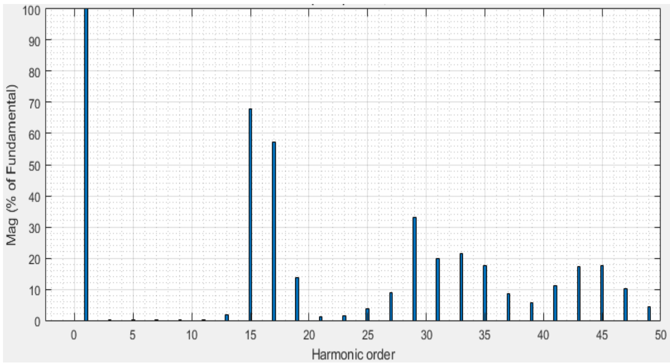

Fig. 4: FFT Analysis of Voltage Waveform for MI=0.9

We see that from the above FFT analysis we have eliminated upto 13th Harmonics of voltage completely.

Simulation-2: Simulation of Single Phase CSI for Parallel RC Load

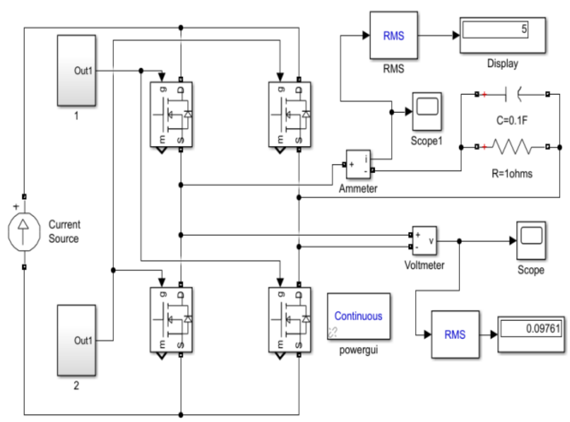

Fig. 5: Block diagram of Single Phase CSI for Parallel RC Load with PWM Technique

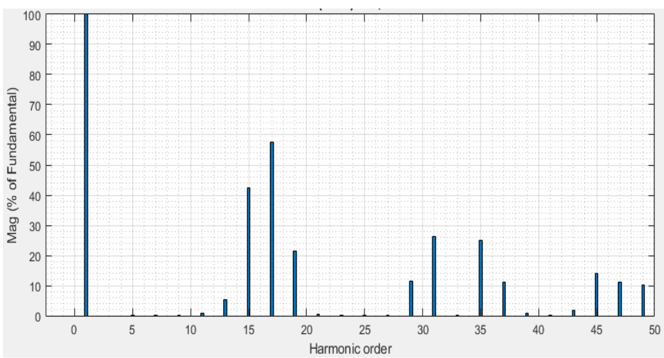

Fig. 6: FFT Analysis of Current Waveform for MI=1

We see that from the above FFT analysis we have eliminated upto 13th Harmonics of current completely.

Simulation-3: Simulation of Three Phase VSI for Series RL Load

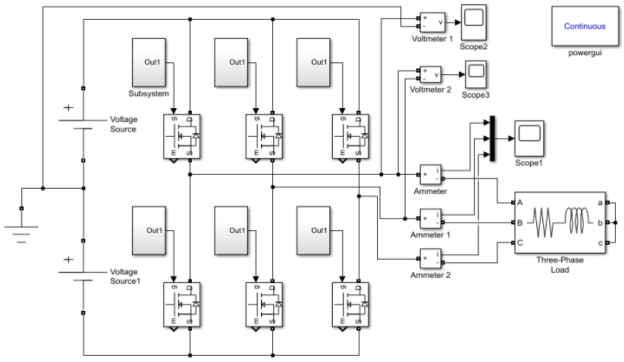

Fig. 7: Block diagram of Three Phase VSI for series RL Load with PWM Technique

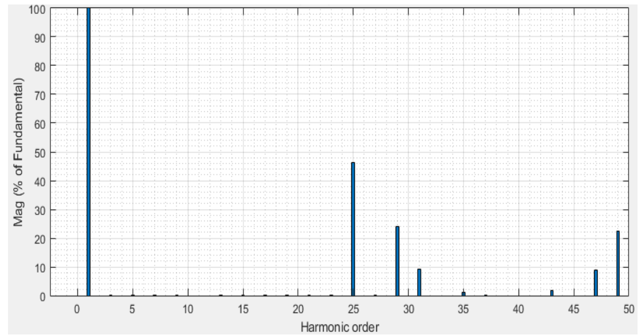

Fig. 8: FFT Analysis of Line Voltage Waveform for MI=0.9

We see that from the above FFT analysis we have eliminated upto 23rd Harmonics of voltage completely.

