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Space Vector Pulse Width Amplitude Modulation for a VSI Fed Induction Motor Drive

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ABSTRACT: This paper proposes a converter -inverter fed induction motor drive which can be used in plug in hybrid electric vehicle or electric vehicle. The advantage of this PWM technique is that by eliminating the zero vectors the switching loss can be reduced. By maintaining a 6ω varied dc link voltage reduced dc link capacitor decreases the size of the system which can increase the power density. The simulation of the system has been done using MATLAB/SIMULINK. It can be seen that the THD is relatively less. It is feasible for applications which require high efficiency, high power density, low cost. The theoretical analysis for switching loss calculation is also derived.

KEYWORDS: SVPWAM, Induction motor, 6ω dc link voltage, Switching loss reduction, FFT analysis

I.INTRODUCTION

Plug in hybrid electric vehicles (PHEV) makes use of both conventional fuel and electric energy which is stored in the battery. Utilizing electricity from the grid for charging the battery costs less and reduces fuel consumption compared to conventional vehicles. These vehicles can also reduce emissions depending on the electricity source. A Bidirectional dc-dc converter serves the purpose of stepping up or stepping down the voltage level between its input and output along with the capability of power flow. They have applications in the area of energy storage systems for hybrid vehicles, renewable energy storage systems and fuel cell storage systems. The general block diagram is shown in figure 1.

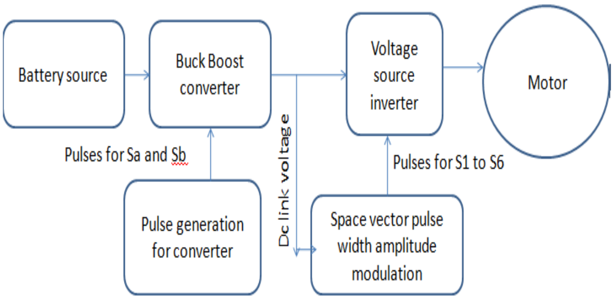

Fig 1 Block diagram of the system

PHEV consists of converter, inverter and motor which use energy stored in a battery. The batteries in PHEV can be charged in several ways that is by an outside electric power source, by the internal combustion engine or else by regenerative braking. A battery is used to store the electrical energy which powers the motor. These vehicles require less maintenance due to few moving parts.

Currently two topologies are used in plug in hybrid electric vehicles they are the conventional three phase inverter with high voltage battery which imposes high stress on switching devices that can be eliminated by using three phase PWM inverter with dc-dc boost at the front end. In order to reduce the winding loss and core loss the switching frequency of

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inverter should be in the range 15 to 20 kHz which results in high switching losses. PWM schemes can be used to reduce such problems like Sinusoidal pulse width modulation and Space vector pulse width modulation. SVPWM is widely used because of their easier digital realization and better dc bus utilization.

Soft switching methods were used to reduce switching losses effectively [2]-[6]. Instead of dc/dc converters active switching rectifier or diode rectifier with small dc link capacitors are proposed in [7]-[11]. Regenerative capability was not attained in such system. The conventional SVPWM method was proposed in [12] which reduce the switching loss by 13% compared to SPWM technique. Another prominent technique is discontinuous PWM [13] which reduces the number of switching instances up to one-third of fundamental period. But it causes unwanted stress in the power semiconductor devices. A method similar to SVPWAM technique is seen in [14] which reduce the average switching frequency by a factor of three to reduce the switching power loss.

In this paper space vector pulse width amplitude modulation (SVPWAM) method for a voltage source inverter fed Induction motor drive with 6ω varied dc link voltage is implemented by using MATLAB/SIMULINK. The simulations have been done for a 2HP Induction motor. The advantages of using Induction motor in electric vehicle are also discussed. The theoretical analysis for switching loss calculation is done to verify the improvement in efficiency. FFT analysis had been done for the whole system and was seen to be 4.57%.

II.SVPWAM METHOD

A. *Operating Principle*

Space vector pulse width modulation (SVPWM) is a special switching sequence of the upper three switches of a three phase inverter. It has advantages like less harmonic distortion in the output voltages which are applied to the phases of an AC motor and to provide more efficient use of supply voltage compared with sinusoidal modulation technique. Among the eight possible switching states for which two of them are zero vectors and six of them are active switching states. The conventional zero vectors are eliminated in each sector in Space vector pulse width amplitude modulation technique thus V_{ref} will be at its maximum amplitude. Thus SVPWAM method is a combination of amplitude modulation and pulse width modulation such that each inverter leg is switched during one third of fundamental period. The modulation principle of SVPWAM is shown in figure 2.The voltage vectors only follow the sides of the hexagon. As zero vector are not utilized during each sector two switches and their complementary switches does not change its state and thus only one pair of switches need to do PWM switching.

