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Design of SPWM Converter for Improving the Performance of Hybrid Electric Vehicles

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ABSTRACT
The interest has grown in Hybrid Electric Vehicles (HEVs) because of the worries over environmental pollution and fuel consumption. The main components of an HEV are the power converter, electric motor, storage system which may be a battery, ultracapacitor, etc. and the internal combustion engine (ICE). A three phase inverter changes fixed dc voltage into ac voltage whose magnitude and frequency can be obtained as required. Power electronics is an empowering technology which helps in development of such an inverter which can be utilized for many purposes. Adjustable output voltage and frequency can be got from a number of pulse width modulation (PWM) methods. Sinusoidal Pulse Width Modulation (SPWM) is a mostly used method of Pulse Width Modulation. This paper focuses on the development of Sinusoidal pulse width modulation inverter using SPWM technique as SPWM has the advantages of lesser harmonics in the output voltage. The concept of unipolar and bipolar modulation is illustrated. Simulation of SPWM inverter has been presented to analyze the output line voltage, phase voltage and SPWM technique. Simulation of SPWM inverter has been done without and with filter and FFT analysis has been done to find the total harmonic distortion (THD) in the output line voltage. Hardware development of SPWM inverter has been done. dSPACE controller has been used for the generation of the firing pulses. Finally experimental results have been presented which include the waveforms of the firing pulses, output line voltage and output phase voltage.

KEYWORDS
Hybrid Electric Vehicle, Voltage Source Inverter, Power MOSFET, SPWM, Opto isolator,dSPACE, THD

1. INTRODUCTION

Renewable energy sources are large in number and can meet the world's energy requirement. Examples of renewable energy sources are wind, solar, hydropower, etc. Renewable based energy systems are being used increasingly as their cost is decreasing and the cost of fossil fuels and other sources are increasing. In the last 30 years there has been a fast growth in solar and wind energy resources and their performance has been better than before. It is expected that the trend in growth will be towards renewable energy resources and not in pollution spreading oil and coal resources. The growth and use of renewable energy sources can bring a greater scope in energy supply market, give lasting energy supplies, decrease the environmental pollution and give attractive alternatives to achieve specific energy requirements and help to develop new employment opportunities. Most of the renewable energy resources exist in dc form hence a dc- ac inverter is necessary to utilize them [1], [3], [5], [7], [9], [10], [17]-[23].
Hybrid Electric Vehicle has attracted attention due to the reasons of pollution, fuel saving, greenhouse effect and diminishing fossil fuel reserves [2], [7], [9]. Electric vehicle can be divided into three classes: Battery Electric Vehicles (BEVs), Hybrid Electric Vehicles (HEVs) and Fuel Cell Electric Vehicles (FCEVs) [10], [11], [15]. The internal combustion engine vehicles which were used previously used only an ICE for its propulsion but had the problem of pollution [15].

HEVs use an electric motor and ICE and eradicate the shortcomings of ICEVs and BEVs. The advantages of HEVs are that their driving range is extended and refueling time is also less. HEVs result in less pollution and less fuel consumption. In an HEV there are two energy storage systems and one of them is electrical energy. The energy sources can be gasoline fuel, battery, ultracapacitors, etc. [7], [14], [15], [21]. The development of FCEVs is still under progress. The BEVs have become less popular. The HEVs have now become accepted and their growth is on the rise [4].
The electric motor employed is a significant part of a Hybrid Electric Vehicle. Induction motors and Brushless dc motors are now finding use in HEVs. [6]. Power electronic applications in hybrid electric vehicles includes rectifiers, inverters and dc/dc converters [8]. The aim is to achieve highly efficient systems, with less space and reduced cost [5].

An inverter is a device that changes power from a dc source into ac power at desired output voltage and frequency. A three phase VSI used in HEV produces three phase ac voltage which is used to control the electric motor [12]. The transistor family of devices is now widely used in inverter circuits. The use of IGBTs and MOSFETs in inverters is now gaining popularity [12], [13], [16].

This paper is organized as follows. Section 2 deals with the design of VSI for HEV. Section 3 describes the technique of SPWM. Section 4 discusses the simulation of SPWM inverter without and with filter. Section 5 discusses the hardware and experimentation of SPWM inverter. The output line voltage and phase voltage waveforms are obtained. Finally conclusion is given.

2. COMPONENTS OF AN INVERTER

2.1 Inverter bridge

The inverter is made up of semiconductor switching devices. The semiconductor devices which are commonly used are thyristors, MOSFETs and IGBTs. The use of thyristors has now become obsolete and MOSFETs and IGBTs are widely used in inverters. Power MOSFET is a voltage controlled device and has the advantages that it can be used for high frequency switching and has low switching losses. In this work IRFP 460 MOSFET is used as the switching device. Its ratings are 500 V, 20 A.