Simulation-4: Simulation of Three Phase CSI for Parallel RC Load

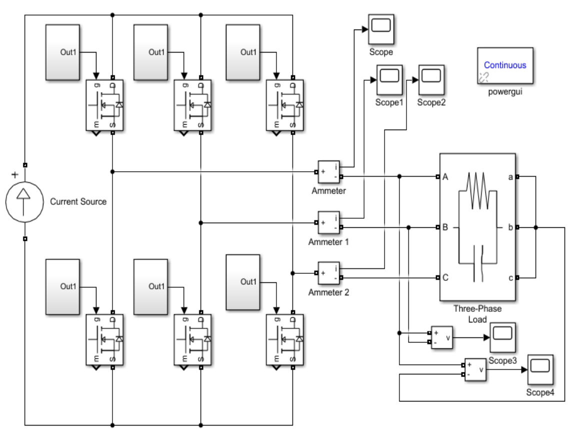

Fig. 9: Block diagram of Three Phase CSI for Parallel RC Load with PWM Technique

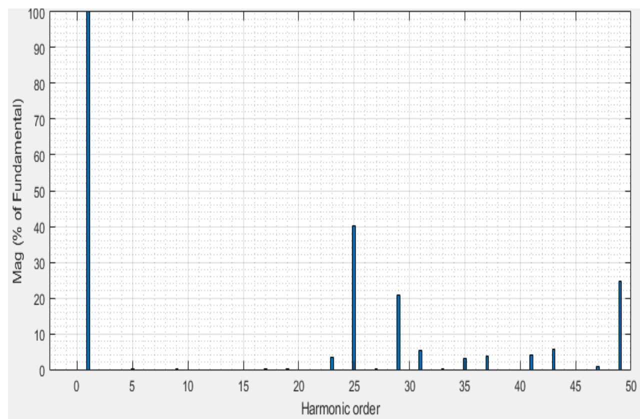

Fig. 10: FFT Analysis of Current Waveform for MI=0.9

We see that from the above FFT analysis we have eliminated upto 23rd Harmonics of current completely.

Simulation-5: Simulation on Speed Control Of Three Phase Induction Motors

The V/F control technique is used to control the speed of Induction Motor to maintain magnetic flux constant in the motor. If only Voltage is reduced to reduce the speed then current flowing in windings increases which will overheat the machine. If frequency is reduced to reduce the speed then flux increases which leads to core saturation, and if frequency is increased to increase the speed then maximum torque value decreases. To avoid these drawbacks V/f control technique is used.

In our approach we tune the value of the Modulation Index so that we can get appropriate values of voltage. For factor of change in voltage we are supposed to change the frequency by the same factor to maintain V/f ratio constant. To do so we are supposed to change the time period(T) by the same factor. This is how we get different values of speed.

The following approach shows the results for the speed control of the motor with MI=0.9

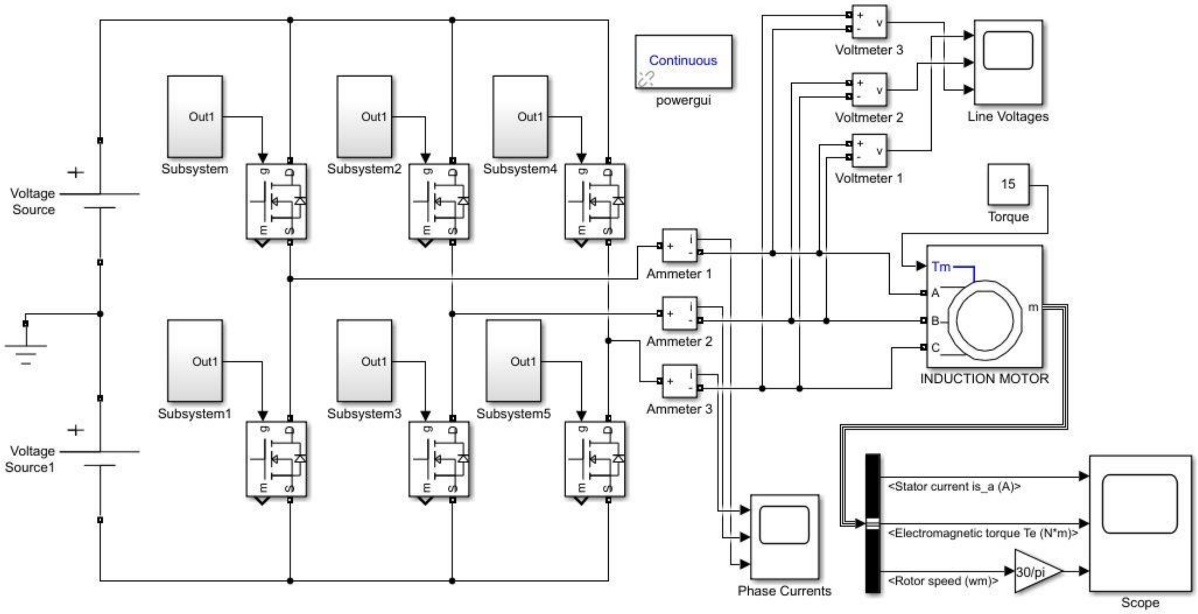

Fig 11: Block diagram of Induction Motor fed by Three Phase VSI with PWM Technique