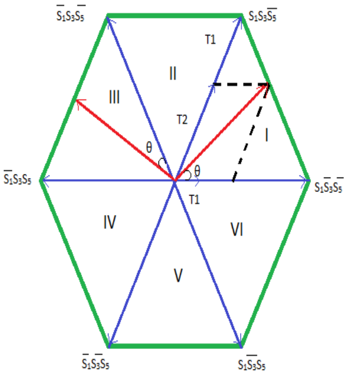
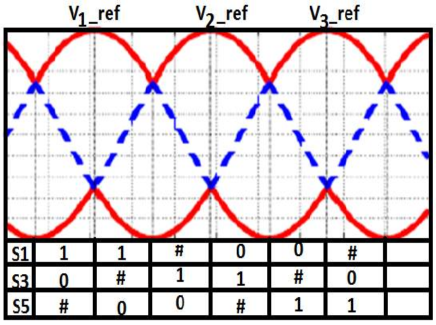


Fig 2.Representation of inverter states

The inverter switching pattern can be as shown in figure 3. Here S1, S3, S5 represents the upper switch of three phase inverter. Consider the case V1>V3>V5 as example [21]. Here phase a voltage is larger and is turned on all the time denoted by ‘1’.Phase c is the smallest upper switch is set to be off all time denoted as ‘0’.So only phase b is doing PWM switching denoted by ‘#’ denoted in figure 3.Thus dc link voltage is directly generated from the output line to line voltage. So using this method only one phase leg of inverter is doing switching action. In all these cases zero vectors are eliminated from each sector which adds the benefit to reduce switching losses.



S1	1	1	#	0	0	#	
S3	0	#	1	1	#	0	
S5	#	0	0	#	1	1	

Fig. 3 Switching pattern for SVPWAM method

Compared to conventional SVPWM technique the vector placement is also changed which does not have a transition to zero vector time period. The vector placement within one switching cycle in each sector is shown in figure 4. The new time period [1] can be calculated as:

$$\frac{T1'}{Ts} = \frac{T1}{T1+T2} \tag{1}$$

Where the time periods T1 and T2 are

$$T_1 = \frac{v_{ref}\sin(60-\theta)T_s}{V_d \sin 60} \tag{2}$$

$$T_2 = \frac{v_{ref}\sin\theta T_s}{V_d \sin 60} \tag{3}$$

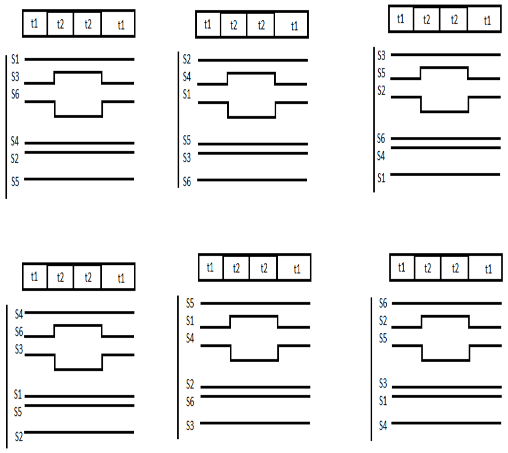


Fig 4 Vector placement diagram

B. *Inverter switching loss Calculations*

The inverter switching loss per IGBT from [15] using conventional sinusoidal PWM in the inverter system is:

$$Psw_{\_spwm} = \frac{1}{2\pi}\int_0^{\pi}[E\,sw(on) + Esw(off)]d\omega t \tag{4}$$

Assume switching energy losses Esw (on) and Esw (off) are variables that change linearly with the product of drain to source voltage Vs and drain current Id. It can be expressed as:

$$\frac{Eon}{Eon{,}0} = \frac{Vs\ is}{Vs0\ Id0} \qquad (5)$$

$$\frac{Eoff}{Eoff{,}0} = \frac{Vs\ is}{V's0\ I'd0} \qquad (6)$$

Where is= $I_s$sinωt
So the switching loss of each IGBT can be represented as

$$Psw_{\_spwm} = \frac{VsIsfsw}{\pi}\left[\frac{Eon{,}0}{Vs0Id0} + \frac{Eoff{,}0}{V's0\ I'd0}\right] \qquad (7)$$