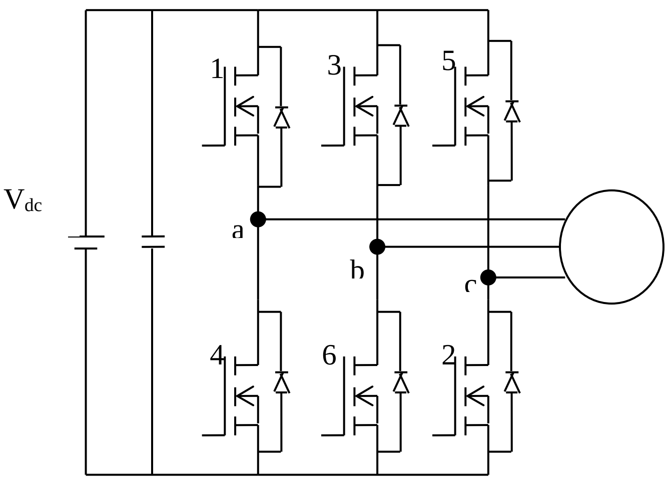

Fig. 1: Three phase VSI

2.2 Triggering circuit for MOSFETs

Use of TLP 250 is made for gate firing of IRFP 460 power MOSFET. Firing pulses are provided to TLP 250 from the dSPACE controller. TLP 250 consists of an LED and a photo transistor. It provides isolation between the dSPACE controller and the MOSFETs. The TLP 250 output is supplied to the gate - source terminals of the MOSFET as shown in Figure 2.

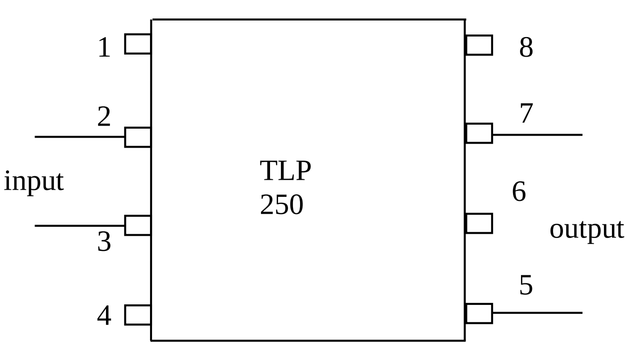

Fig. 2: TLP 250 Pin diagram

2.3 dSPACE controller:

dSPACE: For an HEV to give less fuel consumption and to reduce the environmental pollution good control algorithms have to be developed. dSPACE offers a dais on which models can be build, control is rapid, code can be generated automatically and hardware in the loop (HIL) testing, justification of the developed model and managing of data can be done. First, the Simulink model is developed on a computer. Simulation of these models can be done and the required tests can be performed. Model and the tests can be kept for future use again and easily. dSPACE saves time and money. In combination with MATLAB/ Simulink/ Stateflow, dSPACE provides a platform on which models can be built using Simulink Block Libraries, tested and also the hardware can be run. The response of a system can be checked by the use of a beforehand PC based simulation. The errors in the program can be found out and corrected thus making the process very simple before connecting the generated signals with the actual hardware. With the use of dSPACE the vehicle is being electrified and the fuel consumption is being decreased and the comfort and safety is increasing. The vehicle manufacturer's cost and environmental pollution are reduced. Applications of dSPACE are: Hybrid Vehicles, Electric vehicle, fuel cell and battery management, electric steering. RTI (Real time interface) provides the connection of dSPACE hardware with the developed software MATLAB/ Simulink.

A Simulink model is built on a PC for generating the SPWM pulses for the six MOSFETs. Before generating the pulses, the simulation is done to check whether the pulses are generated as required. Then the pulses are generated for the hardware. The stepped output wave has a frequency of 50 Hz. To prevent any two MOSFETs in the same leg from conducting simultaneously a time delay is introduced between the turning OFF of one MOSFET and the turning ON of other MOSFET.

Six 5 V pulses are obtained from the dSPACE controller and applied to the sixTLP 250s. The value of output pulses from the TLP is 12 V. These pulses are supplied to the G-S terminals of the MOSFET.

Fig. 3: dSPACE controller

2.4 Power supply:

The power inverter requires dc supply which is provided from a

(0-63) V regulated dc power supply. A dc supply of 60 V is given. TLP 250 requires 12 V dc at its 8 and 5 terminals. A dc voltage of 12 V is made for each TLP 250 as shown in Figure. A 230/13.76 V six winding transformer is used.

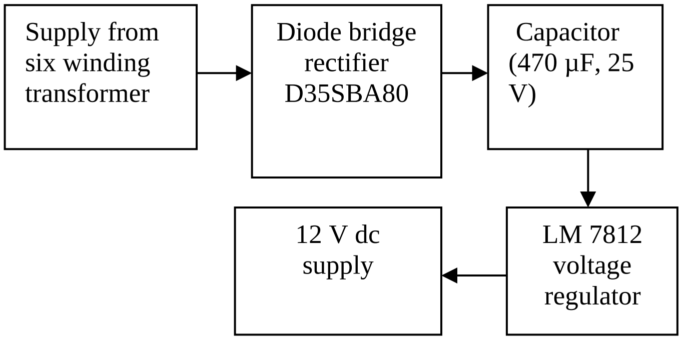

Fig. 4: Power supply of TLP 250

3 SPWM PRINCIPLE

PWM control is a frequent technique of controlling the output voltage in an inverter. A dc voltage is fed to the input terminals of the inverter and a controlled ac voltage is obtained at the output terminals of the inverter. The advantages of PWM techniques are that no additional components are required and the output voltage has lesser harmonics. PWM technique has constant amplitude pulses and the width of these pulses are changed to obtain output voltage control in an inverter. In SPWM there are many pulses in a half cycle.
A carrier wave Vc which is normally a triangular wave of high frequency is compared with a reference wave Vr which is sinusoidal of desired frequency. The firing pulses are produced at the points where the carrier and the reference signal waves intersect. When the magnitude of the sinusoidal signal is greater than the triangular signal a triggering pulse is generated.

