Analysis, Simulation and Implementation of Space Vector Pulse Width Modulation Inverter

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Abstract: - This paper presents analysis, simulation and implementation of Space vector pulse width modulation (SVPWM) inverter. Principles of the SVPWM is introduced and analyzed. Modeling of the switching intervals and control signal generators are introduced. Implementation and Experimental results of SVPWM inverter are presented to realize the validity of the SVPWM technique.

Key-Words: - Inverter – Pulse width modulation – Space vector pulse width modulation

1 Introduction
The inverters are used to convert the dc voltage into ac voltage with controlled voltage and frequency. The waveform of the output voltage depends on the switching states of the six switches. Many applications of inverters face three major requirements and limitations [1-4]. The harmonic contents, the switching frequency, and the best utilization of dc link voltage. In general, drive systems with low harmonic contents are better than that with high harmonic contents. High switching frequency usually improves the quality of the motor currents and consequently the whole performance of the drive system. However, high switching frequency leads to more switching losses in the inverter switches. Also high switching frequency is limited by the switching capability and dead time of the switches. The best utilization of the dc link voltage depends on the applied technique of switching. There are several techniques of switching the inverter switches such as the six step inverter, hysteresis current controller, sinusoidal pulse width modulation, and space vector pulse width modulation. Each technique has its own advantages and disadvantages. Importance of SVPWM technique leads to recent utilization of parallel three phase Inverters using SVPWM technique [5].

This paper presents three main PWM techniques. Analysis, modeling and implementation of SVPWM technique are presented due to its more advantages than the other techniques. Implementation and experimental results verify the inverter analysis and simulation.

2 Voltage-Source Pulse Width Modulation (PWM) Inverter
A typical voltage-source converter performs the voltage and frequency conversion in two stages: ac to dc as a first stage and dc to ac for the second stage. Although the three phase six-step inverter offers simple control and low switching loss, lower order harmonics are relatively high resulting in high distortion of the current wave (unless significant filtering is performed). On the other hand, PWM inverter offers less harmonic contents than six-step inverter. The basic three-phase voltage-source converter is shown in Fig. 1

3 PWM Principle
The dc input to the inverter is “chopped” by switching devices in the inverter (bipolar transistors, thyristors, Mosfet, IGBT …etc). The amplitude and harmonic contents of the ac waveform are controlled by controlling the duty cycle of the switches. This is the basic of the pulse width modulation PWM techniques [1,2].

There are several PWM techniques each has its own advantages and also disadvantages. The basic PWM techniques are described briefly in the following subsections. The considered PWM techniques are:
Sinusoidal PWM (most common)
Hysteresis band current control
Space-Vector PWM
3.1 Sinusoidal PWM

The most popular PWM approach is the sinusoidal PWM. In this method a triangular (carrier) wave is compared to a sinusoidal wave of the desired fundamental frequency and the relative levels of the two signals are used to determine the pulse widths and control the switching of devices in each phase leg of the inverter. Therefore, the pulse width is a sinusoidal function of the angular position of the reference signal. The basic principle of three phase sinusoidal PWM is shown in Fig. 2. The sinusoidal PWM is easy to implement using analog integrators and comparators for the generation of the carrier and switching states. However, due to the variation of the sinewave reference values during a PWM period, the relation between reference values and the carrier wave is not fixed.

This results in existence of harmonics in the output voltage causing undesired low-frequency torque and speed pulsations. The switching frequency is not constant and very narrow pulses may occur depending on the intersection between the carrier wave and the sine reference.

3.2 Hysteresis-band current control

In hysteresis-band current control the actual current tracks the form of command current within a hysteresis band. In this approach the reference current wave is compared to the actual current wave thus producing the current error [6]. When the current error exceeds a predefined hysteresis band, the upper switch in the half-bridge is turned off and the lower switch is turned on. As the current error goes below the hysteresis band, the opposite switching takes place. The principle of hysteresis-band current control is illustrated in Fig. 3.

Peak to peak current ripple and switching frequency are related to the width of hysteresis band. As the width of the hysteresis band increases, the current ripples increases and the switching frequency decreases. On the other hand when the hysteresis band decreases, the current waveform becomes better having less low order harmonic contents but in this case the switching frequency increases and consequently the switching losses. As a result, the selection of the width of the hysteresis band must be carried out to optimize the balance between harmonic ripples and inverter switching losses.

Hysteresis-band current control is very popular because it is simple to implement, has fast transient response, direct limiting of device peak current and practical insensitivity to machine parameters because of the elimination of any additional current controllers. However, PWM frequency is not fixed which results in non-optimal harmonic ripple in machine current.
The current error is not strictly limited and may leave the hysteresis band. There is no interaction between the three phases. These drawbacks limit the application of this approach into special applications.