Under unit power factor condition the SVPWAM has switching in two 60° sections thus the integration over 2π is limited down within two 60°. So the switching action is taken during the periods $(\frac{\pi}{6}, \frac{-\pi}{6})$ and $(\frac{5\pi}{6}, \frac{7\pi}{6})$.
The switching losses are given by:

$$Psw_{\_svpwam} = [Esw(on) + Esw(off)]\ \frac{1}{2\pi}\left[\int_{\frac{-\pi}{6}}^{\frac{\pi}{6}} \sin(\omega t)d\omega t\right] + \frac{1}{2\pi}\left[\int_{\frac{5\pi}{6}}^{\frac{7\pi}{6}} \sin(\omega t)d\omega t\right] \qquad (8)$$

$$= \frac{2-\sqrt{3}}{2}\frac{VsIsfsw}{\pi}\left[\frac{Eon{,}0}{Vs0Id0} + \frac{Eoff{,}0}{V's0\ I'd0}\right]$$

Thus switching loss of SVPWAM method is calculated by

$$\frac{Psw_{\_svpwam}}{Psw_{\_spwm}} = \frac{2-\sqrt{3}}{2} \qquad (9)$$

=13.4% compared to conventional sinusoidal PWM method

III. BUCKBOOST CONVERTER

A converter is present at the front end for energy flow from battery to the dc link and from dc link to battery. The unidirectional dc/dc converter can be replaced by diodes with controllable switches as individually buck converter and boost converter do not have bidirectional power flow capability. By operating the switches both buck and boost operations are possible. The bidirectional switches carries current in both directions and thus double sided power flow occurs. Generally IGBT or MOSFET are used in parallel with diode.

Here a 6ω varied feature is to be present at the dc link. In SVPWAM control, dc-link voltage has to vary with a voltage ripple whose frequency is six times of output frequency. This kind of ripple is called 6ω. [21] The peaks of the ripple are corresponding to the peaks of output three phase line-to-line voltage. The converter generates this ripple. This is the input to the inverter with SVPWAM. This provides nearly sinusoidal variation in the output voltage and the percentage in THD can be reduced. Another added advantage is that the size of dc link capacitor can be reduced. Thus the size of the system can be reduced which increases the power density.

IV.INDUCTION MOTOR

The induction motor is well suited for hybrid electric vehicle application because of its robustness, low maintenance, low price and reliability. Recently a new induction motor technology has been developed [22] for vehicle application which can produce the torque of a permanent magnet motor without using permanent magnet material. It also includes features like reduced manufacturing costs and operation of higher temperature and higher speed.

The power circuit diagram of Induction motor is shown in figure 5. The most popular motor model is the Krause's model from which the flux linkage equations are given by [23]:

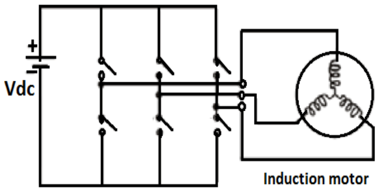


Fig 5 Inverter fed Induction motor drive

$$\frac{dF_{qs}}{dt} = \omega_b[v_{qs} - \frac{\omega_e}{\omega_b}F_{ds} + \frac{R_s}{x_{ls}}(F_{mq} + F_{qs})]$$

$$\frac{dF_{ds}}{dt} = \omega_b[v_{ds} + \frac{\omega_e}{\omega_b}F_{qs} + \frac{R_s}{x_{ls}}(F_{md} + F_{ds})]$$

$$\frac{dF_{qr}}{dt} = \omega_b[v_{qr} - \frac{\omega_{e-}\omega_r}{\omega_b}F_{dr} + \frac{R_r}{x_{lr}}(F_{mq} - F_{qr})]$$

$$\frac{dF_{dr}}{dt} = \omega_b[v_{dr} + \frac{\omega_{e-}\omega_r}{\omega_b}F_{qr} + \frac{R_r}{x_{lr}}(F_{md} - F_{dr})] \qquad (10)$$

The electrical output torque equations are given by:

$$T_e = \frac{3}{2}\frac{p}{2}\frac{1}{\omega_b}\,(F_{dc}i_{qs} - F_{qs}i_{ds}) \qquad (11)$$

$$T_e - T_L = J\frac{2}{p}\frac{d\omega_r}{dt} \qquad (12)$$

Where F_{ij} is the flux linkage
F_{mq}, F_{md} are magnetizing flux linkage
V_{qs}, V_{ds} d and q axis stator voltages
V_{qr}, V_{dr} d and q axis rotor voltages
ω_e stator angular electrical frequency
ω_e motor angular electrical base frequency
ω_r rotor angular electrical speed
The circuit diagram for the system and control circuitry for the converter is shown in figure 6.