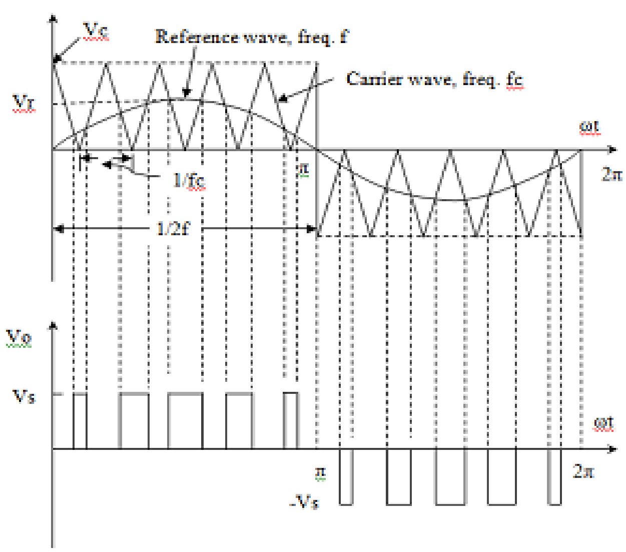

Fig. 5: Sinusoidal Pulse Width Modulation.

Pulses per half cycle: $N = \frac{f_c}{2f}$ where fc = carrier frequency and f = modulating wave frequency. The fraction Vr/Vc gives the modulation index. It is a measure of the amount of harmonics in the output. The fundamental output voltage is proportional to modulation index. By variation of modulation index output voltage can be controlled.

Types of Pulse Width Modulation techniques: (1) Bipolar modulation (2) Unipolar Modulation. To illustrate the concept of Bipolar modulation and Unipolar modulation we consider a single phase voltage source inverter (VSI)

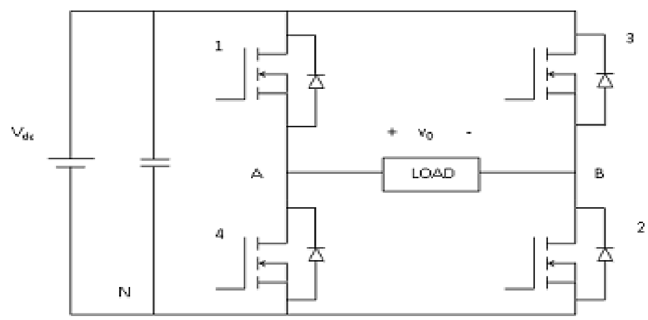

Fig. 6: Single phase VSI

Operation of Voltage Source Inverter: When M1 and M2 switches are ON load voltage is Vdc. When M3 and M4 switches are ON load voltage is – Vdc. When M1 and M2 switches and M3 and M4 switches are ON load voltage is zero.

Bipolar Modulation

In bipolar switching the reference voltage waveform of maximum value Vr is compared with the carrier voltage waveform of maximum value Vc. At any time two switches M1 and M2 are ON and M3 and M4 are OFF. In the next state M3 and M4 are ON and M1 and M2 are OFF. The waveforms of the output are shown in Figure 7.

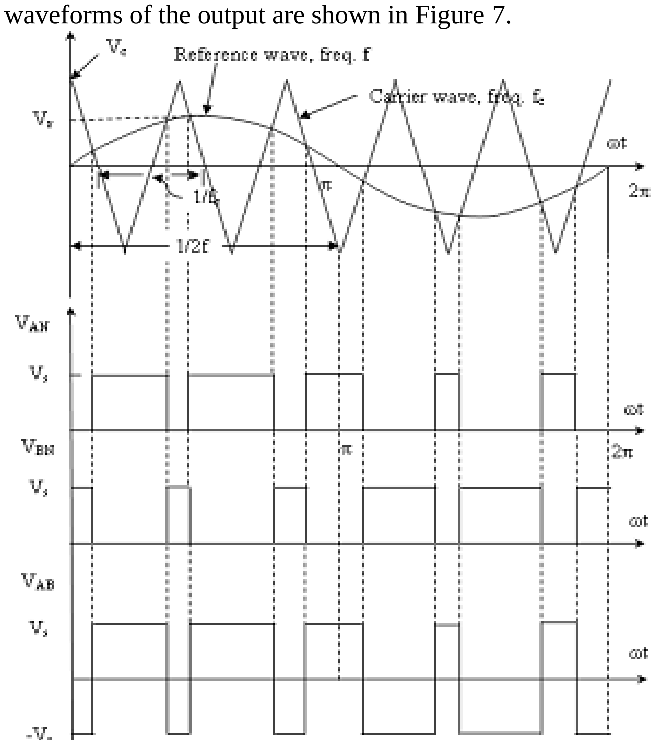

Fig. 7: Bipolar pulse width modulation

Unipolar modulation

In unipolar switching one carrier wave and two reference waves are used. One of the reference waves lags the other by 180°. The output voltage varies from 0 to +Vdc or from 0 to -Vdc and the switching frequency is doubled. The switches are turned ON and OFF when one carrier wave and two reference waves are compared as shown in Figure 8 generating the gate pulses.

