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Voltage Control by DQ Frame Technique of SVPWM AC-DC Converter

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Abstract

This article presents a simulation model of Space vector Pulse Width Modulation (SVPWM) Rectifier using MATLAB/Simulink which ability is to stabilize an output voltage of 500 Vdc from a 3 phase 300V system using a decoupling feed-forward control method by dq frame technique. The model is tested due to a variation of ± 10% of rated input voltage. From the simulation model, it can use for implementation into a real-time control system by Digital Signal Processing Board (such as DS1104). Together, it also can be designed into a real circuit easily and effectively. The experimental results show that the SVPWM Rectifier which is presented in this paper has an adequate performance which can be applied widely.

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Keywords: About DQ Frame; SVPWM Rectifier; Decoupling Control

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1. Introduction

Nowadays, the pulse width modulation technique which is applied in AC-DC converter has a lot of interesting aspects. Such as a stabilization of DC output voltage, less harmonics in output voltage and its better power factor. These could help in supporting and improving the power system quality. This paper presents a voltage control of such AC-DC converter utilized by the space vector pulse width modulation (SVPWM) technique and a novel d-q frame approach. Thus, the converter will transform an unstable input voltage from three phase AC system into a stabilized DC output voltage in a short time response.

2. Mathematical model of SVPWM AC-DC converter

Nowadays, the pulse width modulation technique which is applied in AC-DC converter has a lot of interesting aspects. Such as a stabilization of DC output voltage, less harmonics in output voltage and its better power factor. These could help in supporting and improving the power system quality. This paper presents a voltage control of such AC-DC converter utilized by the space vector pulse width modulation (SVPWM) technique and a novel d-q frame approach. Thus, the converter will transform an unstable input voltage from three phase AC system into a stabilized DC output voltage in a short time response.

Considering the three phase sinusoidal input voltage of the converter as a stationary reference frame,

\[ V_{sa}(t) = V_m \cos(\omega t) \]  
\[ V_{sb}(t) = V_m \cos(\omega t - \frac{2}{3}\pi) \]  
\[ V_{sc}(t) = V_m \cos(\omega t + \frac{2}{3}\pi) \]  

Which \( V_m \) is maximum voltage of the arbitrary three phase system. From the circuit in figure 1, equations of inductive voltage in each phase and capacitive current can be written as follows.

\[ L \frac{di_a}{dt} = V_{sa} - f_a \cdot V_{dc} \]  
\[ L \frac{di_b}{dt} = V_{sb} - f_b \cdot V_{dc} \]  
\[ L \frac{di_c}{dt} = V_{sc} - f_c \cdot V_{dc} \] 

![Fig. 1. Mathematical model of SVPWM AC-DC converter circuit](image_url)
\[
C \frac{dv_c}{dt} = f_a i_{sa} + f_b i_{sb} + f_c i_{sc} - I_{load}
\] (7)

\[f_a, f_b, f_c\] Represent as switching function of the AC-DC converter, which is

\[
f_a = \frac{(2S_a - S_b - S_c)}{3}
\] (8)

\[
f_b = \frac{(2S_b - S_a - S_c)}{3}
\] (9)

\[
f_c = \frac{(2S_c - S_a - S_b)}{3}
\] (10)

Fig. 2. The relationship of abc to dq reference frame

Given Sa, Sb, Sc is also represented as control signals that use to control in arbitrary phase of such converter. Each of control signals is significant as “1” or “0”. This means that, if Sa is ‘1’ the upper switch in phase A is ‘ON’ (the lower switch in phase A is OFF). Otherwise, when Sa is ‘0’ the upper switch in phase A is ‘OFF’ and lower switch will be ON. Therefore, these control signals that utilized in arbitrary 3 phase can be transforms into a two axis vector, which called as synchronous d-q reference frame. In which, it can be written as follows

\[
\begin{bmatrix}
X_d \\
X_q
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
\cos \omega t & \cos(\omega t + \frac{2}{3} \pi) & \cos(\omega t - \frac{2}{3} \pi) \\
-sin \omega t & sin(\omega t + \frac{2}{3} \pi) & -\sin(\omega t - \frac{2}{3} \pi)
\end{bmatrix} \begin{bmatrix}
X_a \\
X_b \\
X_c
\end{bmatrix}
\] (11)

As described above, output voltage of the AC-DC converter can be mentioned into totally 8 switching states (refer to 2^3 bit). These eight vectors are called the basic space vectors and are denoted by V (0)-V (7). This is due to the transformation of the arbitrary 3 phase control state into D-Q frame as shown in Figure-2. The voltage vector of the converter can be illustrated as shown in Figure 3. Mean by that, Table 1 shows the relationship between each switching state in any phase correspond to an arbitrary voltage vector and the occurrence of output phase voltage, respectively.

However, there are only six active voltage vectors (V1-V6) that will provide an output voltage value. These voltage vectors are corresponding to each others in a hexagonal shape as seen in Figure 3. Mean
while, there are two of zero vector (V0 and V7) that lied on the origin and provide no output voltage value.

The objective of SVPWM technique is to approximate the reference voltage vector ($V_{ref}$) in an arbitrary sector as illustrated in Figure-3 by using eight switching patterns. One simple method of approximation is to generate the average output of the inverter in a small period $T$ respect ($V_{ref}$) in such period. Mean by that, it utilize all six switching states together with an additional two more states in order to calculate the time period ($T_1$, $T_2$, $T_0$).

