# THD Minimization of a Cascaded Nine Level Inverter Using Sinusoidal PWM and Space Vector Modulation

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**ABSTRACT:**

*Multi-level inverters offer several advantages such as a better output voltage with reduced total harmonic distortion (THD), reduction of voltage ratings of the power semiconductor switching devices and also the reduced electro-magnetic interference problems etc. Multilevel inverters synthesis the AC output voltages from various DC voltages. Space Vector Modulation (SVM) is one of the most popular PWM techniques used in multilevel inverters. SVM provides a best space vector performance, sequences of different space vectors suitable for voltage source inverter is identified. In this paper a 9 level cascaded H-bridge inverter model for space vector PWM is established and simulated using MATLAB/SIMULINK software and its performance is compared with sinusoidal PWM. The simulation study reveals that space vector PWM utilizes dc bus voltage more effectively and generates less THD when compared with sine PWM.*

***KEYWORDS:*** *Multilevel Inverters, THD, Sinusoidal Pulse Width Modulation (SPWM), Space Vector PWM.*

## I. INTRODUCTION

The multilevel inverters have drawn tremendous interest in the power industry that is well suited for use in reactive power compensation. The increasing number of energy sources and controlled AC drives requires new strategies for the operation and management of the electricity grid in order to maintain or even to improve the power supply reliability and quality [1]. Controlled AC drives in the megawatt range are usually connected to the medium-voltage network. For these reasons, a new family of multilevel inverters has emerged as the solution for working with higher voltage levels [2]. These inverters are suitable in high-voltage and high-power applications due to their ability to synthesize waveforms with better harmonic spectrum and attain higher voltages with a limited maximum device rating [3], the increased power ratings and reduced electromagnetic interference (EMI) emission that can be achieved with the multiple DC levels that are available for synthesis of the output voltage waveforms [4].Pulse-width modulation (PWM) techniques are gaining importance to control the multilevel inverters for multi megawatt industrial applications, recently.

The output voltage waveforms of the multilevel inverters can be generated at low switching frequencies with high efficiency, low distortion and also harmonics are shifted towards higher frequency bands. Many of the PWM techniques have been developed to achieve the following advantages [6]:

- wide linear modulation range,
- less switching losses,
- less total harmonic distortion (THD) in the spectrum of switching waveform,
- Easy implementation and less computation time.

One of the most popular PWM techniques in the multilevel inverters is Space Vector Pulse Width Modulation (SVPWM).

It was originally developed as a vector approach to PWM for three-phase inverters. Typical claims made for SVPWM include the following [7]:

- It achieves the wide linear modulation range associated with PWM third-harmonic injection automatically, without the need for distorted modulation.
- It has lower baseband harmonics than regular PWM or other sine based modulation methods optimizes harmonics.
- Only one switch changes state at a time.
- It is fast and convenient to compute.

## II. MULTILEVEL INVERTER

Multilevel inverters easily produce high-power, high voltage output with the multilevel structure because of the way in which device voltage stresses are controlled in the structure. Increasing the number of voltage levels in the inverter, without requiring higher ratings on individual devices, can increase the power rating. The unique structure of multilevel voltage source inverters allows them to reach high voltages with low harmonics without the use of transformers or series-connected synchronized switching devices. As the number of voltage levels increases, the harmonic content of the output voltage decreases significantly [6],[10],[11]. The multilevel inverters synthesize a near sinusoidal voltage from several levels of DC voltages. As the number of levels increases, the output has more steps, resembling a staircase wave that approaches a desired waveform. The harmonic content of the output decreases as the number of levels increases [6], [12]. As the number of levels increases, the output voltage that can be spanned by summing multiple voltage levels also increases [12], [7], [8]. The multilevel inverter can be classified into three types: i) diode clamped multilevel inverter ii) flying capacitors multilevel inverters and iii) cascaded multilevel inverter.