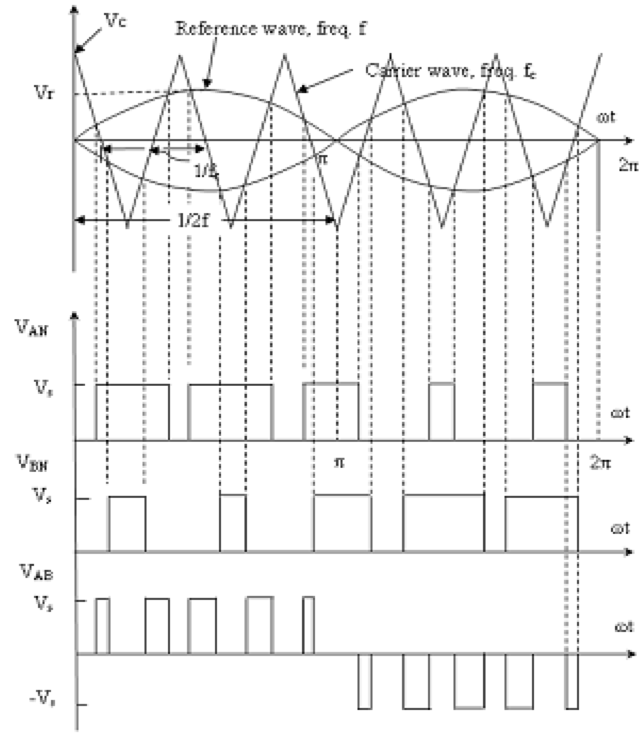

Fig. 8: Unipolar pulse width modulation

Total harmonic distortion (THD) = $\frac{V_h}{V_{L1}} = \frac{({V_L}^2 - {V_{L1}}^2)^{1/2}}{V_{L1}}$ where V_h = sum of rms value of harmonics and V_{L1} = fundamental component of line voltage

4 MATLAB BASED SIMULATION OF SPWM VSI AND RESULTS

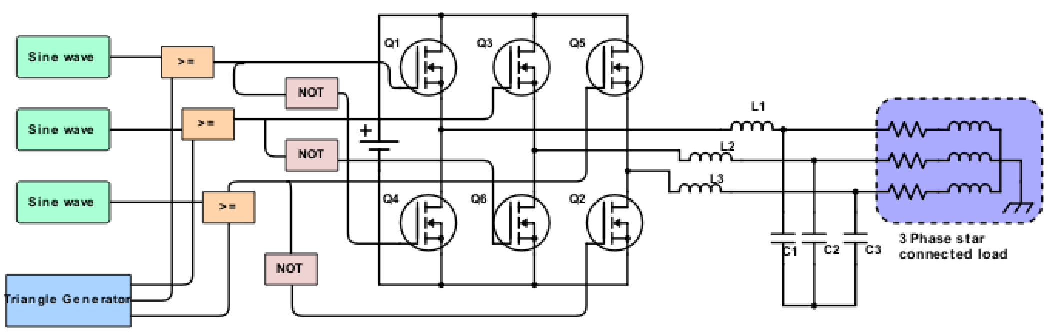

Fig. 9: Block diagram of three phase SPWM VSI with three phase LC filter

4.1 Simulation results with R-L load and three phase LC filter

Three phase LC filter values: L = 10 mH, C = 60 µF. Simulation parameters: input dc voltage is 400 V. Carrier wave frequency is 1 kHz. Sine wave frequency is 50 Hz. The carrier wave peak to peak voltage is 2 V and the sine wave peak to peak voltage is 1.6 V. The value of R-L load is taken as 2 kW at 0.8 p.f. lagging by using the three phase series RLC load block from the simulink library with Active power P = 2000 W ,Inductive reactive power QL = 1500 VAR.

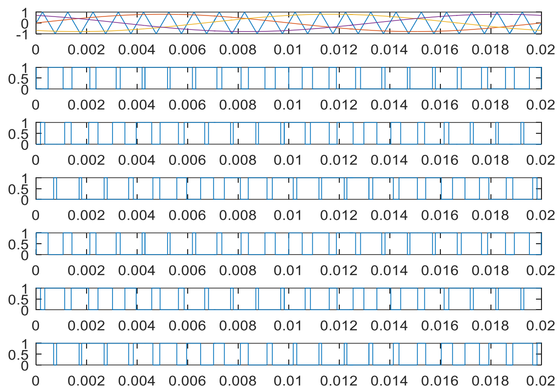

Fig. 10: SPWM generation, gate pulses g1-g6.

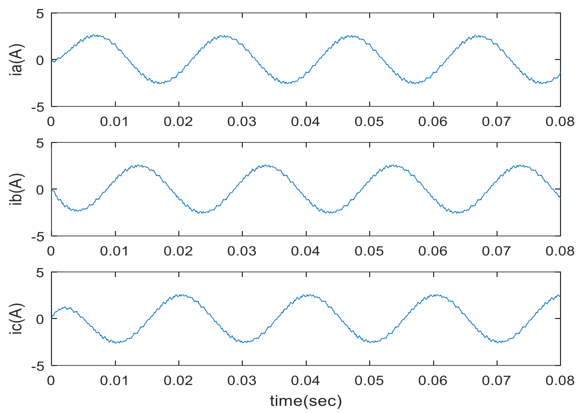

Fig. 11: Phase currents of load ia, ib and ic without filter.

