Optimization Method of Output Power Quality of Z-Source Inverter Based on SVPWM

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Abstract. A linear modulation of SVPWM control strategy employed in Z-source inverter is proposed in this paper. The DC bus voltage is regulated by adjusting the shoot through duty based on load. The reference voltage vectors are limited in the inscribed circle of hexagon of basic voltage vectors. Overmodulation is avoided. The linear relationship between the peak value of the output voltage and the DC bus voltage is kept in all regions. The change of system load is responded by this control strategy. The system control algorithm is simplified and the output capability of the system is enhanced. To validate its advantages, analytical, simulation, and experimental results are also presented.

1. Introduction
SVPWM has higher utilization efficiency of DC voltage, lower output line voltage harmonics and phase current harmonics. So SVPWM is wildly employed in three-phase voltage source type inverters. However, the traditional SVPWM can only get the amplitude of output fundamental voltage to 0.907 times of DC-link voltage. That is the maximum modulation index of the traditional SVPWM is only 0.907 when the traditional voltage source type inverter is working in linear region\textsuperscript{[1]}. In order to obtain high output voltage, the inverter using SVPWM must run at an overmodulation region until it reaches saturational state in six-step wave operation mode. So overmodulation algorithm is wildly used in the traditional voltage source type inverter\textsuperscript{[2-3]}. There are two strategies of overmodulation algorithm at present. One kind of the overmodulation algorithm is that the voltage source inverter work in three different regions according to the value of modulation index ($M$), such as the SVPWM overmodulation algorithm and its application in two-level inverter proposed by Wu Xiaoxin as in\textsuperscript{[4]}. The other kind of the overmodulation algorithm is there is only one method of modulation in all the regions, such as the overmodulation algorithm proposed by Fang Hui as in\textsuperscript{[5]}. Unity studies between three-level SVPWM and CBPWM in the overmodulation region were considered and the implementation method of CBPWM was deduced in this strategy. Moreover, a SVPWM overmodulation method based on three-phase bridge arm coordinates is proposed by Wu Dehui and others as in\textsuperscript{[6]}. The calculation of the reference angle and holding angle was avoided, the computation is simplified and traditional sector division is canceled in this method.
Overmodulation method can improve the utilization efficiency of DC-link voltage. However, those strategies are based on traditional voltage source type inverter. The output fundamental voltage amplitude has a nonlinear relationship with modulation, resulting in saturation in controller. The problem of saturation widely distributed in matrix inverter and multilevel inverter is low power factor, serious harmonic pollution and voltage unbalance between the two group capacitors. The Z-source inverter can provide regulation mechanisms for DC-link voltage to overcome those disadvantages. But the present strategies focus on the implementation of the short through states and the stability of the DC-link voltage by using synovial variable structure controller or fuzzy-PID algorithm. Those strategies can’t follow the load variation, and resulting in decreased voltage.

Therefore, a new optimization method of output power quality based on Z-source inverter is proposed in this paper. The load is calculated and the basic voltage vectors are adjusted according to the load in this method. The complicated calculation caused by overmodulation is eliminated and the harmonic content in output voltage is reduced. The waveform of output current is sinusoidal and the exact linearization control of output voltage is realized in all the SVPWM regions. The output capacity of the voltage source inverter is improved.

2. Optimization Method Based on

2.1. Overmodulation analysis of traditional SVPWM

The vector figure of traditional SVPWM as shown in Fig.1. Where, $V_{ref}$ is the reference output voltage vector, and $\theta$ is the angle between the reference output voltage vector and the bisector of the sector in which the reference output voltage lies.

Take the $V_{ref}$ as example, where $T_0, T_1$ and $T_2$ are the respective durations for which the inverter state 0, 1 and 2 are applied in the subcycle.

It can be obtained that

$$
\begin{align*}
T_0 & = \frac{1}{3} V_{dc} T_1 \left(1 - \cos \frac{\pi}{3}\right) \\
T_1 & = \frac{2}{3} V_{dc} T_2 \sin \frac{\pi}{3}
\end{align*}
$$

(1)

![Fig.1 The vector figure of traditional voltage source inverter](image)

The modulation ratio is defined as

$$
M = \frac{V_B}{2V_{dc}}
$$

(2)

Where, $V_{dc}$ and $V_B$ are the DC-link voltage and the amplitude of output phase fundamental voltage. $V_B$ is equal to $V_{ref}$ during linear modulation region.

According to (1) and (2), $T_0, T_1$ and $T_2$ can be calculated as
From (3), $T_0$ can be obtained that

$$T_0 = T_1 - T_2 = T_1 - T_1 - T_2$$

It is observed that the reference output voltage vector $V_{ref}$ is limited in the inscribed circle of the hexagonal space vector diagram of 6 basic space vectors. Overmodulation is employed to output a large magnetic torque resulting in the peak value of the modulating signal exceeds that of the carrier during overmodulation ($M>0.907$). Hence the three-phase average voltages are no longer sinusoidal. Therefore, the average voltage vector applied can no longer have constant magnitude as well as uniform angular velocity as in case of linear modulation.

2.2. Optimization Method of Output Power Quality of Z-Source Inverter

Z-source inverter can overcome the disadvantages of overmodulation by boosting the DC-source voltage to extend the value of the basic space sectors. The hexagonal space vector diagram of 6 basic space vectors is correspondingly enlarged. As the dotted line shown in Fig.2. Even $V_{ref}$ exceeds the hexagonal space vector diagram with solid lines, but can’t exceeds the hexagon with dotted line. Overmodulation region is eliminated.