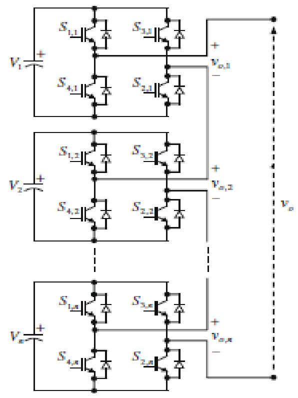

Fig. 1 configuration of cascaded m level inverter

Fig. 1 shows the configuration of cascaded multilevel inverter, the full bridge configuration with a separate DC source, which may be batteries, fuel cells or solar cells and are connected in series [5],[9]. Each full bridge inverter (FBI) unit can generate a three level output: $+V_{dc}$, 0 or $-V_{dc}$ by connecting the DC source to the AC load side by different combinations of the four switches $S_1$, $S_2$, $S_3$ and $S_4$.Using the top level as the example, turning on $S_1$ and $S_4$ yields $+V_{dc}$ output. Turning on $S_2$ and $S_3$ yields -Vdc output. Turning off all switches yields 0 volts output. The AC output voltage at other levels can be obtained in the same manner. The number of voltage levels at the load generally defines the number of FBIs in cascade. If N is the number of DC sources, the number of output voltage levels is m=2N+1.

The number of FBI units *N* is (m-1)/2 where m is the sum of the number of positive, negative and zero levels in multilevel inverter output. The number of converters *N* also depends on: 1) the injected voltage and current harmonic distortion requirements 2) the magnitude of the injected voltage required and 3) the available power switch voltage ratings [8]. The chosen inverter structure is simple since no real power needs to be supplied other than the losses. The DC sources are floating and no transformer is required for coupling to the transmission system. For each FBI unit, the current rating is the nominal current of the transmission system. The AC load rating and therefore the DC source rating depend upon the total compensation voltage required, the number of converters and the sharing of the load voltage among individual units.

The main features of cascaded multilevel inverters are:

- For real power conversions from DC to AC, the cascaded inverters need separate DC sources. The structure of separate DC sources is well suited for various renewable energy sources such as fuel cell, photovoltaic and biomass.
- Least number of components is required to achieve the same number of voltage levels.
- Optimized circuit layout and packaging are possible
- Soft-switching techniques can be used to reduce switching losses and device stresses.
- The modular structure of the inverter leads to advantages in terms of manufacturing and flexibility of application.

## III. SPACE VECTOR MODULATION

Space Vector Modulation (SVM) is quite different from PWM methods. It is a more sophisticated technique for generating sine wave that provides a higher voltage to the motor with lower total harmonic distortion. Space Vector PWM (SVPWM) method is an advanced; computation intensive PWM method and possibly the best techniques for variable frequency drive application. The circuit model of a typical three-phase inverter is shown in Fig. 2. $S_1$ to $S_6$ are the six power switches that shape the output, which are controlled by the switching variables a, a', b, b', c and c'. When an upper switch is switched on, i.e., when a, b or c is 1, the corresponding lower transistor is switched off, i.e., the corresponding a', b' or c' is 0. Therefore, the on and off states of the upper switch $S_1$, $S_3$ and $S_5$ can be used to determine the output voltage. SVPWM is a different approach from PWM modulation.

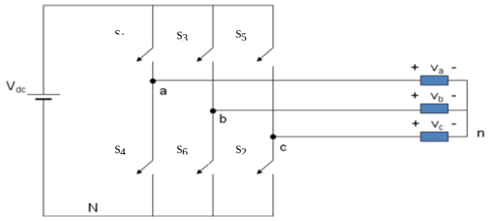


Fig. 2 Typical Three-Phase Inverter

In this modulation technique the three phase quantities can be transformed to their equivalent two-phase quantity either in synchronously rotating frame (or) stationary frame. From these two-phase components, the reference vector magnitude can be found and used for modulating the inverter output. The process of obtaining the rotating space vector is explained in the following section, considering the stationary reference frame.

### 3.1 Switching states of space vector modulation

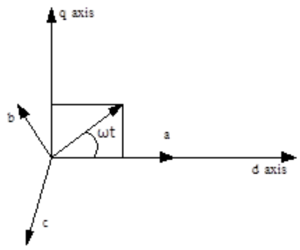


Fig. 3 Relationship of abc and dq reference frame

Considering the stationary reference frame let the three-phase sinusoidal voltage component be,

$V_a = V_m \sin\omega t$ (1)

$V_b = V_m \sin(\omega t-2\pi/3)$ (2)

$V_c = V_m \sin(\omega t+2\pi/3)$ (3)