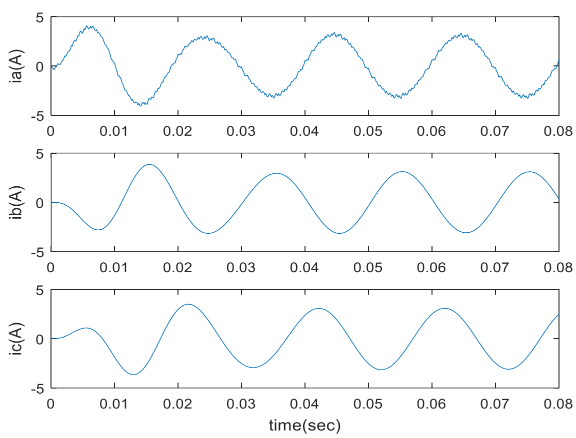

Fig. 12: Phase currents of load ia, ib and ic with filter.

Load phase current has a peak value of 2.561 A without filter. Load phase current has a increase during the first cycle with filter and a peak value of 4 A during the first cycle and then settles down at a current of peak value 3.352 A.

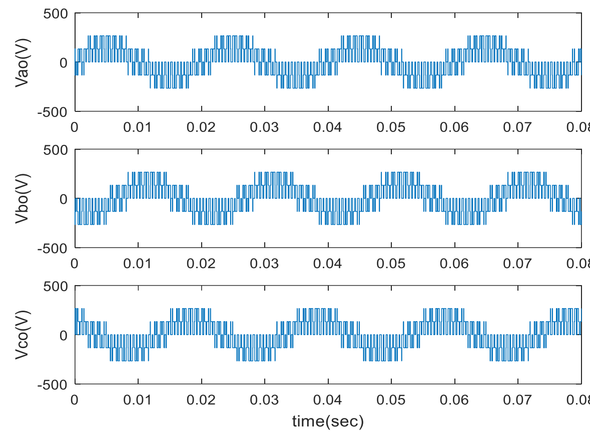

Fig. 13: Phase voltages of load Vao, Vbo and Vco without filter.

Load phase voltage without filter has a peak value of 2 Vs/3 = 266.67 V. Vbo lags Vao by 120° and Vco lags Vbo by 120°.

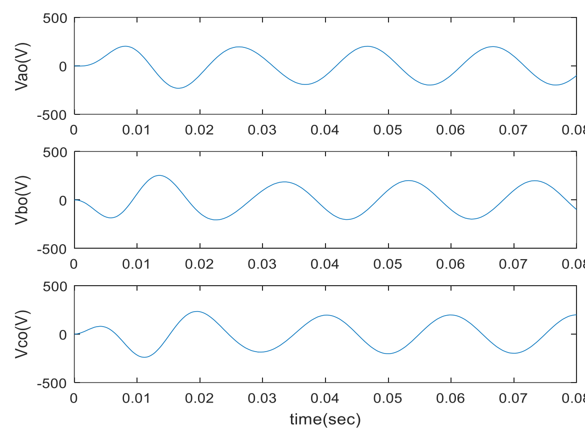

Fig. 14: Phase voltages of load Vao, Vbo and Vco with filter

The load phase voltage has a peak value of 201.5 V.

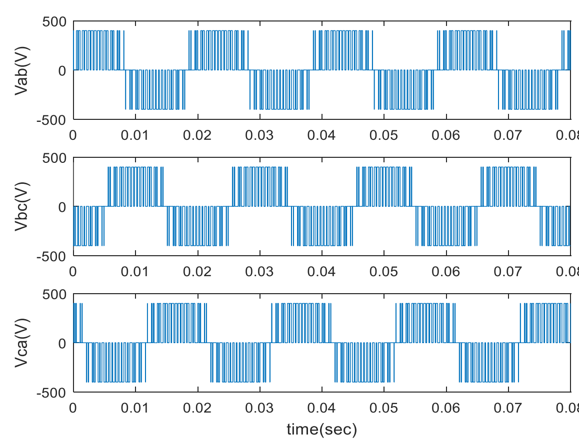

Fig. 15: Line voltages of load Vab, Vbc and Vca without filter.

Load line voltage without filter has a peak value of Vs = 400 V. Vbc lags Vab by 120° and Vca lags Vbc by 120°.

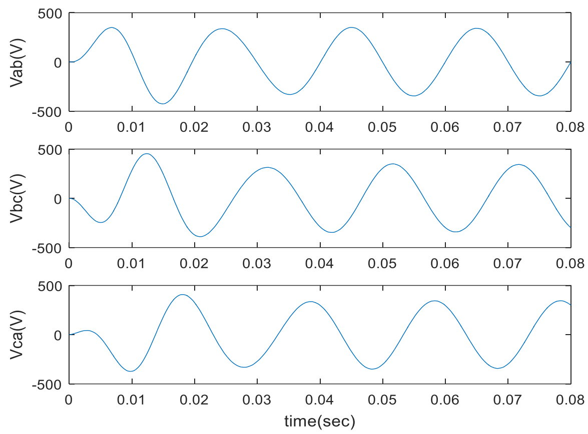

Fig. 16: Line voltages Vab, Vbc and Vca after filtering.

The load line voltage has a peak value of 349.2 V.

Total harmonic distortion

THD analysis of line voltage is done using MATLAB FFT analysis tool for different loads at varying carrier frequency (fc). THD analysis is shown for a load of 2 kW at 0.8 p.f. lagging. The results for other loads are compiled in table 1.