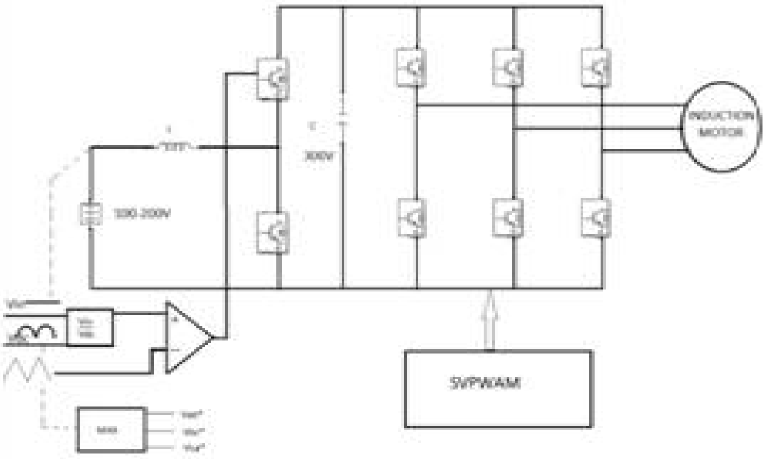


Fig 6 Converter Inverter fed Induction motor drive system

The machine specifications are detailed in Table I which is a 2HP squirrel cage induction motor. The input dc voltage can be varied from 100 to 200V.The dc link voltage is made to be a have a voltage of 300V.

Table I
3 Phase Induction Motor Specifications

Rotor Type	Squirrel Cage
Rated Speed	1450 rpm
Frequency	50 Hz
Rated power	2HP
Reference Frame	Stationary
Poles	4
R_s	0.435 Ω
R_r	0.816 Ω
$L_{ls} = L_{lr}$	2e-3 H
L_m	8e-3 H
J, Moment of inertia	0.089

V. SIMULATION RESULTS

The simulation results for SVPWAM for a voltage source inverter fed Induction motor has been simulated using MATLAB/SIMULINK. The dc input to the inverter is controlled by the bidirectional dc/dc converter through the control circuitry by which a 6ω varied voltage is generated. The following waveforms were obtained. The simulation parameters are V_{in} =100V, L=1mH, C=2μF, f_s=10kHz.
The reference dc link voltage given to the converter with V_{dc}=300V is shown in figure 7. The output of the dc-dc converter by applying certain control in the input side is obtained where the voltage at the output of dc/dc converter as shown in figure 8.

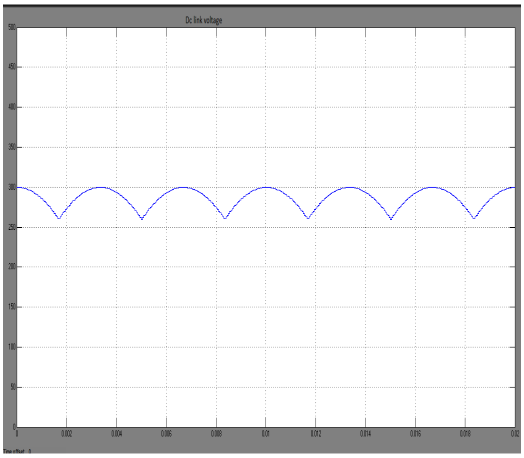


Fig 7 Reference dc link voltage (V_{dc}=300V)
(x axis: 0.002s/div, y axis: 50V/div)

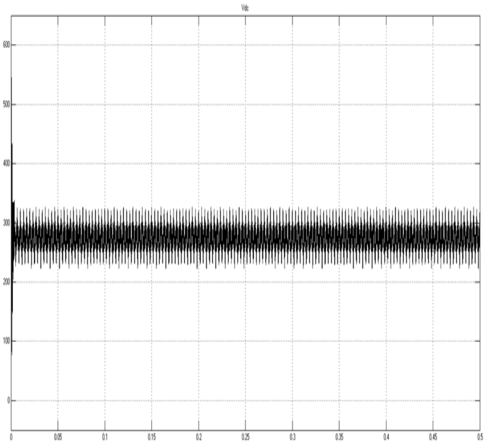


Fig 8 A 6ω dc link voltage (V_{dc}=300V)
(x axis: 0.05s/div, y axis: 100V/div)

The switching pulses for the inverter are shown in figure 9 where we can see the number of switching's reduced as the zero vectors are eliminated. The line voltage has nearly sinusoidal variation as shown in figure10 where the magnitude of voltage is 300V.