The α-β components are found by Clark's transformation. Space Vector Modulation refers to a special switching sequence of the upper three power transistors of a three-phase power inverter. The stationary dq reference frame that consists of the horizontal (d) and vertical (q) axes as depicted in Fig.3. From Fig. 3, the relation between these two reference frames is below

$$V_{dq0} = Ks\ V_{abc} \quad (4)$$

$$K_s = 2\backslash 3 \begin{pmatrix} 1 & -1\backslash 2 & -1\backslash 2 \\ 0 & -\sqrt{3\backslash 2} & -\sqrt{3\backslash 2} \\ 1\backslash 2 & 1\backslash 2 & 1\backslash 2 \end{pmatrix} \quad (5)$$

$$V_{dqo} = [V_d V_q V_o]^T \quad \& \quad V_{abc} = [V_a V_b V_c]^T \quad (6)$$

In fig.3 this transformation is equivalent to orthogonal projection $[a\ b\ c]^T$ onto the two dimensional vector perpendicular to the vector $[1\ 1\ 1]^T$ in a three dimensional system. Six non-zero vectors and two zero vectors are depicted. Six non-zero vectors ($V_1$-$V_6$) shape the axes of a hexagonal as in Fig.4, and supplies power to the load. The angle between any adjacent two non-zero vectors is 60 degrees.

Meanwhile, two zero vectors ($V_0$ and $V_7$) and are at the origin and apply zero voltage to the load. The eight vectors are called the basic space vectors and are denoted by ($V_0$,$V_1$,$V_2$,$V_3$,$V_4$,$V_5$,$V_6$,$V_7$). The same transformation can be applied to the desired output voltage to get the desired reference voltage vector, $V_{ref}$ in the d-q plane. The objective of SVM technique is to approximate the reference voltage vector $V_{ref}$ using the eight switching patterns. One simple method of approximation is to generate the average output of the inverter in a small period T to be the same as that of $V_{ref}$ in the same period. 6 active vectors are ($V_1$,$V_2$,$V_3$,$V_4$,$V_5$,$V_6$). DC link voltage is supplied to the load. Each sector (1 to 6): 60 degrees. Two zero vectors are ($V_0$ and $V_7$). They are located at origin. No voltage is supplied to the load.

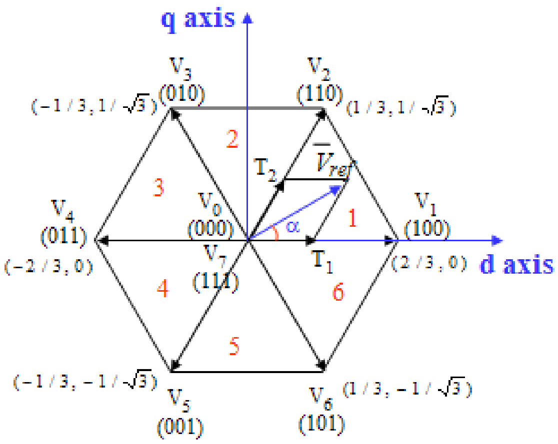


Fig .4 basic switching vectors and sectors

For 180° mode of operation, there exist six switching states and additionally two more states, which make all three switches of either upper arms or lower arms ON. To code these eight states in binary (one-zero representation), it is required to have three bits ($2^3$ = 8). And also, as always upper and lower switches are commutated in complementary fashion, it is enough to represent the status of either upper or lower arm switches.

Table-1 Switch states for three phase inverter

| Voltage Vectors | Switching Vectors | | | Line to neutral voltage | | | Line to line voltage | | |
|---|---|---|---|---|---|---|---|---|---|
| | a | b | c | $V_{an}$ | $V_{bn}$ | $V_{cn}$ | $V_{ab}$ | $V_{bc}$ | $V_{ca}$ |
| $V_o$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $V_1$ | 1 | 0 | 0 | 2/3 | -1/3 | -1/3 | 1 | 0 | -1 |
| $V_2$ | 1 | 1 | 0 | 1/3 | 1/3 | -2/3 | 0 | 1 | -1 |
| $V_3$ | 0 | 1 | 0 | -1/3 | 2/3 | -1/3 | -1 | 1 | 0 |
| $V_4$ | 0 | 1 | 1 | -2/3 | 1/3 | 1/3 | -1 | 0 | 1 |
| $V_5$ | 0 | 0 | 1 | -1/3 | -1/3 | 2/3 | 0 | -1 | 1 |
| $V_6$ | 1 | 0 | 1 | 1/3 | -2/3 | 1/3 | 1 | -1 | 0 |
| $V_7$ | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |

$S_1$ through $S_6$ are the six power transistors that shape the output voltage. When an upper switch is turned on (i.e., a, b or c is "1"), the corresponding lower switch is turned off (i.e., a', b' or c' is "0").Eight possible combinations of on and off patterns for the three upper transistors ($S_1$, $S_3$, $S_5$) are possible.

## IV. SIMULATION RESULTS

The main aim of any modulation technique is to obtain variable output having maximum fundamental component with minimum harmonics. The objective of Pulse Width Modulation techniques is enhancement of fundamental output voltage and reduction of harmonic content in Three Phase Voltage Source Inverters. In this paper different PWM techniques are compared in terms of Total Harmonic Distortion (THD). Simulink Models has been developed for SPWM, SVPWM, and the Simulation work is carried in MATLAB /Simulink.

### 4.1 Simulation Sinusoidal PWM

In Sinusoidal PWM three phase reference modulating signals are compared against a common triangular carrier to generate the PWM signals for the three phases. Fig.5 shows the Simulink of cascaded nine level inverter with sinusoidal pulse width modulation scheme. Simulation has been carried out by varying the modulation index between 0 and 1.

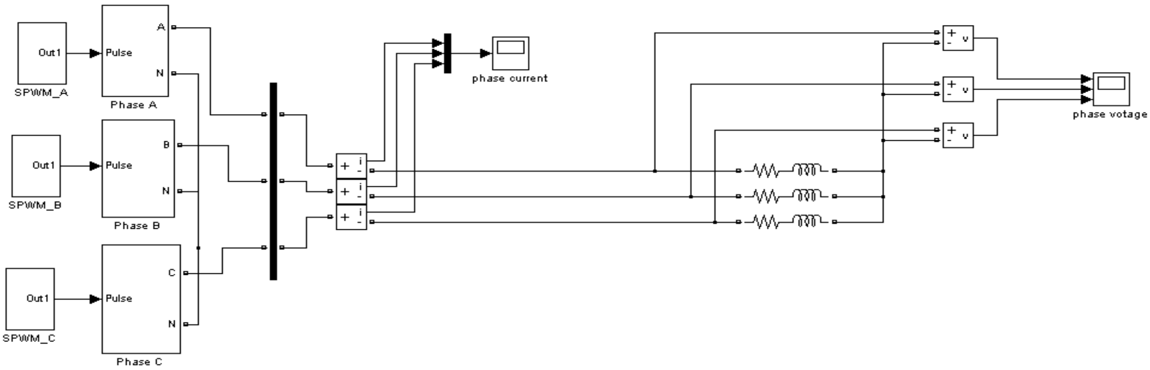


Fig.5 Simulink of cascaded nine level inverter with SPWM

### 4.2 Simulation Space vector modulation

Space vector PWM is an advanced technique used for variable frequency drive applications. It utilizes dc bus voltage more effectively and generates less THD in the Cascaded H Bridge Inverter. SVPWM utilize a chaotic changing switching frequency to spread the harmonics continuously to a wide band area so that the peak harmonics can be reduced greatly. Figs.6 and 7 shows the Simulink of cascaded nine level inverter with space vector pulse width modulation scheme and switching strategy of SVPWM. Simulation has been carried out by varying the modulation index between 0 and 1.

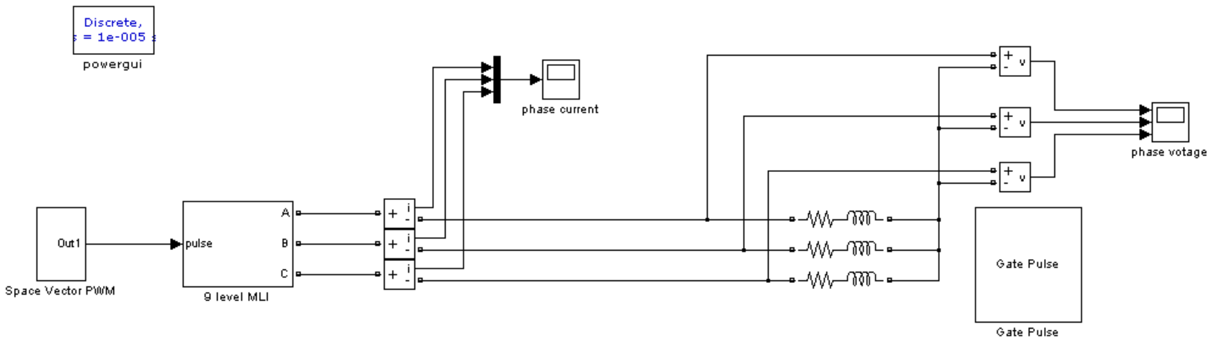


Fig.6 Simulink of cascaded nine level inverter with SVPWM

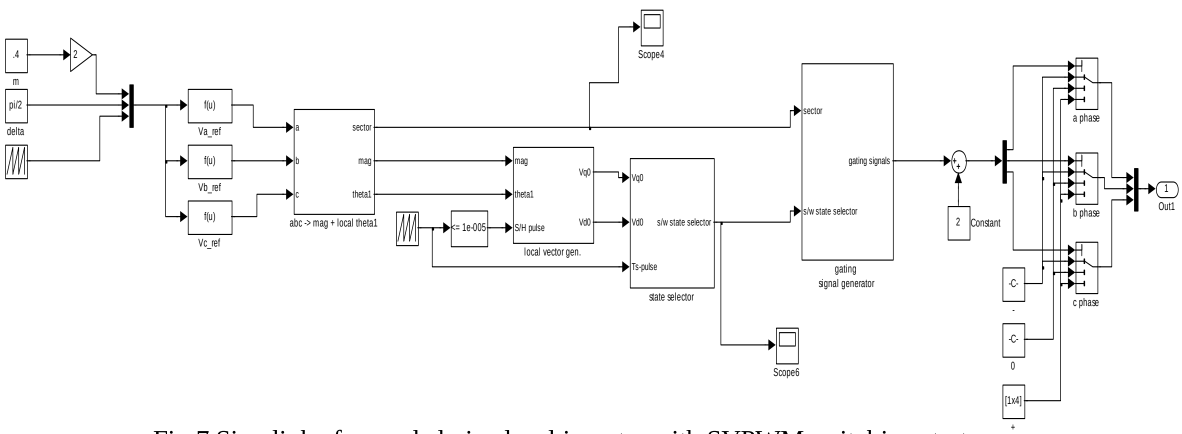


Fig.7 Simulink of cascaded nine level inverter with SVPWM switching strategy

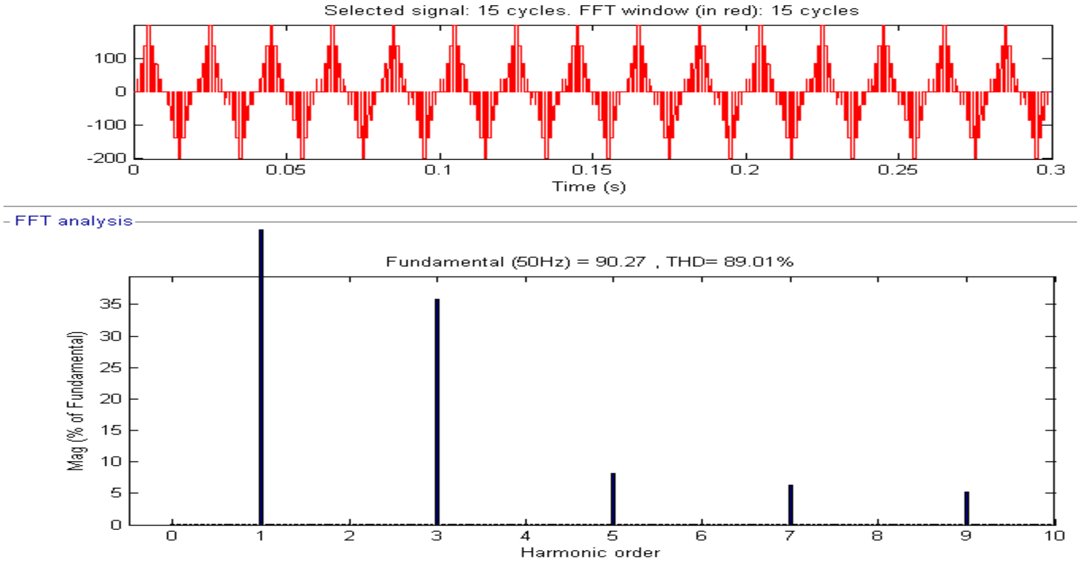


Fig.8. FFT and THD analysis of cascaded nine level inverter using SPWM with $m_a$=0.8

