Pulse Width Modulation Technique for Nine-phase Electric Vehicle Drive System

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Abstract. Multiphase machines have many advantages such as smoother torque and low stator current at each phase without increasing the stator voltage per phase and are mainly used in industrial applications. By implementing nine phase drive system the stator current reduces at each phase, which neglects the use of high-cost bulky power harnessing equipment’s that are used in the conventional 3-phase electric vehicle drive system. In this article, a nine phase electric vehicle inverter is designed for the electric vehicle drive system. Choosing a pulse width modulation technique is the foremost criterion. In this article sinusoidal pulse width modulation and space vector pulse width modulation technique is simulated and comparison is made based on the quality of power output. The simulation is modeled through Simulink software and the results are presented.

Keywords: Electric vehicle, Drive system, Nine phase inverter, Pulse width modulation.

1. INTRODUCTION

In recent years even developing countries are taking initiatives to replace conventional internal combustion engines (ICE) with smart hybrid engines which consist of both ICE and Electric motor for propulsion [1]. This shows that the days of ICE engines are ending with the new innovative advancements of electric motor driven vehicles also known as Electric vehicles (EV). The major setback in the commercialization of EV is the cost and its short battery lifetime (5-8 years) [2]. The cost of the battery and motor drive unit is the major reason for the high cost of EV when compared to the ICE engine. Employing new advancements or change of materials used for battery making the cost of the battery tends to reduce in upcoming years [3]. The cost of a motor drive unit can only be reduced with converter technology and by neglecting the high power harnessing and protection circuit. Since the EV operates the 3-phase motor at the high voltage the cost of the high voltage wiring harness system and the high voltage protection and power distribution system need to be eliminated to cut the cost of the EV [4]. This can be rectified by increasing the conventional 3-phase system into a Multi-phase drive system. This will replace the high power bulky components with low power smaller components [5]. Thus, the size of the components is reduced by 1/4th and a power capacity of 100kW can be achieved by a 48V battery system.

Multi-phase machine drives are used for high power industrial applications. The ability to distribute the high power across multiple inverter legs increases the fault tolerance capability made it an ideal choice for EV application. Increase in phase count the torque ripple is reduced and the resultant torque will be smoother [6]. Since, with a higher the phase count, higher the frequency of operation resulting in complex
pulse generation technique. In this article nine phase inverter is chosen for the EV drive system; because of the limitation such as frequency, power handling capability, and reliability of the semiconductor switch [7]. This article presents the construction and working principle of nine phase inverter and its advantages as an EV drive system. The rest of the paper organised as follows: section 2 - construction and working of nine phase inverter, Section 3 - Pulse Width Modulation control scheme, Section 4 - Simulation results and comparison, Section 5 - Conclusion.

2. CONSTRUCTION AND WORKING OF NINE PHASE INVERTER

The nine-phase machine consists of nine stator windings operate at an angle of 40° phase shift (360°/9). Each winding is energised by a separate inverter leg triggered by individual PWM signals at intervals of 40° out of phase with each other [9]. These nine stator windings are fed with help of a nine-phase inverter as shown in Figure 1.

![Figure 1. The fundamental structure of nine phase inverter.](image)

The nine phase inverter consists of nine legs; each leg consists of two semiconductor switch connected in series that operates at 180° conduction mode. Thus the two switches in the same leg will be either ON or OFF state depending upon control signals generated by pulse-width modulated (PWM) [11]. In this article due to high frequency and low power handling the MOSFETs are used as semiconductor switches at each leg. Here the load chosen for simulation is a star-connected RL load. Another important factor to be considered in designing of Nine-phase inverter is the nonlinear characteristic of EV. Nonlinear loads cause harmonics in electrical power converters resulting in poor power factor and high switching loss [12]. To overcome the above cons, various PWM techniques are used that varies the modulation index to minimize harmonic content. Different methods of PWM techniques used in power electronics in which Sinusoidal Pulse Width Modulation (SPWM) and Space Vector Pulse Width Modulation (SVPWM) is the most promising one. SVPWM is a complex technique and is under research in the other hand SPWM is simple and easy to implement. In this work, the SPWM technique is used to simulate a nine-phase inverter with RL load.

3. PWM TECHNIQUES FOR INVERTER

3.1. SPWM technique:

SPWM technique is the most predominantly implemented PWM technique in inverter technology. The pulses are generated by comparing the sinusoidal signal as a modulating signal with the carrier signal [13]. The carrier wave determines the switching frequency and the modulating wave which determines the frequency of the output wave. The frequency and amplitude of carrier wave frequency are higher than the
modulating wave. In this work sinusoidal wave is compared with the saw-tooth wave to generate a pulse for all 18 switches presented. 2.

Figure 2. Gate pulse generated using SPWM

The values of the modulation index are determined by the amplitude of the generated pulse. The amount of harmonic distortion is minimised by varying the modulation index [14]. The modulating sinusoidal signal is the fundamental frequency of inverter operation and the carrier saw-tooth wave (fs) must be of higher frequency compared to the fundamental frequency. Thus sinusoidal frequency gives the frequency at which the inverter operates and the frequency of carrier wave gives the switching frequency. Higher the carrier frequency, the smoother the output waveform.

The frequency modulation (f_m) is given by the ratio of the fundamental frequency (f_n) to the carrier saw tooth wave (f_s)

\[ f_m = \frac{f_s}{f_n} \]  

The modulation index (M) is given by the ratio of the peak amplitude of the sinusoidal signal (V_s) to the sawtooth signal (V_c)

\[ M = \frac{V_s}{V_c} \]  

PWM signals for nine phase inverter are generated using the SPWM technique and the corresponding results were obtained. SVPWM is another promising technique for quality inverter power output is also modeled for the nine phase inverter system.

3.2 SVPWM technique.

SVPWM distinguishes the switching sequence by assigning a switching vector in d-q planes [15-17]. There are nine inverter legs termed as shown in Figure 1 and the ON state of a particular switch is denoted as 1 and the OFF state is denoted as 0. The switching pattern of SVPWM for each leg is shown in Figure 3.

The space vectors for a nine phase system is 2^9 = 512 with four planes each with 18 sectors as shown in Figure 4. Since there are more number of space vectors, their derivations are neglected and only their final expressions are presented.

\[ \delta_{a1} = K_1 M \sin(s \pi/9 - \theta) ; \quad \delta_{b1} = K_1 M \sin(\theta - (s - 1) \pi/9) ; \]
\[ \delta_{a2} = K_2 M \sin(s \pi/9 - \theta) ; \quad \delta_{b2} = K_2 M \sin(\theta - (s - 1) \pi/9) ; \]
\[ \delta_{a3} = K_3 M \sin(s \pi/9 - \theta) ; \quad \delta_{b3} = K_3 M \sin(\theta - (s - 1) \pi/9) ; \]
\[ \delta_{a4} = K_4 M \sin(s \pi/9 - \theta) ; \quad \delta_{b4} = K_4 M \sin(\theta - (s - 1) \pi/9) ; \]
\[ \delta_0 = \delta_{511} = \frac{1}{2} \delta_0 = \frac{1}{2} \left[ 1 - K_4 M \cos \left( (2s - 1) \pi/18 - \theta \right) \right] ; \]

(3)
Where,

\( \delta \) - is the duty cycle and the subscripts denote the inverter legs.

\( M \) - Modulation index.

\( \theta \) - position of space vector in the d-q plane.

\[ K_p = \sin \left( p \frac{\pi}{9} \right) \]  

Figure 3. Switching pattern of SVPWM.

The modulation index \( M \) is given by the ratio of peak fundamental phase voltage (\( V_s \)) to one half of the DC bus voltage (1/2 \( V_{dc} \)) [18]. To generate a sinusoidal output there is a need for 8 active space vectors. The active space vectors at different planes are expressed in Figure 4.

The solution obtained with equation 3 is applicable for all the sectors (\( s = 1 \) to 18) and the constants are given as,

\[ K_p = \sin \left( p \frac{\pi}{9} \right) \]  

where \( p=1,2,3,\ldots9 \).
The duty cycle for an individual leg is obtained by summation of equation 3 with the switching pattern pre-determined for every pattern. The sequence of SV in all even and odd sectors are 0, \(b_1, a_2, b_3, a_4, b_4, a_3, b_2, a_1, 511, a_1, b_2, a_3, b_4, a_4, b_1, a_2, b_1, 0\) and 0, \(a_1, b_2, a_3, b_4, a_1, b_2, a_3, b_4, a_4, b_1, 511, b_1, a_2, b_3, a_1, b_4, a_3, b_2, a_1, 0\) respectively.

### 4. SIMULATION RESULTS AND COMPARISON

The output waveform of nine phase inverter with SPWM and SVPWM is obtained and a comparison is made. The output voltage and current waveform obtained for SPWM and SVPWM are shown in Figure 5 & 6. The presented waveforms are measured for line voltage and line current. When compare with SVPWM the output obtained by the SPWM technique has a high ripple; hence it requires an extra filter circuit to obtain a pure sine wave [19].
The fundamental frequency of the inverter is 50Hz and the input voltage is of 200V DC supply. The switching frequency is 2kHz for both SPWM and SVPWM. The value of the star-connected RL load is $R= 10\, \text{ohm}$ and $L= 56\, \text{mH}$. SVPWM also exhibits ripples in the output current waveform which can be overcome by increasing the switching frequency. Total Harmonic Distortion (THD) is an important factor to be considered for a drive system [20-22]. Since with presence of harmonics causes switching loss and power dissipated in the motor winding as heat which affects the reliability of the system. Hence the THD must be measured and need to be maintained within the limit. The value of THD is calculated using Fast Fourier Transform analysis using Matlab Simulink and is presented in Figure 7.
From the figure, it is observed that the THD of SPWM is higher when compared with the THD value of SVPWM. Though SPWM has higher THD the implementation of the SPWM technique is simpler and is used for practical implementation for a longer period which increases the reliability. SVPWM is a complex technique and is still in research to reduce the complexity of implementation for inverters. The inverter design is the heart of the electric drive system that produces a high-quality AC output to drive the machine at maximum efficiency.

5. CONCLUSION

Nine phase inverter is a is well known for high power applications in industries. By implementing nine phase inverter in the EV drive system the need for high input power to drive the machine is neglected. Thus the need for series connection of large number batteries can be reduced resulting in low power harnessing equipment and improves safety. The pulse generation for nine phase inverter is a prominent thing to be considered for quality power output. In this article, SPWM and SVPWM are simulated to drive a nine-phase inverter with RL load and the results are presented and a comparison is made. The results show that SVPWM has better performance than SPWM with fewer ripples. The power output of SPWM can be improved by using an optimum filter circuit. When compared with SPWM, SVPWM has better performance yet complex for implementation. Thus with reduced complexity, the SVPWM technique will be the best technique for EV drive systems in the future. On the other hand, SPWM with additional power processing equipment will be the best option for easy implementation and reliability of the EV drive system.

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