3.3 Space vector pulse width modulation

Space vector PWM refers to a special switching scheme of the six power semiconductor switches of a three-phase power converter [7]. Space vector PWM (SVPWM) has become a popular PWM technique for three-phase voltage-source inverters in applications such as control of induction and permanent magnet synchronous motors. The mentioned drawbacks of the sinusoidal PWM and hysteresis-band current control are reduced using this technique. Instead of using a separate modulator for each of the three phases (as in the previous techniques), the complex reference voltage vector is processed as a whole. Therefore, the interaction between the three motor phases is considered. It has been shown, that SVPWM generates less harmonic distortion in both output voltage and current applied to the phases of an ac motor and provides a more efficient use of the supply voltage in comparison with sinusoidal modulation techniques. SVPWM provides a constant switching frequency and therefore the switching frequency can be adjusted easily. Although SVPWM is more complicated than sinusoidal PWM and hysteresis-band current control, it may be implemented easily with modern DSP-based control systems.

The phase voltages corresponding to the eight combinations of switching patterns can be calculated and then converted into the stator two-phase (αβ) reference frame. This transformation results in six non-zero voltage vectors and two zero vectors. The non-zero vectors form the axes of a hexagon containing six sectors (V_1 - V_6) as shown in Fig. 4.

The angle between any adjacent two non-zero vectors is 60 electrical degrees. The zero vectors are at the origin and apply a zero voltage vector to the motor. The envelope of the hexagon formed by the non-zero vectors is the locus of the maximum output voltage.

The maximum output phase voltage and line-to-line voltage that can be achieved by applying SVPWM are:

\[ V_{ph\ max} = \frac{V_{dc}}{\sqrt{3}} \quad V_{ll\ max} = V_{dc} \]

And the r.m.s. output phase voltage and line-to-line voltage are:

\[ V_{ph\ rms} = \frac{V_{dc}}{\sqrt{6}} \quad V_{ll\ rms} = \frac{V_{dc}}{\sqrt{2}} \]

Therefore the dc voltage \( V_{dc} \) for a given motor r.m.s. voltage \( V_{ph\ rms} \) is:

\[ V_{dc} = \sqrt{6} \times V_{ph\ rms} \]

8.4 Principle of space vector pulse width modulation

Eight possible combinations of on and off patterns may be achieved. The on and off states of the lower switches are the inverted states of the upper ones. Practically, only two adjacent non-zero voltage vectors \( V_1 \) and \( V_{1+60} \) and the zero vectors should be used. Depending on the reference voltages \( V_\alpha \) and \( V_\beta \), the corresponding sector is firstly determined. The sector identification is carried out using the flow chart in Fig. 5. The switching patterns in the six sectors are illustrated in Fig. 6. This is the best
choice of three general patterns that will be introduced later in this paper. The procedure of calculating the time intervals $T_k$ and $T_{k+1}$ is discussed as follows:

The non-zero vectors can be represented by the following equation:

$$V_s^*(k) = \frac{2}{3} v_d e^{j(k-1)\frac{\pi}{3}}$$

(k=1, 2, 3, 4, 5, 6)

Therefore

$$V_s^*(k) = \frac{2}{3} v_d [\cos(k-1)\frac{\pi}{3} + j\sin(k-1)\frac{\pi}{3}]$$

(2)

$$V_s^*(k+1) = \frac{2}{3} v_d e^{j\frac{\pi}{3}} = \frac{2}{3} v_d [\cos\frac{k\pi}{3} + j\sin\frac{k\pi}{3}]$$

(3)

Due to symmetry in the patterns in the six sectors, the following integration can be carried out for only half of the pulse width modulation period ($T_s/2$).

$$\int_0^{T_s/2} V_a^* dt = \int_0^{T_0/4} V_a^* dt + \int_{T_0/4}^{T_0/T_k + T_{k+1}} V_a^* dt + \int_{T_0/T_k + T_{k+1}}^{T_s/2} V_a^* dt + \int_{T_s/2}^{T_0} V_7 dt$$

(4)

Assuming that the reference voltage $\vec{V}_{\text{ref}}$ into its two components $V_a$ and $V_\beta$ gives the following result:

$$\begin{bmatrix} V_a \\ V_\beta \end{bmatrix} = \frac{2}{3} v_d \begin{bmatrix} \cos \frac{(k-1)\pi}{3} \\ \sin \frac{(k-1)\pi}{3} \end{bmatrix} + \begin{bmatrix} \cos \frac{k\pi}{3} \\ \sin \frac{k\pi}{3} \end{bmatrix}$$

(5)

Solving the last equation, the time intervals $T_k$ and $T_{k+1}$ can be calculated as:

$$\begin{bmatrix} T_k \\ T_{k+1} \end{bmatrix} = \frac{\sqrt{3}T_s}{2v_d} \begin{bmatrix} \sin \frac{k\pi}{3} \\ -\sin \frac{(k-1)\pi}{3} \end{bmatrix}$$

(6)

Since the sum of $2T_k$ and $2T_{k+1}$ should be less than or equal to $T_s$, the inverter has to stay in zero state for the rest of the period. The period of zero voltage is

$$T_0 = T_s - 2(T_k + T_{k+1})$$

(7)

Having determined the time intervals $T_k$, $T_{k+1}$, and $T_0$, every PWM period, three general patterns can be applied.