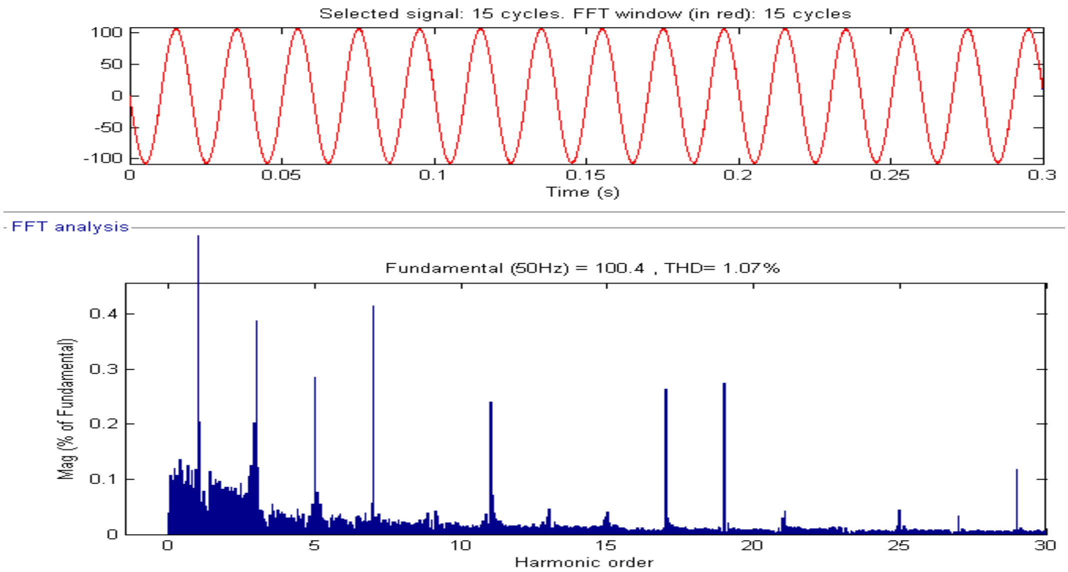


Fig.9. FFT and THD analysis of cascaded nine level inverter using SVPWM with $m_a$=0.8

Table-2 Comparisons between SPWM and SVPWM by varying modulation index
(For 9 level cascaded H- bridge inverter)

| **Technique** | **Sinusoidal PWM** | | **Space Vector PWM** | |
|---|---|---|---|---|
| **Modulation Index (M)** | **Output line voltage (volts)** | **THD (%)** | **Output line voltage (volts)** | **THD (%)** |
| 0.4 | 57.60 | 148.57 | 61.45 | 1.57 |
| 0.6 | 65.70 | 121.60 | 83.74 | 1.25 |
| 0.8 | 90.27 | 69.01 | 100.40 | 1.07 |
| **1.0** | **117.80** | **61.56** | **123.00** | **0.92** |

## V. CONCLUSION

Space vector Modulation Technique has become the most popular and important PWM technique for Three Phase Voltage Source Inverters. In this paper first comparative analysis of Space Vector PWM with conventional SPWM for a 9 level Inverter is carried out. The Simulation study reveals that SVPWM gives 0.92% enhanced fundamental output with better quality i.e. lesser THD compared to SPWM. Space vector Modulation Technique has become the most popular and important PWM technique for Three Phase Inverters. In this paper first comparative analysis of Space Vector PWM with conventional SPWM for a 9 level Inverter is carried out. The Simulation study reveals that SVPWM gives 0.92% enhanced fundamental output with better quality i.e. lesser THD compared to SPWM. PWM strategies viz. SPWM and SVPWM are implemented in MATLAB/SIMULINK software and its performance is compared with conventional PWM techniques.

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