From (4), $\theta = \frac{\pi}{6}$ when, $M = \frac{\pi}{2\sqrt{3}}$, and then $T_1 + T_2 = T_5$ and $T_0 = 0$. Meanwhile, $T_1 + T_2 < T_5$ when $\theta \neq \frac{\pi}{6}$.

Therefore, if the system is satisfied by the $D$ (shoot through duty) at this time, the reference output voltage vector can be obtained in any point.

![Fig.2 The demonstration for enlargement of hexagonal space vector diagram](image-url)

(3) can be rewritten as

$$\begin{align*}
\frac{T_1}{T_S} &= \frac{2\sqrt{3}}{\pi} \times \frac{1}{2} \\
\frac{T_2}{T_S} &= \frac{2\sqrt{3}}{\pi} \times \frac{1}{2} \\
\end{align*}$$

Take (5) into (4), it can be obtained
According to Z-source inverter, the DC-link voltage can be written as 
\[ V_{dc} = f(D)V_{in} \quad (7) \]
where, \( 0 \leq D \leq 1 \).

Take (7) into (6), it can be obtained 
\[ \frac{\sqrt{3}V_{ref}}{V_{in}f(D)} + D = 0 \quad (8) \]
where \( V_{in} \) can be assumed known, therefor 
\[ D = f(V_{ref}) \quad (9) \]
Then, 
\[ B = f(D) = g(V_{ref}) \quad (10) \]
and 
\[ V_{dc} = BV_{in} = g(V_{ref})V_{in} \quad (11) \]

3. Performance Analysis

The Cascaded Z-source inverter\(^{[20]}\) is used to verify the optimization method. The boost factor of this inverter is
\[ V_a = \left( \frac{1}{1-4D} \right)V_{in} \quad (12) \]
(9) can be rewritten as
\[ D = \frac{\sqrt{3}V_{ref} - V_{in}}{4\sqrt{3}V_{ref} - V_{in}} \quad (13) \]
(10) can be rewritten as 
\[ B = \frac{1}{1-4D} = \frac{1}{1-4 \times \frac{\sqrt{3}V_{ref} - V_{in}}{4\sqrt{3}V_{ref} - V_{in}}} = \frac{4\sqrt{3}V_{ref} - V_{in}}{3V_{in}} \quad (14) \]
(11) can be rewritten as 
\[ V_{dc} = BV_{in} = \frac{4\sqrt{3}V_{ref} - V_{in}}{3} \quad (15) \]

The relationship of \( V_{ref} \) and \( V_{dc} \) as shown in Fig 2 (\( V_{dc} \) is assumed to be 50V). From Fig 2, DC-link voltage is boosted with the increasing of \( V_{ref} \) (which means the load increases), and the basic vector correspondingly increase.

The relationship of \( M \) and \( V_{ref} \) can be calculated as
\[ M = \frac{3\pi V_{ref}}{8\sqrt{3}V_{ref} - 2V_{in}} \quad (16) \]
The relationship of \( V_{in} \) and \( V_{dc} \) as shown in Fig 3, and the relationship of \( M \) and \( V_{ref} \) as shown in Fig 4.
4. Simulation And Experimental Results

Simulations were performed using MATLAB Simulink. The prototype is a three phase load, Y-connected, and R=5Ω each phase \[V_{in}=50\text{V}, \quad V_{ref1}=19\text{V}, \quad V_{ref2}=32\text{V}, \quad V_{ref3}=44\text{V}. \quad C_A=C_B=650\mu\text{F}, \quad C_C=1500\mu\text{F}, \quad L_A=L_B=350\mu\text{H}].

According to (6), when \(V_{ref1}\) is equal to 19V, the \(M_I\) is equal to 0.6, and the \(D\) is equal to 0. When \(V_{ref2}\) is equal to 32V, that \(V_{ref} > V_{in}/\sqrt{3}\), and then \(D\) is equal to 0.032 and \(V_{dc}\) is equal to 57.3V. When \(V_{ref2}\) is equal to 44V, that \(V_{ref} > V_{in}/\sqrt{3}\), and then \(D\) is equal to 0.1 and \(V_{dc}\) is equal to 83.3V. The conclusion was validated by the results of simulation as shown in Fig 5.
The validity of proposed optimization method is also demonstrated by experimental results. The parameters of experimental prototype are same as that of simulation prototype. The results as shown in

Fig5 Simulation result--shoot through duty $D$ and $T_0$

Fig6 Experimental results--output current of inverter

Fig7 Experimental results--output voltage of inverter
Fig. 7, and are same as that of simulation prototype. The results of simulations and experiments are coincident with the theoretical ones.

5. conclusion

An optimization method of output power quality of Z-source inverter based on SVPWM is proposed in this paper. By boosting the DC-link voltage according to the load to improve the basic voltage vectors, the peak value of the modulating signal no longer exceeds that of the carrier during all the regions. The complicated calculation caused by overmodulation is eliminated and the harmonic content in output voltage is reduced. The waveform of output current is sinusoidal and the exact linearization control of output voltage is realized in all the regions. The output capacity of the voltage source inverter is improved. Simulation and experimental results verify the proposed method.

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