Electric Vehicle Control System Design

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The era of the internal combustion engine is moving towards an end, the world now seeks environment-friendly and more efficient systems for the automobile industry. Various nations have taken serious steps towards their Electric Vehicles (EV) due to shortage of fossil fuels and to reduce pollution thus by eliminating the greenhouse gases emission into the atmosphere. This paper describes the working and modeling of motors used in EVs, power electronics, and control systems used in them. The control system used is Space Vector Pulse Width Modulation (SVPWM). The work is modeled and simulated in MATLAB Simulink™ .

Keywords: Electric vehicles, Permanent Magnet motors, Synchronous Machines, Power Electronics, 3-Phase Inverters, PWM, Sine PWM, Space Vector, SVPWM, Field-Oriented Control.

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1 Introduction

Green Vehicles are considered as the best alternatives to overcome the issue of increased pollution in the environment caused by regular IC engine vehicles. These vehicles can help to reduce pollution to an acceptable level. These green vehicles include purely Electric vehicles, Hybrid vehicles, and some run on bio-fuels. In any case, all of them use electric motors like BLDC (Brushless DC) motors or PMSM (Permanent Magnet Synchronous Motors) to drive them. As both these motors run basically on a 3-Phase AC supply, they need inverters for power conversion from DC battery or in the case of a hybrid vehicle, from the alternator. Inverters have improved a lot since the usage of electric vehicles is increased. Many different techniques are used for power conversion and control of inverter outputs.

Pulse Width Modulation (PWM) has become a very common and easy-to-use method in power output control. Different types of PWM techniques like Sine-Wave PWM and Space Vector PWM are being used in inverters. The Sine-Wave PWM is quite inefficient as compared to Space Vector PWM. So, this paper describes the Space-Vector PWM technique of power conversion in inverters and its simulation.

2 Components of Electric Vehicle

Unlike and IC engine, an EV doesn't have too many moving parts. These components basically consist of driving motor, high-capacity battery, inverters for power conversion, control system, power trains, and different circuits for sensors. The battery is the fuel supply of an EV, it stores energy in form of DC voltage. Usually large capacity, lightweight and highly-efficient batteries are used to make the vehicle dynamics feasible. These batteries are connected to DC/DC convertors. These convertors supply power to inverters to convert DC into AC. Inverters are mostly made of IGBTs and MOSFETs in common H-Bridge configurations. The Gates of these transistors are connected to a reference source like PWM, Sine-PWM or Space Vector-PWM. This helps to have a control over amplitude and frequency of power supplied to electric motor. The steering wheel and brakes are mostly designed like common vehicles and connected to the control system through an electronic differential to adjust according to the speed of motor. All the power electronics' circuits and control systems are thermally cooled with help of air or coolant. Traction motors are the last stage of vehicle, they convert the supplied electrical energy to mechanical energy (rotating motion). Motors are connected to the wheels through gears or pulleys for desired torque requirements.

3 Electric Motor of an EV

Electric Vehicles use Brushless DC motors, Induction motors, and Permanent Magnet Synchronous Motors for traction. Induction motors are the least used nowadays due to their low torque at high speeds and inefficiency caused due to back emf. PMSM and BLDC motors are widely used in modern-day EVs. PMSMs have a sinusoidal back emf whereas BLDCs have a trapezoidal back emf. BLDC can work on stepped input DC voltage whereas PMSM requires a purely sinusoidal voltage. PMSM has reduced torque ripple and current-ripple than BLDC motors. PMSMs are expensive and highly efficient. Suitable for high-power and high-efficiency applications. BLDC motors are cost-effective. Suitable for low-power and low-cost applications.

In this paper, Permanent Magnet Synchronous Motors are used for experimentation and simulation. The Permanent Magnet Synchronous Motor is a 3-phase AC machine. PMSM is a brush-less motor since the excitation field is a permanent magnet that is mounted in the rotor. PMSMs are widely used in servo-systems, driving electric drivers, hybrid vehicles, industrial robots, etc. PMSMs have high efficiency, excellent controllability in full torque-speed operating range, lower weight-torque and weight power ratio, easier maintenance.

4 Modelling of a Permanent Magnet Synchronous Motor

This machine has 3-phase windings in stator which are either Y-connected or Δ-connected and spaced 120˚ apart around the surface of motor. The windings are distributed in sinusoidal fashion so as to minimize higher order harmonic component and to build up a magnetic field in the air gap that mainly consists of the fundamental sinusoidal component.

5 Power Inverters

The inverter functions to change the direct current (DC) on the battery into an alternating current (AC) and then this alternating current is used by an electric motor. In addition, the inverter on an electric car also has a function to change the AC when regenerative braking to DC and then used to recharge the battery. The type of inverter used in some electric car models is the bi-directional inverter category. A category of Voltage Source Inverter (VSI) called Pulse Width Modulated VSI is used to convert a DC voltage to sinusoidal voltage. IGBTs and MOSFETs are used to make inverter circuits. These components when connected in an H-Bridge configuration act as switches. This switching sequence creates an AC output which can be controlled through gates of these transistors.

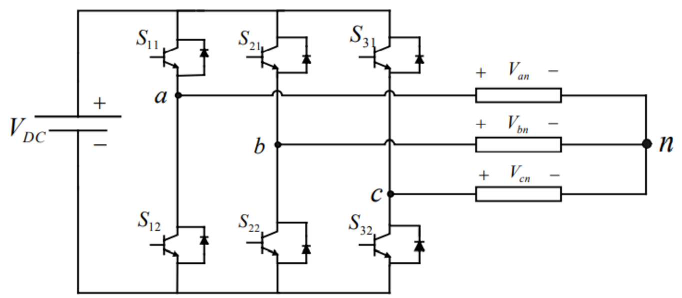

Fig. 1: Three-Phase Voltage Source Inverter

Both MOSFETs and IGBTs can be used in the h—bridge full wave rectifier. The transistors, when connected in this configuration act as switches. These switches act simultaneously on the reference gate signals sent to them. Following diagram shows how these transistors represent switches in the circuit.

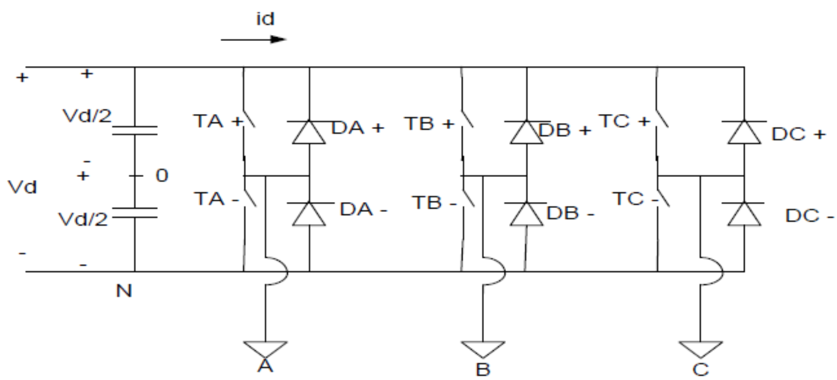

Fig. 2: Transistors as switches in 3-Phase VSI

The switches are mentioned as TA+, TA-, TB+, TB-, TC+ and TC-, whereas diodes DA+, DA-, DB+, DB-, DC+ and DC- are present to restrict current to flow in opposite direction. The switches open and close in a sequence directed by the gates of transistors. The wave output depends on the input gate signal.

6 Pulse Width Modulation (PWM)

It is a method of generating variable width pulses at discrete timing that average out the amplitude of an analog input signal. The output switching transistor is on more of the time for a high-amplitude signal and off more of the time for a low-amplitude signal. PWM circuits are mostly made with transistors. These transistors switch on and off as directed by the gate signals. When the signal is high, we call it “on time”. To determine the duration on time we use the concept of duty cycle. The duty cycle is the percentage of time of a digital signal over a period of time.
The power inverters output such an on-off signal which averages out an amplitude to drive the desired device. A PWM signal shown below can produce a sine wave.

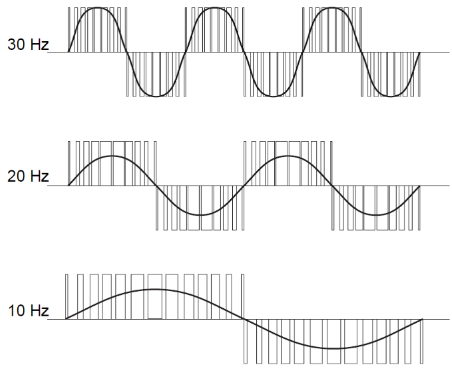

Fig. 3: PWM signal for sine-wave of different frequencies

There are three methods of PWM; Sinusoidal PWM Technique, Space Vector PWM Technique, and Hysteresis PWM Technique.

The Space Vector PWM technique generates less harmonic distortion in the output voltage or current and more efficient use of the DC link. Therefore, we will consider and use Space Vector PWM Technique only.

7 Space Vector Pulse Width Modulation (SVPWM)

Space Vector PWM (SVPWM) technique generates the signal gate (PWM signal) of IGBT or MOSFET by estimating the switching sequence of the upper IGBT groups of three phase inverters. This technique is used to reduce switching loses and increase inverter efficiency. It decreases the distortion in output alternating current of the inverter.

In this technique, the armature plane is divided in 6 planes, each of 60°. It has six active vectors (V_0-V_7) and two null vectors (V_0 and V_7). The switching sequences are generated in each sector. The eight possible switching vectors are six active vectors, V_1(100), V_2(110), V_3(010), V_4(011), V_5(001), V_6(101) and two null vectors V_0(000) and V_7(111). For generating the switching sequences V_{ref} and angle θ must be determined for every sector. This reference vector V_{ref} is generated as the resultant of voltage vectors (V_1, V_2) and one null vector in that sector. Also, the associated time duration T_1, T_2, T_0 of the voltages V_1, V_2, V_{ref} should be defined as well as the switching time of each transistor of the inverter.

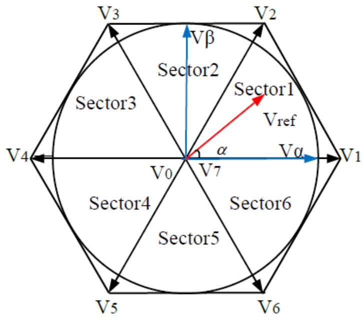

Fig. 4: Switching vectors, Sectors and Inscribed circle

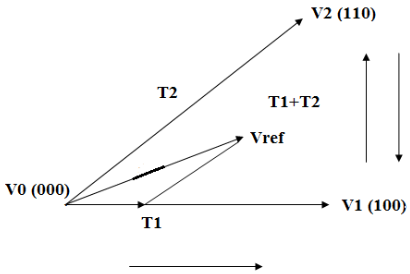

Fig. 5: Time interval calculation in SVPWM

In sector 1, V_1 with an interval time T_1 and vector V_2 has interval time T_2 then vector V_0 or V_7 for interval time To. While Vref varies from zero to the maximum amplitude, $V_{ref\text{-}max}$, before nonlinear over modulation is reached. To make sure, the summation of time for these states equals to the reference vector period. The interval time can be calculated with the help of the following equations:

$$V_{ref} = V_n.t_1 + V_{n+1}.T_2 + V_{null}.T_0 \qquad (1)$$
$$T_1 = T.m.\sin(60\text{-}\Delta\theta)$$
$$T_2 = T.m.\sin(\Delta\theta)$$
$$T_0 = T - T_1 - T_2 \qquad (2)$$

Here T is a switching period, m is the modulation factor (0-1), and $\Delta\theta$ is the angle between V_{ref} and V_n.

8 Application of SVPWM

The goal of SVPWM technique is to approximate V_{ref} vector by using the combination of eight switching vectors. There are 2 major steps to implement SVPWM:

1. Determine V_α, V_β, V_{ref} and the vector reference angle ($\alpha°$)
   By Clarke's Transformation we can write:

$$\begin{pmatrix} v_\alpha \\ v_\beta \end{pmatrix} = \frac{2}{3}\begin{pmatrix} v_a \\ v_b \\ v_c \end{pmatrix}\begin{pmatrix} 1 & -\frac{1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix} \qquad (3)$$

$$|v_{ref}| = \sqrt{v_\alpha^2 + v_\beta^2} \quad (4)$$

$$\alpha^0 = tan^{-1}\left(\frac{v_\alpha}{v_\beta}\right) = \omega t = 2\pi f t \quad (5)$$

Here f is the fundamental frequency of the desired output voltage.

2. Determine time duration T_1, T_2 and T_0

From figure 6: The Reference vector as a combination of Adjacent Vectors at sector 1, the switching time can be calculated as follows:
-Switching time duration at Sector 1

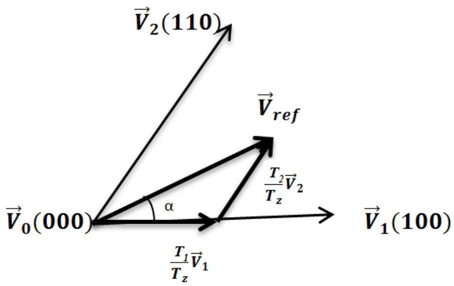

Fig. 6: Reference Vector as resultant of combination of Adjacent Vectors at Sector 1

$$\int_7^{Tz} \bar{v}_{ref} = \int_{T_0}^{T_1} v_4\,dt + \int_{T_1}^{T_1+T_2} v_6\,dt + \int_{T_1+T_2}^{Tz} v_0\,dt$$

$$T_z = T_1 + T_2 + T_0 \quad (6)$$

These equations can be used in simulation of the control system and inputs for input blocks.

9 Simulation of Control System with MATLAB

The Simulink Model of the 3-phase inverter, along with reference signals, VSI and PMSM is shown in figure 6, 7 and 8 based on SVPWM.

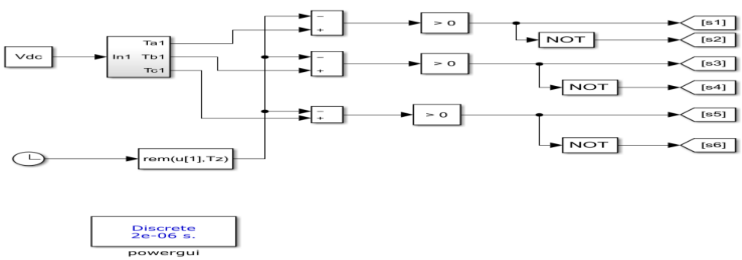

Fig. 6: Input reference signal

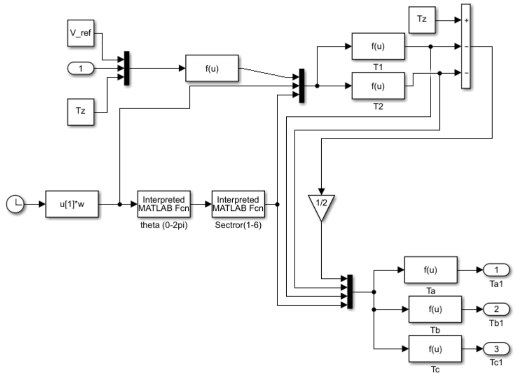

Fig. 7: 3-Phase SVPWM reference function subsystem

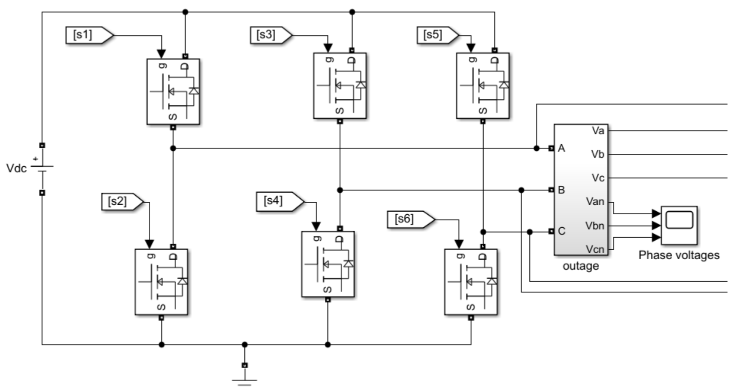

Fig. 8: Three-Phase Inverter Block Diagram

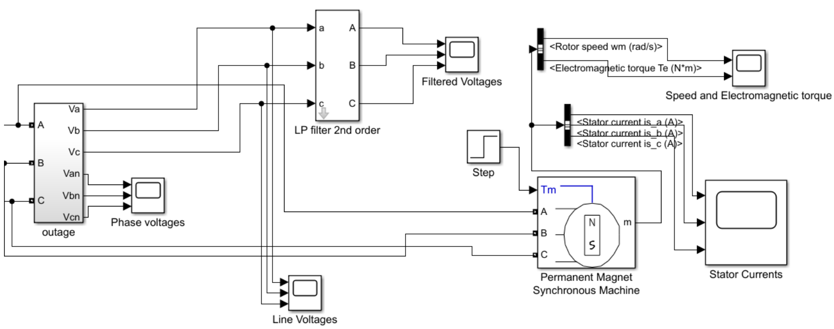

Fig. 9: Inverter output scopes and Motor System

The simulation is run for 0.5 seconds. Following figures are the readings of scopes for Phase voltages, line voltages, stator currents, speed & Electromagnetic torque of motor.

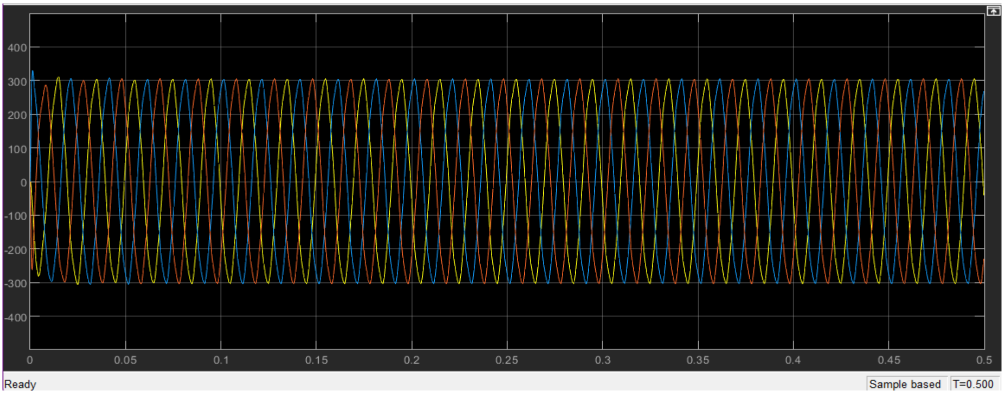

Fig. 10: Filtered Line voltages

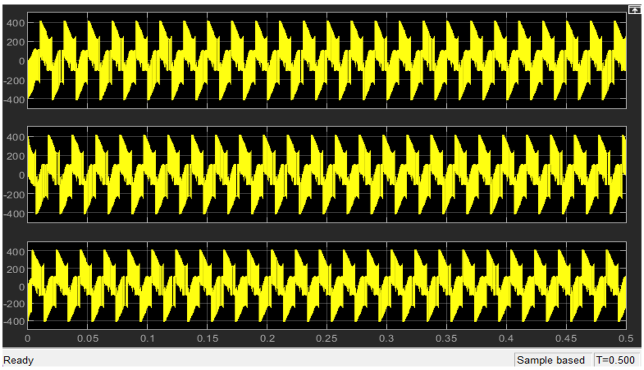

Fig. 11: PWM signal for Line Voltages

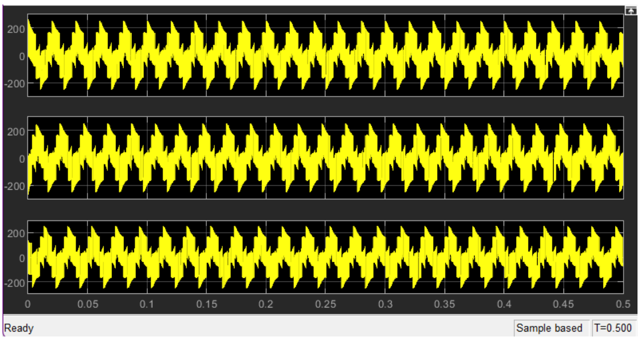

Fig. 12: PWM signal for Phase Voltages

Output Voltage Line-Line and Line-Neutral for One Cycle of Simulation
VSI Based on SVPWM shows the pulsing (switching frequency) of IGBTs to create the output voltage for one cycle.