Fig. 5 Flow chart for determining the sector.
4 Inverter Model

The inverter is modeled using three functions that calculate the output phase voltages of the inverter depending on the following relations between the dc voltage \( V_{dc} \) and the switching states of the upper switches \( S_a, S_b, \) and \( S_c \).

\[
V_a = (2S_a - S_b - S_c) \times \frac{V_{dc}}{3} \quad (8)
\]
\[
V_b = (2S_b - S_a - S_c) \times \frac{V_{dc}}{3} \quad (9)
\]
\[
V_c = (2S_c - S_a - S_b) \times \frac{V_{dc}}{3} \quad (10)
\]

5 Switching Intervals Generator

The current controllers produce the voltage references in the d-q rotor reference frame. The voltage references \( V_d \) and \( V_q \) are transformed to the stator two phase (αβ) reference frame to give the reference voltages \( V_\alpha \) and \( V_\beta \). These voltage references are the inputs to the switching intervals generator that is shown in Fig. 8. This block works according to equation 6 to produce finally the switching intervals \( T_k \) and \( T_{k+1} \). The outputs of this block are supplied to the control signals generator which is described in the following section.

6 Control Signal Generator

The block of the control signals generator and its details are illustrated in Fig. 9. The input of the model is the switching intervals \( T_k \) and \( T_{k+1} \). The off period \( T_0 \) is calculated as given in equation 7.
To generate the control signals, a repeating sequence as shown in Fig. 10a is built. During each SVPWM period ($T_s$), the repeating sequence is compared with the values of the switching intervals $T_0/4$, $T_0/4 + T_k$, and $T_0/4 + T_k + T_{k+1}$. The outputs of the three comparators are the control signals of the upper switches of the inverter as shown in Fig. 10b for a certain sector. Depending on the sector number, the control signal generator outputs the suitable control signal to each switch using look up tables and multiport switches.

### 7 Inverter Hardware

An intelligent power module (IPM) PM25RSB120 is used to implement the inverter. The power module is advanced hybrid power devices that combine high speed, low loss IGBTs with optimized gate drive and protection circuitry. Highly effective over-current and short-circuit protection is realized through the use of advanced current sense IGBT chips that allow continuous monitoring of power device current. The IGBT power switches in the IPM are controlled by a low level input signal.
The active low control input keeps the power devices off when it is in the high state and the power switches are kept off when the input signals are high. IPMs have sophisticated built-in protection circuits that prevent the power devices from being damaged. A fault output signal is provided to alert the system controller if any of the protection circuits are activated. The fault and on/off control signals are usually transferred to and from the system controller using isolating interface circuits.

8 Implementation and Experimental results
The SVPWM is achieved by applying a software C program to control the position and speed of a permanent magnet synchronous motor [10]. Switching patterns in two different sectors of SVPWM are given in Fig. 11 and inverter output voltage is illustrated in Fig. 12.

Details of this program explained in the following steps:
1- Read analogue signals from A/D converters simultaneously
2- Executing the main program until the step of generating the reference voltages \( v_q \) and \( v_d \).
3- The reference voltages \( v_q \) and \( v_d \) are transformed to the reference voltages \( v_\alpha \) and \( v_\beta \). The reference voltages \( v_\alpha \) and \( v_\beta \) are utilized to determine the sector of the vectors from 1 to 6

![Diagram](image1)

a- Comparing a repeating sequence with switching intervals

![Diagram](image2)

b- Control signals

![Diagram](image3)

Fig. 10 Control signals in a certain section and calculate the corresponding pattern and durations \( T_k \), \( T_{k+1} \), and \( T_0 \). Over modulation is detected and corrected if the case \( T_k + T_{k+1} \) exceeds the pulse width modulation period.

4- Output the control signals and wait for the instantaneous PWM period to complete.

Fig. 11 Switching patterns in two different sectors of SVPWM

![Diagram](image4)

Fig. 12 inverter output voltage

**Conclusion**
Analysis of space vector pulse width modulation is presented. Different patterns are introduced and the most effective one is selected. Analysis, modeling and simulation of the switching intervals generators...
and control signal generators are introduced. Experimental results and steps of generating SVPWM patterns using microcomputer are presented to verify the effectiveness of the analysis and simulation.

References: