Performance Evaluation of SV PWM Technique for 7-Phase VSI

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Abstract

This paper presents the performance evaluation SVPWM technique for 7-phase voltage source inverter in matlab/simulink environment. Seven-phase voltage source inverters are dominantly used to supply the seven-phase drives which are used for high power applications. It is necessary to develop appropriate space vectors for the inverters to provide required output voltages to a seven phase machine. The performances 7-phase VSI are analyzed for MSV, LMSV and LSV techniques. The output voltage and THD are observed through simulation. The performances of the inverter with the above switching vectors are compared for different modulation indices and the results are presented.

Keywords

Large space vectors (LSV), large and medium space vectors (LMSV), medium space vectors (MSV), voltage source inverter (VSI)

I. INTRODUCTION

Multi-phase VSI are becoming as a front end converter for multi-phase drive applications, such as ship propulsion, electric aircraft, and electric/hybrid electric vehicles etc. The multi-phase inverter circuit topology uses two switches connected in series as one inverter pole. The number of inverter poles depends on number of phases. For example, a three-phase inverter will have three inverter arms whereas a nine-phase inverter will have nine inverter arms. Conventional PWM technique adapted for conventional three phase VSI which can be extended for multi-phase VSI also. The most widely used PWM techniques for multi-phase inverters are the carrier-based SPWM and SVPWM [1-15]. The SPWM technique is simple, easy to implement and extensively reported in the literature [1]. However the limitation of SPWM is that the maximum peak of the fundamental component in the output voltage is 50% of the DC link voltage is discussed in [1]. The Carrier-based methods for five-phase VSIs were analyzed in [8-11]. By extending the well-known third harmonic injection principle for three-phase VSIs [8], it has been shown that in the case of a five-phase VSI injection of the fifth harmonic leads to an increase in the DC bus utilization in the linear modulation region is 5.15%. A simplified SVPWM approach is developed in [10-14] by using the concept of offset time. However, SVPWM has become the most popular one because of the easiness of digital implementation and better output voltage compared to sinusoidal PWM method. Moreover, imaginary switching times based SVPWM algorithm is used in [14]. In this method dc bus utilisation is less compared to conventional SVPWM. SVPWM for three-phase voltage source inverter has been extensively discussed in the literature [4]. As far as space vector modulation of a five-phase VSI is concerned, there are a very few SVPWM schemes currently available. The simplest method of realising SVPWM is to utilise only ten large vectors, belonging to the largest decagon in the d-q plane, in order to implement the symmetrical SVPWM [15-18]. It is seen that two active space vectors and two zero space vectors are utilised in one switching period to synthesise the input reference voltage. This method is a simple extension of space vector modulation of three-phase VSIs. The only attempt to realise sinusoidal output voltages by means of SVPWM of a five-phase VSI is described in [19,20]. The space vector PWM based seven phase voltage source inverter is considered only in [21,22]. However, in this scheme six active and two null vectors are considered.

In this paper the performance evaluation SVPWM technique for seven-phase voltage source inverter in matlab/simulink environment is developed. SVPWM technique of a large, medium and combinations of large and medium space vectors are detailed. An attempt is made in this paper for various simulation results are obtained for seven-phase inverter at different modulation indices. The effectiveness of this method is investigated in terms of percentage increase of fundamental voltage and THD for different space vector combinations.

II. POWER CIRCUIT OF SEVEN-PHASE VOLTAGE SOURCE INVERTER

Fig.1 Power circuit diagram of seven-phase VSI
The power circuit of a seven-phase VSI is shown in Fig.1. The circuit consists of 7 half-bridges, which are mutually displaced by $2\pi/n$ degrees to generate the 7-phase voltage waves. The input dc supply is obtained from a single phase or 3-phase utility power supply through a diode-bridge rectifier. The voltages $V_a, V_b, V_c, V_d, V_e$ and $V_f$ are the inverter pole voltages connected to load terminals. It is seen that the switching states of each pole should be combined with each other pole to create the required 7-phase output voltages. The load phase voltages and inverter pole voltages is as given in the following relations

$$
\begin{align*}
V_a &= \frac{1}{n} \left( V_c + V_e + V_f + V_d + V_V + V_f + V_e \right) \\
V_b &= \frac{1}{n} \left( V_d + V_e + V_f + V_a + V_b + V_d + V_c \right) \\
V_c &= \frac{1}{n} \left( V_f + V_b + V_a + V_c + V_d + V_f + V_g \right) \\
V_d &= \frac{1}{n} \left( V_g + V_a + V_b + V_c + V_d + V_g + V_e \right) \\
V_e &= \frac{1}{n} \left( V_c + V_b + V_a + V_d + V_e + V_c + V_f \right) \\
V_f &= \frac{1}{n} \left( V_g + V_b + V_a + V_c + V_f + V_g + V_e \right) \\
V_g &= \frac{1}{n} \left( V_e + V_a + V_b + V_c + V_g + V_e + V_f \right)
\end{align*}
$$

(1)

The svpwm technique for seven phase VSI is discussed in the following sections.