1. THD (4.75%) of line voltage for fc = 1 kHz (Load = 2 KW at 0.8 p.f. lagging)

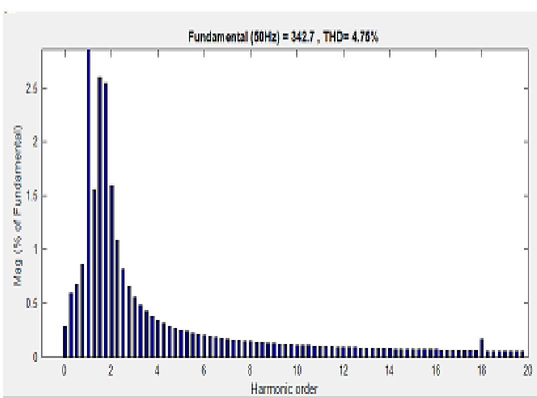

Fig. 17: FFT analysis of line voltage for fc = 1 kHz

2. THD (4.26%) of line voltage for fc = 2 kHz

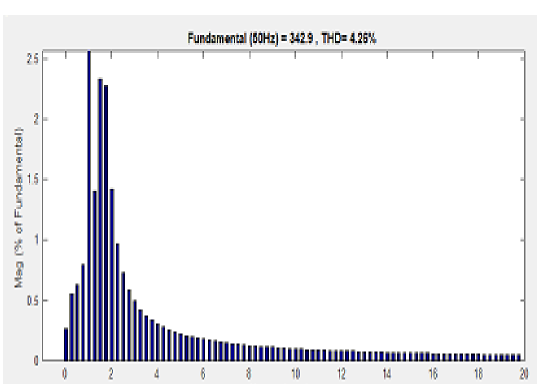

Fig. 18: FFT analysis of line voltage for fc = 2 kHz

3. THD (4.11%) of line voltage for fc = 4 kHz

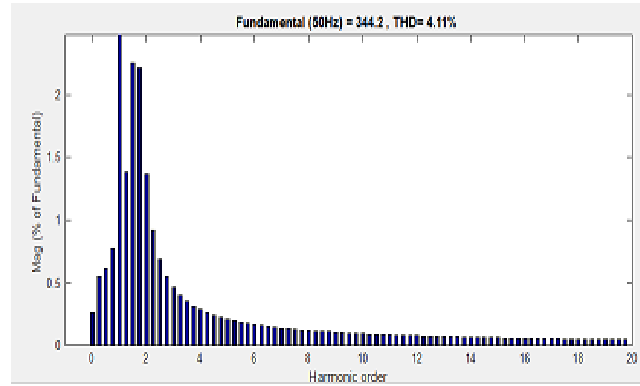

Fig. 19: FFT analysis of line voltage for fc = 4 kHz

4. THD (4.03%) of line voltage for fc = 6 kHz

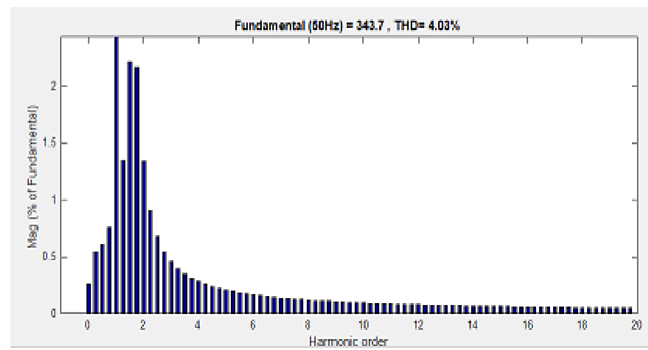

Fig. 20: FFT analysis of line voltage for fc = 6 kHz

5. THD (3.98%) of line voltage for fc = 8 kHz

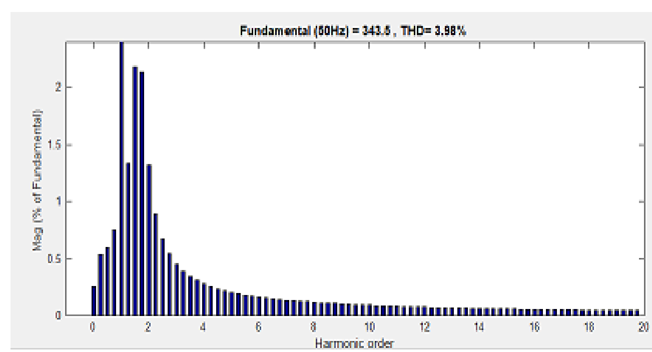

Fig. 21: FFT analysis of line voltage for fc = 8 kHz

6. THD (3.95%) of line voltage for fc = 10 kHz

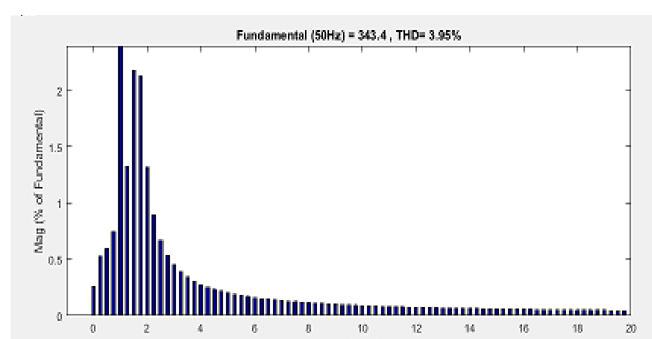

Fig. 22: FFT analysis of line voltage for fc = 10 kHz

Table 1: THD analysis of line voltage at different carrier frequency (fc) for varying loads