Table 1. Switching patterns and output vectors

<table>
<thead>
<tr>
<th>Number of Vector</th>
<th>Switching state</th>
<th>Output phase voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sa</td>
<td>Sb</td>
</tr>
<tr>
<td>$V_0$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$V_5$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$V_3$</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>$V_4$</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>$V_1$</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$V_6$</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$V_2$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$V_0$</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
The time period \((T_1, T_2, T_0)\), it can be written as follows

\[
T_0 = \frac{T_s - T_1 - T_2}{2}
\]  
(12)

\[
T_1 = \frac{2\sqrt{3}}{\pi} MT \sin\left(\frac{\pi}{3} - \alpha\right)
\]  
(13)

\[
T_2 = \frac{2\sqrt{3}}{\pi} MT \sin(\alpha)
\]  
(14)

\[
T_s = \frac{1}{f_s}
\]  
(15)

\[
M = \frac{V^*}{V_{\text{sixstep}}} = \frac{V^*}{\frac{2}{\pi} V_{dc}}
\]  
(16)

By given \(M\) as modulation ratio, \(f_s\) as switching frequency.

3. Voltage feed-forward decoupling concept

This article is to control output voltage using the principle voltage feed-forward decoupling for optimized to provide more efficiency. it can be written as follows equation (17)-(29).

\[
L \frac{d i_{sd}}{dt} = V_{sd} + \omega L i_{sq} - f_d V_{dc}
\]  
(17)

\[
L \frac{d i_{sq}}{dt} = V_{sq} - \omega L i_{sq} - f_q V_{dc}
\]  
(18)

\[
C \frac{d V_{dc}}{dt} = \frac{3}{2} (f_d i_{sd} + f_q i_{sq}) - I_{\text{load}}
\]  
(19)

When determine

\(i_{sd}\) and \(i_{sq}\) are current values in \(d-q\) axis

\(f_d\) and \(f_q\) are switching functions in \(d-q\) axis

\(V_{sd}\) and \(V_{sq}\) are voltage values in \(d-q\) axis

\(\omega\) is Radian/sec.

Which,

\[
V_{sd} = V_m
\]  
(20)

\[
V_{sq} = 0
\]  
(21)

Replace equation (20) and (21) into (17) and (18).

\[
L \frac{d i_{sd}}{dt} = V_m + \omega L i_{sq} - f_d V_{dc}
\]  
(22)
\[
L \frac{d i_{sq}}{dt} = -\omega L i_{sq} - f_q V_{dc} \tag{23}
\]
\[
V_d = f_d V_{dc} \tag{24}
\]
\[
V_q = f_q V_{dc} \tag{25}
\]
\[
L \frac{d i_{sd}}{dt} = V_m + \omega L i_{sq} - V_d \tag{26}
\]
\[
L \frac{d i_{sq}}{dt} = -\omega L i_{sq} - V_q \tag{27}
\]
\[
v_d^* = V_{sd} - (K_{pi} + \frac{K}{S})(i_{sd}^* - i_{sd}) + \omega L i_{sq} \tag{28}
\]
\[
v_q^* = V_{sq} - (K_{pi} + \frac{K}{S})(i_{sq}^* - i_{sq}) + \omega L i_{sd} \tag{29}
\]

From equation (28) and equation (29), it can be built a block diagram as

![Fig. 4. Voltage Feed-Forward decoupling block diagram](image)

### 4. Simulation and results

This article is controlling and analysis the stability of SVPWM AC-DC Converter output voltage using a decoupling feed-forward control method by d-q frame technique. The model of SVPWM AC-DC Converter circuits has built using Matlab/Simulink as shown in Figure-5.
The simulation parameter of SVPWM AC-DC converter as described in Table-2 which Kp, Ki value obtained trial of error method.

Table 2. Simulation parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rs</td>
<td>1000</td>
<td>Ω</td>
</tr>
<tr>
<td>R(load)</td>
<td>5</td>
<td>Ω</td>
</tr>
<tr>
<td>R(Snubber)</td>
<td>10</td>
<td>Ω</td>
</tr>
<tr>
<td>C (snubber)</td>
<td>100e-6</td>
<td>F</td>
</tr>
<tr>
<td>C (DC link)</td>
<td>1e-3</td>
<td>F</td>
</tr>
<tr>
<td>Tf</td>
<td>110e-6</td>
<td>s</td>
</tr>
<tr>
<td>Tt</td>
<td>2e-6</td>
<td>s</td>
</tr>
<tr>
<td>Kp(Id-q)</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Kp(Id-q)</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>S.W frequency</td>
<td>10000</td>
<td>Hz</td>
</tr>
</tbody>
</table>
Fig. 6. Voltage input on step load

Fig. 7. Voltage output on step load

Fig. 8. Voltage input varied from 300 V to 270 V
5. Conclusion

The experimental result of SVPWM AC-DC Converter circuits can control output voltage using d-q frame technique in a good response when load changes as shown in Figure-7. Another result shows that the output voltage can be keep stable when the input voltage is varied from 300 V down to 270 V at a constant load as shown in Figure-8 and Figure-9. By the researcher’s opinion the times response of SVPWM AC-DC Converter output voltage have to be improved in further.

Nevertheless the simulation model that prescribe above can be modify to use as implementation model which use with DSP board such as DS1104 in order to generate the real time control signal. This can control a real time converter, which apply in any application such as wind generator and so on as shown Figure-10. Which the researcher was successfully developed as shown Figure-11. The may be a significant aspect for some power electronics application in renewable energy area.
References