III. SVPWM Technique

In a seven phase system the inverter space vectors are seven-dimensional space. A space can be decomposed into three two-dimensional sub-spaces ($d_1-q_1$, $d_2-q_2$ and $d_3-q_3$) and one single dimensional sub space (zero-sequence). The problems in the $d_1-q_2$, $d_1-q_3$ and zero sub-spaces are extensively reported in [15]. Therefore, in order to generate pure sinusoidal output voltages, SVPWM technique must synthesize fundamental component in the $d_1-q_1$ plane. In the proposed work, only the $d_1-q_1$ plane for different space vector is considered. Fig.2 shows the $d_1-q_1$ plane for seven-phase VSI. In a seven-phase system the inverter space vectors are two-dimensional space as expressed in (3).

$$
V_{ref} = \begin{bmatrix}
1 & \cos \alpha & \cos 2\alpha & \cos 3\alpha & \cos 4\alpha & \cos 5\alpha & \cos 6\alpha \\
0 & \sin \alpha & \sin 2\alpha & \sin 3\alpha & \sin 4\alpha & \sin 5\alpha & \sin 6\alpha
\end{bmatrix}
$$

(3)

where $\alpha=2\pi/n$

Thus $d_1-q_1$ plane can be visualized as being composed of three different space vectors, each plane can be divided into 14 sectors. In the proposed work, a large (outer-most) space vector is considered. This is the simplest extension of a three-phase SVPWM and only the outer most plane is considered in order to generate output voltages, based on the reference space vector.

The three types of space vector techniques are detailed in the following subsections.

a) SVPWM using medium space vectors

The SVPWM scheme discussed in this section considers the medium decagon of space vectors in $d_1-q_1$ plane. The input reference voltage vector is synthesised from two active neighbouring and zero space vectors. The switching times are calculated by using the reference space vector $V_{ref}$, magnitude of the medium plane and sector (sec) number respectively. The switching time sequence of active and zero space voltage vectors are derived from the expressions (4) & (5).

$$
\begin{align*}
t_{am} &= \frac{\sqrt{V_{ref}} \sin(\text{sec} \pi / 7 - \theta)}{\sqrt{V_m} \sin \pi / 7} t_s \\
t_{bm} &= \frac{\sqrt{V_{ref}} \sin(\theta - (\text{sec} - 1) \pi / 7)}{\sqrt{V_m} \sin \pi / 7} t_s
\end{align*}
$$

(4)

$$
t_0 = t_s - t_{am} - t_{bm}
$$

(5)

Fig.2. $d_1-q_1$ plane of seven-phase VSI

Fig.3 Phasor diagram of Medium space vector
Fig. 3 shows the phasor diagram of medium space vector of seven-phase VSI. Here, $t_{am}$ and $t_{bm}$ correspond to times of application of medium space vectors where each sector starts with $V_{am}$ and ends with $V_{bm}$ respectively. Thus, in sector 1, $t_{am}$ is the time of application of the medium space vector $V_{115}$, while $t_{bm}$ is the time of application of the medium space vector $V_{06}$. Total time of application of zero space vectors (equally shared by zero space vectors $t_0$ and $t_{127}$). In odd sectors, sequence of the space vectors over the switching period is ($t_0 t_{bm} t_{am} t_{127} t_{am} t_{bm} t_0$), while in even sectors it is ($t_0 t_{bm} t_{am} t_{127} t_{bm} t_{0} t_{am}$) respectively. The maximum peak fundamental phase voltage of medium space vectors is $V_{max} = 0.4V_{dc}$. The switching time sequence of medium space vector of sector 1 is shown in Fig. 4.

![Switching time sequence of medium space vectors](sector 1)

**b) SVPWM using large and medium space vectors**

In the large and medium SVPWM scheme discussed in this section considers the outer and medium decagon of space vectors in $d_1$ – $q_1$ plane. The switching times are calculated by using the reference space vector $V_{ref}$, magnitude of the large and medium plane and sector (sec) number respectively. The switching time sequence of active and zero space voltage vectors are derived from the expressions (6) & (7).

\[
\begin{align*}
    t_a &= t_{al} + t_{am} \\
    t_b &= t_{bl} + t_{bm} \\
    t_{al} &= \left| V_s \right| = t_{am} \left| V_m \right| \\
    t_{bl} &= \left| V_s \right| = t_{bm} \left| V_m \right|
\end{align*}
\]

(6) & (7)

By solving the system (6) & (7), switching times for active space vectors are obtained as

\[
\begin{align*}
    t_a &= \frac{\left| V_s \right|}{\left| V_m \right|} t_{am} \\
    t_{am} &= \frac{\left| V_s \right|}{\left| V_m \right| + \left| V_m \right|} t_{am} \\
    t_{bm} &= \frac{\left| V_m \right|}{\left| V_m \right| + \left| V_m \right|} t_{bm}
\end{align*}
\]

(8) & (9)

Fig. 5 shows the phasor diagram of large and medium space vector of seven-phase VSI. In odd sectors the switching sequence is ($t_0 t_{bm} t_{am} t_{0} t_{127} t_{am} t_{bl} t_{0} t_{bm}$), while the sequence is ($t_0 t_{bm} t_{am} t_{0} t_{127} t_{bm} t_{0} t_{bl} t_{am}$) in even sectors. The switching time sequence of large and medium space vector of sector 1 is shown in Fig. 6.

![Switching time sequence of large and medium space vectors](sector 1)

**c) SVPWM using large space vectors**

In this section, the outer-most of large space vectors in $d_1$ – $q_1$ plane is considered. The input reference voltage vector is synthesised from two active vectors and zero space vectors respectively. The switching times are calculated by using the reference space vector $V_{ref}$, magnitude of the larger plane and sector (sec) number respectively. The switching time sequence of active and zero space voltage vectors are derived from the expressions (10) & (11).
\[ t_{al} = \frac{V_{ref} \sin(\sec \pi / 7 - \theta)}{V_i \sin \pi / 7} t_s \]

\[ t_{bl} = \frac{V_{ref} \sin(\theta - (\sec-1)\pi / 7)}{V_i \sin \pi / 7} t_s \]

\[ t_0 = \frac{1}{2}(t_s - t_{al} - t_{bl}) \]

Fig. 7 shows the phasor diagram for large space vectors of seven-phase VSI. Here, \( t_{al} \) and \( t_{bl} \) correspond to times of application of large space vectors. In sector 1, \( t_{al} \) is the time of application of the voltage space vector \( V_{97} \), while \( t_{bl} \) is the time of application of the voltage space vector \( V_{113} \). \( t_0 \) and \( t_{127} \) is the time of application of zero voltage vectors of \( V_0 \) and \( V_{127} \). For odd sectors, the sequence of the switching period is \( t_0 t_{al} t_{bl} t_{127} t_{al} t_{bl} t_{0} \), while in even sectors it is \( t_0 t_{bl} t_{al} t_{127} t_{bl} t_{al} t_{0} \) respectively. The maximum possible fundamental peak voltage of large space vector is \( V_{max} = 0.642 V_{dc} \). The switching time sequence for large space vectors of sector 1 is shown in Fig. 8.

IV. SIMULATION RESULTS

A simulation is performed in order to prove the efficiency of the schemes is compared in terms of percentage increase of fundamental voltage and THD. In the simulation the dc link voltage is set to 1 p.u. and the modulation index \( M \) is varying from 0.2 to 1. The switching frequency of the VSI is chosen as 10 kHz and the reference fundamental frequency is kept equal to 50 Hz. Fig. 9 to Fig. 14 shows the simulation results of MSV, LMSV and LSV for 7-phase VSI. Fig. 9 shows the resultant modulating waveform for medium space vectors. Fig. 10 shows the phase voltage and its spectrum of medium space vector. From the observation the fundamental rms value equals 0.3589 (0.5075 peak) and THD is 75.16%. The large and medium space vector modulating signals and output phase voltage is shown in Fig. 11 and 12. It is seen that the fundamental rms value equals 0.4215 (0.5961 peak) and THD is 54.65% respectively. The large space vector modulating signals and output voltage is shown in Fig. 13 and 14. It is seen that the fundamental rms value equals 0.4474 (0.6328 peak) and THD is 46.57% respectively. The deviation of the percentage decrease of THD versus different space vectors is shown in Table 1 and it is projected in Fig. 15.
Table I

<table>
<thead>
<tr>
<th>MI</th>
<th>Medium space vectors THD%</th>
<th>Large &amp; Medium space vectors THD%</th>
<th>Large space vectors THD%</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>199.02</td>
<td>181.93</td>
<td>169.75</td>
</tr>
<tr>
<td>0.4</td>
<td>126.52</td>
<td>110.16</td>
<td>100.66</td>
</tr>
<tr>
<td>0.6</td>
<td>87.12</td>
<td>69.71</td>
<td>61.94</td>
</tr>
<tr>
<td>0.85</td>
<td>75.16</td>
<td>54.65</td>
<td>46.57</td>
</tr>
</tbody>
</table>

Fig.11. Resultant modulating signal for large and medium space vectors

Fig.12. Output phase voltage and its spectrum of large and medium space vectors when \( M = 0.85 \)

Fig.13. Resultant modulating signal for large space vectors

Fig.14. Output phase voltage and its spectrum of large space vectors when \( M = 0.85 \)

Fig.15. Percentage decrease of THD for different space vectors combinations

V. CONCLUSION

A simulation study of a seven-phase VSI with three different space vector switching technique is presented in this paper. From the simulation results, it is seen that the large, medium space vector technique involves two active vectors whereas large and medium as four active vectors, thus increasing the complexity in the LMSV switching scheme. The THD is observed to be 75.16\%, 54.65\% and 46.57\% for MSV, combination of LMSV and LSV at the rated modulation index of 0.85. The THD increases with decreasing modulation index and it is minimum for large space vectors. Based on the THD, fundamental voltage and switching pattern and space vector disposition complexity the large space vectors is optimum for seven-phase voltage source inverter.

REFERENCES