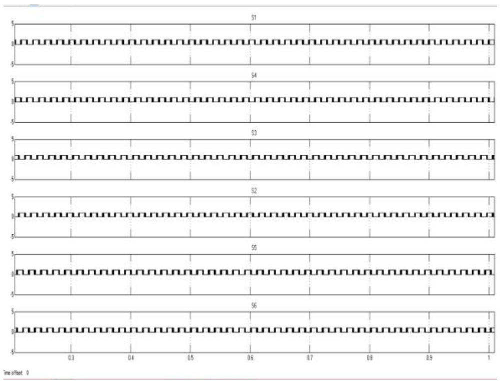


Fig 9 Switching pulses for SVPWAM method (x axis: 0.1s/div, y axis: 5V/div)

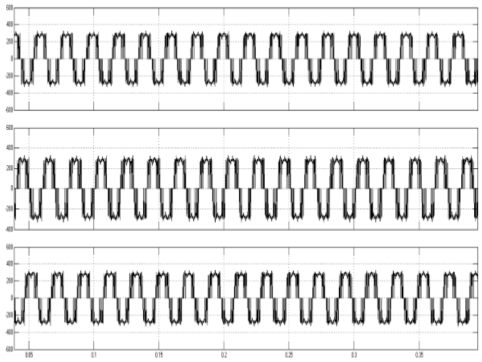


Fig 10 Line voltage for the inverter Vin = 100 V, Vdc avg = 300 V, Po = 1 HP, fo = 50 Hz, fs = 10 kHz. (x axis: 0.15s/div, y axis: 200V/div)

The speed response and the torque response of the machine are shown in figure 11 -12 where the speed response is almost steady and torque will less ripples. The torque waveform settles at a load torque of 2Nm. The speed waveform settles at its reference speed at 314rad/sec.

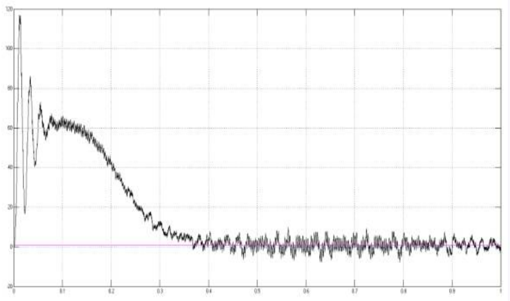


Fig 11 Torque waveform for SVPWAM inverter fed motor drive for a load torque of 2Nm (x axis: 0.1s/div, y axis: 20Nm/div)

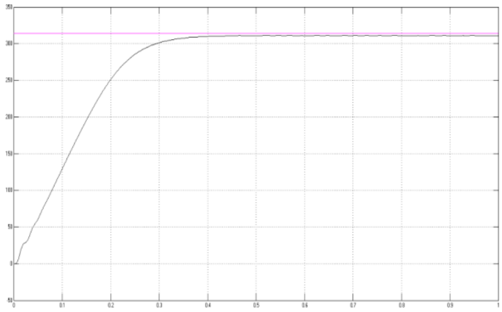


Fig 12 Speed waveform for SVPWAM inverter fed motor drive (x axis: 0.1s/div, y axis: 50rad/s/div)

VI. FFT ANALYSIS

By using FFT analysis overall THD of the output voltage is calculated. THD stands for Total Harmonic Distortion which is often used to define the degree of harmonic content in an alternating signal. Also keeping low THD values on a system will ensure proper operation of equipment and a longer equipment life span. In the case of SVPWAM the modulation index is always kept at its maximum value. When FFT analysis is done for converter - inverter fed Induction motor drive system it was found to be 4.57% as shown in figure 13.

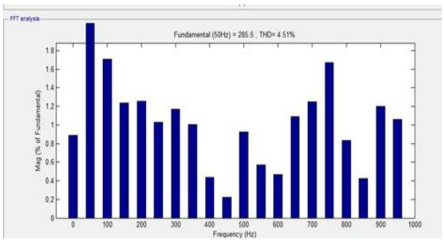


Fig 13 THD analysis of the system at 50Hz frequency

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VII. CONCLUSION

The implementation of Space vector pulse width amplitude modulation for a voltage source inverter fed Induction motor drive which has application in plug in hybrid electric vehicle is done using MATLAB/SIMULINK. The SVPWAM method was found to have less switching loss and THD when compared to any other PWM techniques. A rippled dc link voltage is maintained at the dc link using bidirectional dc/dc converter which gives the advantage of small dc link capacitor that reduces the size of the system. Another advantage is use of small heat sink due to reduced losses. Theoretical analysis is done for the switching losses and found as less. Efficiency of system can be improved with close loop control. Also a plug in hybrid vehicle that has solar array to recharge can be developed with reduced losses.

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