Load	fc (kHz)	1	2	4	6	8	10
R-L load (2 KW at 0.8 p.f.)	THD (%)	4.75	4.26	4.11	4.03	3.98	3.95
	Voltage (V)	342.7	342.9	344.2	343.7	343.5	343.4
R-L load (3 KW at 0.8 p.f.)	THD (%)	2.10	1.79	1.65	1.61	1.59	1.57
	Voltage (V)	266.8	268.8	267.9	267.6	267.4	267.3
R-L load (4 KW at 0.8 p.f.)	THD (%)	0.99	0.81	0.75	0.73	0.72	0.72
	Voltage (V)	220.9	219.4	218.7	218.4	218.3	218.3

THD decreases with increase in carrier frequency and the line voltage remains approximately the same. With increase in load, the line voltage decreases and THD also decreases.

4.2 Simulation results for SPWM inverter with three phase induction motor load

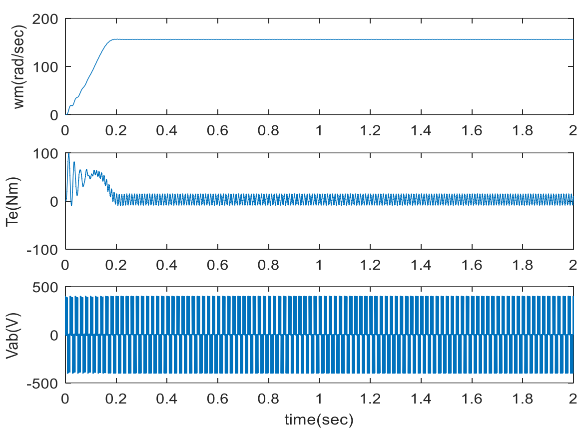

Fig. 23: Rotor speed, electromagnetic torque and line voltage Vab for a three phase induction motor load.

5 HARDWARE EXPERIMENTAL SET UP OF VSI

The components required for the development of the hardware were regulated dc power supply, capacitor of rating 470 μF, 250 V, six nos. of IRFP 460 power MOSFETs, three 1 KΩ resistors for the star connected load, dSPACE controller, six nos. of TLP 250 opto couplers. fc = 500 Hz.

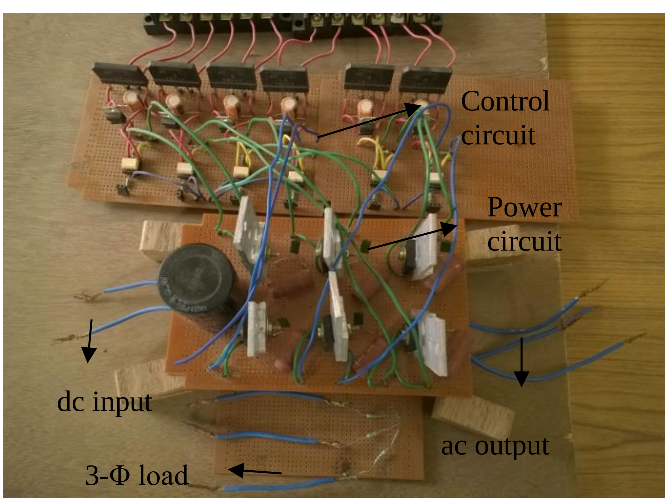

Fig. 24: Hardware for three phase VSI

5.1 Generation of sinusoidal PWM

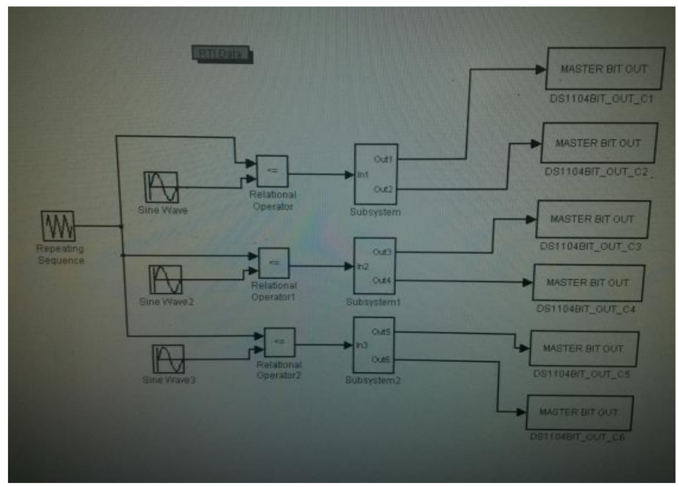

Fig. 25: Interface between Matlab/ Simulink and dSPACE

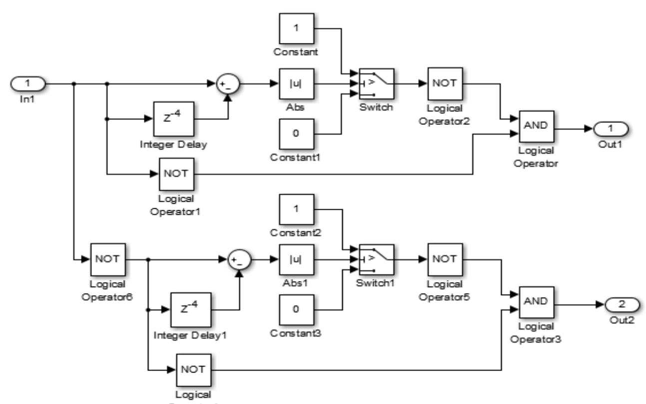

Fig. 26: Delay circuit represented by subsystem.