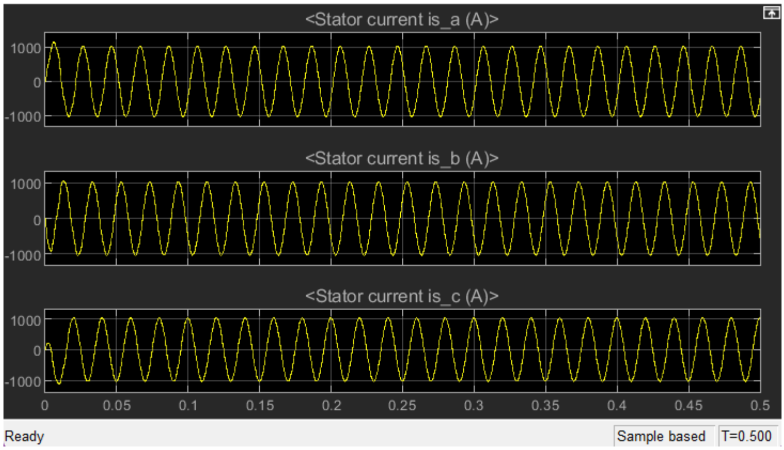

Fig. 13: Stator Current of PMSM

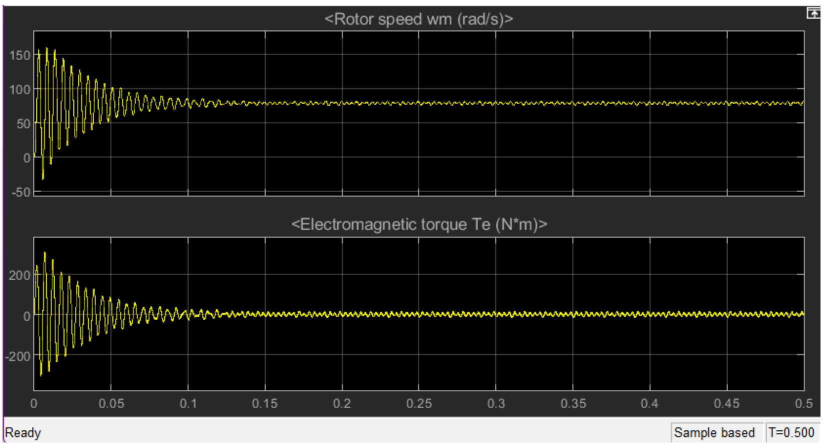

Fig. 14: Speed and Electromagnetic Torque output of motor

10 Field-Oriented Control (FOC)

This technique is developed for high performance control. It was first proposed by F. Blascke in 1971 to control an induction motor. The objective of FOC is to control the torque and the magnetic field, independently. The principle of FOC is to maintain an orthogonal angle between stator and rotor field component. Applying this, the stator filed does not affect the rotor field. Hence, the term Field-oriented control is adapted field angle control or angle control for systems which depart from the 90° orientation. In synchronous machines, the rotor winding (or permanent magnet) is the field winding whereas the stator winding is the armature winding.

11 Conclusions

In this paper a control system of electric vehicle using 3-Phase VSI and SVPWM is developed and simulated in MATLAB-Simulink. The circuit can produce a sinusoidal signal with some harmonics. The permanent magnet synchronous motor in simulation produces a speed about 76 rad/sec in 0.1 seconds. The gate signals can further be controlled for desired motor speed. The results satisfy the EV standards. For future development the control system may be adapted in heavy work vehicles and passenger vehicles.

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