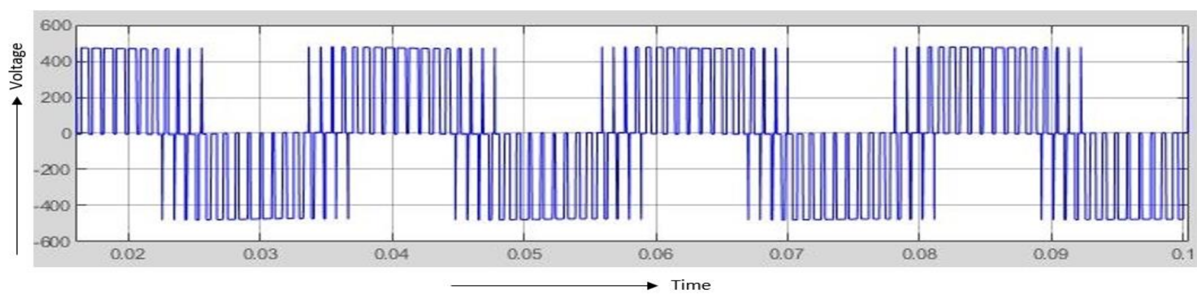

Fig 12: Waveform of Line voltage

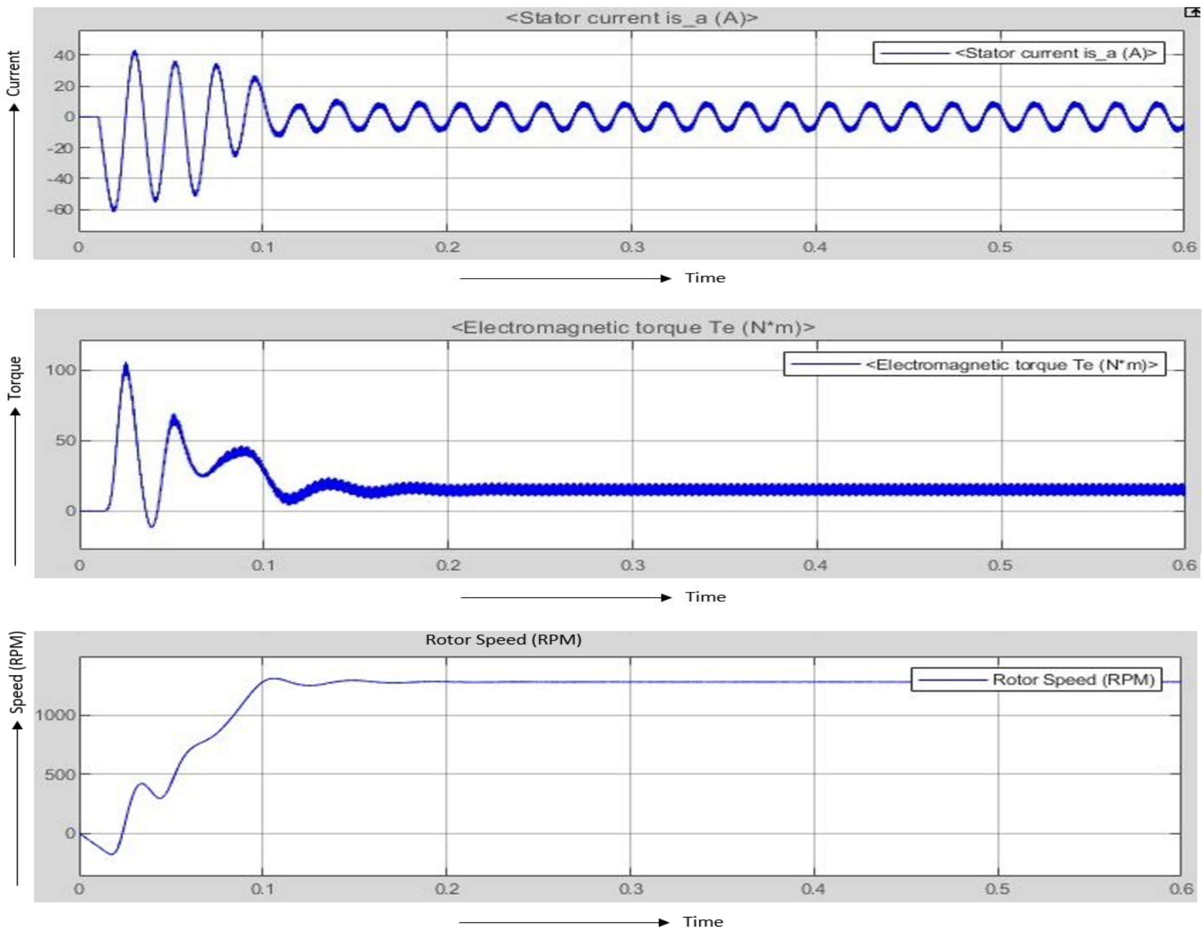

Fig. 2.1: Stator Current, Rotor Speed, and Torque Waveforms

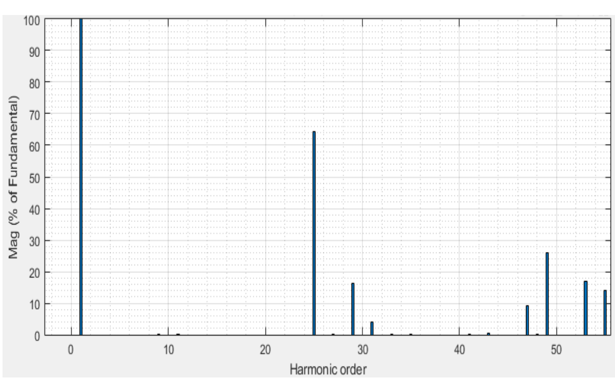

Fig 6: Voltage Waveform's FFT Analysis at **MI=0.9** – Bar Graph (relative to fundamental)

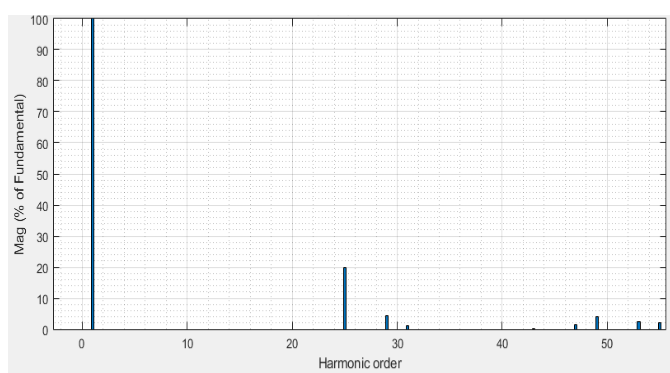

Fig 7: Current Waveform's FFT Analysis at **MI=0.9** – Bar Graph (relative to fundamental)

CONCLUSION

The switching angles are obtained from Newton Raphson Method. Thus, 5th, 7th, 11th, 13th, 17th, 19th, and 23rd harmonics are eliminated and 25th harmonic is present which can be eliminated by using filters. The FFT analysis for each use case in obtained. The harmonic spectra of the line-line voltage and current are also illustrated. The results of the simulation demonstratethat the method is efficient in removing the undesired low-order harmonics, and controlling fundamental voltage at the same time. Thus, the above simulation results verify the efficiency of Selected Harmonic Elimination for three phase as well as single phase inverter action and this approach for generating PWM patterns for CSI features, unconstrained SHE and fundamental current control. This approach uses the chopping angles obtained for VSI in combination with a logic circuit to generate the gating patterns for CSI. The circuit also generates and includes naturally and symmetrically distributed shorting pulses. Thus, the approach avoids the hassle of positioning the shorting pulses and defining and solving a set of nonlinear equations dedicated to CSI. Moreover, the approach allows the elimination of an even or odd arbitrary number of harmonics (e.g., 5th, 7th, and 11th harmonics). We have also obtained speed control of three phase Induction Motors using v/f method The input voltage is controlled by using the time period of pulses. Thus, SHE can be used to eliminate multiple lower-order harmonics which would mitigate the detrimental effects of harmonic current on electrical power system and devices.

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