5.2 Experimental Results

dSPACE controller firing pulses

Figure 27 depicts the gate pulses for the MOSFETs 1 and 4. MOSFETs 1 and 4 in the same leg do not conduct simultaneously. When MOSFET 1 conducts MOSFET 4 is OFF. When MOSFET 1 is OFF then MOSFET 4 conducts. Similar happens in the second and third leg of the inverter.

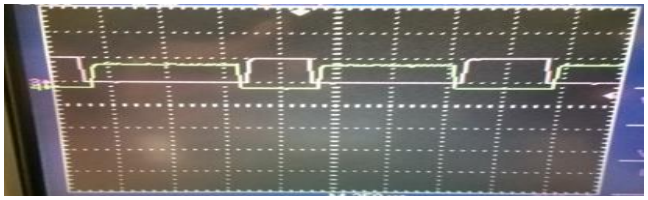

Fig. 27: Triggering pulse of MOSFETs 1 & 4

Fig. 28: Triggering pulse of MOSFETs 3 & 6

Fig. 29: Triggering pulse of MOSFETs 5 & 2

Experimental results with three phase balanced star connected load

Figure 30 depicts phase voltages of the load for a 3 phase star connected resistive load. The output phase voltage has the same six stepped wave shape as in a 180° conduction mode inverter but here the number of pulses per half cycle is more. Figure 31 depicts line voltages of the load. The line voltage also has the same wave shape as in a 180° conduction mode inverter but here the number of pulses per half cycle is more.

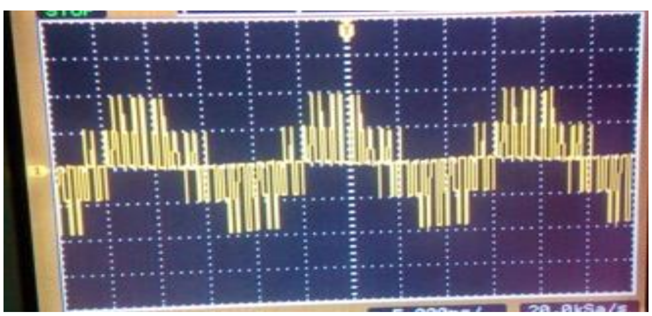

Fig. 30: Phase voltage of load

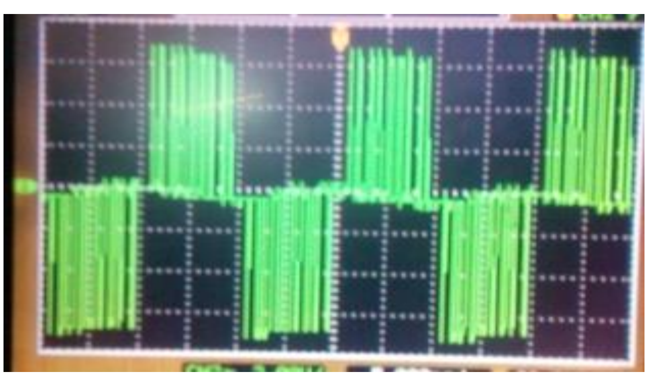

Fig. 31: Line voltage of load

Table 2: Comparison between continuous pulse inverter and SPWM inverter

	Continuous Pulse Inverter	SPWM inverter
a.	Switching frequency is low	Switching frequency is high
b.	Harmonics in the output is more	Harmonics in the output is less. Filter requirement is reduced
c.	There is one pulse per half cycle	Number of pulses per half cycle is more
d.	Output voltage control is not so easy	Output voltage control is easier
e.	Power losses are more	Power losses are less

Table 3: Comparison with other research works

Research	Total Harmonic Distortion
[21]	9.44 %
[22]	5.58 %
[23]	3.98 %
Proposed work	3.95 %

6 CONCLUSION

HEV is becoming more popular in the modern world because it reduces air pollution and at the same time increases fuel efficiency. Power converter is one of the major parts of HEV because it controls the propelling of the vehicle. A sine PWM voltage source inverter has been designed using power MOSFETs. Its triggering circuit has been developed using dSPACE 1104. Experiment has been done. Its load voltage has been shown. It has been found that because of sine PWM the total harmonic distortion (THD) decreases with increase in switching frequency. Switching frequency was changed from 1 - 10 kHz. THD changes from 4.75 - 3.95%. A bold assertion can be made that implementing sine PWM to traction motor of Hybrid Electric Vehicle, improves its performance. THD decreases, harmonic decreases, and the heating losses and heating effect also decreases with an increase in frequency. So this work is very useful in the field of Hybrid Electric vehicle (HEV). The results of waveforms obtained from Sinusoidal Pulse Width Modulation Inverter are as those obtained theoretically. The developed Sinusoidal Pulse Width Modulation Inverter can be utilized for many purposes particularly like those in an Hybrid Electric Vehicle.

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