A New Type of Super-Sparse Matrix Converter with Γ Source and Its Characteristics Analysis

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Abstract. To solve the problem of low voltage transmission in ultra sparse matrix converter (USMC), a novel ultra sparse matrix converter (USMC) is proposed. The new USMC topology contains of a Γ source boost circuit in the DC link. By increasing the output voltage of DC link, the inverter stage can output higher voltage, thus widening the range of voltage transmission ratio. Furthermore, combined with the SVPWM modulation strategy, the voltage transfer ratio of the new USMC topology is derived, which lays a theoretical foundation for the application of USMC. Finally, Matlab / Simulink simulation results verify the correctness and feasibility of the topology.

1. Introduction

Ultra sparse matrix converter (USMC) is an indirect matrix converter\cite{1} with the least switching devices. With the traditional matrix converter, the number of power switching devices is reduced to 9, and the simpler zero current commutation technology is adopted, which makes it a new matrix converter with potential development\cite{2-4}.

However, the traditional USMC is not widely used in industrial production due to the limitation of voltage transfer ratio. Many scholars have studied the modulation strategy and topology respectively to solve this problem. The over modulation strategy of space vector modulation is proposed in reference\cite{5}, which can improve USMC voltage transmission ratio in a certain range. However, the algorithm implementation is more complex and the output harmonics are large. In reference \cite{6}, boost inverter and buck boost inverter are used to replace the inverter stage of indirect matrix converter (IMC) to form hybrid matrix converter. These two hybrid matrix converters can improve the voltage transfer ratio without adding power switching devices. However, there are many new components, low compactness and complex control. Reference \cite{7-9} improves the voltage transfer ratio of traditional bipolar matrix converter by introducing traditional Z-source, but its regulation range has certain limitations.

For this reason, this paper proposes a super-sparse matrix converter topology with Γ source and its modulation strategy. This new Γ source topology uses a transformer to replace the two inductors in
the traditional Z source network, energy transfer is achieved through magnetic coupling, thereby reducing a capacitance and making the Γ source network structure more compact [10]. A transformer is added to the Γ source, and the transformer turns ratio ranges from 1 to 2. The smaller the turns ratio, the stronger the boosting ability [11-13]. Compared with the traditional USMC, this topology can not only improve the voltage transfer ratio but also flexibly adjust the boost range. At the same time, the parameter design of the Γ source network is analyzed, and the feasibility and superiority of the proposed topology and control strategy are verified through Matlab/Simulink simulation.

2. USMC with Γ source

2.1. Topology and working principle

Fig. 1 shows the proposed novel USMC topology, which is composed of a traditional USMC and a Γ source. The Γ source is composed of a transformer and a capacitor. Because its output voltage decreases with the increase of the transformer ratio, the transformer turns ratio is set as

$$1 < N_\Gamma \leq 2$$  \hspace{1cm} (1)

The topological structure of the Γ source of the boost link is shown in Fig. 2(a), and the working modes are divided into direct mode and non-direct mode. The equivalent circuit diagram of the through mode is shown in Fig. 2(b). At this time, the upper and lower switch tubes of a bridge arm or multiple bridge arms of the USMC inverter stage are turned on at the same time. In the disconnected state, it can be obtained by the Kirchhoff’s voltage law:

$$u_{n_1} = u_{n_2} + u_C, u_{n_1} = \gamma_\Gamma u_{n_2}, \gamma_\Gamma = n_1 / n_2$$  \hspace{1cm} (2)

It can be obtained from equation (1):

$$u_{n_2} = u_C / (\gamma_\Gamma - 1)$$  \hspace{1cm} (3)

The non-through mode is shown in Fig. 2(c). At this time, the upper and lower switch tubes of any bridge arm of the USMC cannot be turned on at the same time, the output DC current of the rectifier stage is not 0, the diode D in the Γ source is in a conductive state, the inverter stage can be equivalent to a voltage source, and the inductance is n_2. It forms a loop with DC voltage, and according to Kirchhoff’s voltage law, we can get:

$$u_{n_2} = U_{dc} - u_C, u_{n_1} = \gamma_\Gamma u_{n_2}$$  \hspace{1cm} (4)
In a switching cycle, the average voltage across the inductor in the \( \Gamma \) source is zero, which can be obtained:

\[
C \geq \frac{D_{ST}I_L}{6f_s} \left\{ \frac{1-\left[1+\frac{1}{(n-1)}\right]D_{ST}}{U_{dc}(1-D_{ST})} \right\}
\]

Where \( D_{ST} \) is the switching duty cycle.

It can be obtained from the equation (5) that \( \Gamma \) Source voltage transmission ratio \( b \) is:

\[
B = \left( \frac{\gamma_s - 1}{\gamma_s (1-D_{ST}) - 1} \right)
\]

2.2. Parameter Design of \( \Gamma \) Source Network Capacitance

For the capacitor in the \( \Gamma \) source, its parameter design is mainly based on the magnitude of the voltage ripple. As shown in Fig. 2(b), when it is in the through mode, the switch is in the off state, and the capacitor is charged to the inductor. At this time, the inductor current is equal to the capacitor current, which can be obtained from its volt-ampere characteristics:

\[
C = i_c \cdot dt / \mu
\]

Since the through zero vector action time is very short, it can be approximated that the inductor current does not change, and the capacitor current can be the inductor average current in this state. In one cycle, the through zero vector is equally divided into six equal parts to act on the through state, that is, the capacitor voltage must pulsate at 6 times the switching frequency, and the through zero vector action time is:

\[
dt = D_{ST}T_s / 6 = D_{ST} / (6f_s)
\]

It can be obtained from equations (7) and (8):

\[
C = D_{ST}I_L / (6f_sdu_c)
\]

Therefore, to ensure that the capacitor voltage ripple is not greater than \( ru_c \), it needs to meet: \( C \geq D_{ST}I_L / (6f_sru_c) \). And from the voltage relationship in equation (5), it can be derived as:

\[
C \geq \frac{D_{ST}I_L \left\{ \frac{1-\left[1+\frac{1}{(n-1)}\right]D_{ST}}{6f_sU_{dc}(1-D_{ST})} \right\}}{6f_sru_c}
\]

To sum up, the capacitor can be selected according to equation (10).

3. Modulation strategy

The new USMC adopts space vector modulation strategy, in which the rectifier stage adopts zero vector space modulation strategy and the inverter stage adopts zero vector space modulation strategy. As shown in Fig. 3(a), three bidirectional power switches of the rectifier stage can be
synthesized $I_1^* - I_6^*$. At the same time, the state of the switch tubes on the three bridge arms can be represented by numbers 1 and 0, with numbers 1 indicating that the switch tubes in their phases are turned on and 0 indicating that the switch tubes in their phases are turned off. Therefore, the modulation mode of the new USMC rectifier stage three-phase switch in one cycle is: always keep one phase switch closed, and the other two-phase switches are turned on in turn according to their respective duty ratios. As shown in Fig. 3(b), six bidirectional power switches in the inverter stage can be synthesized $U_1^* - U_6^*$. There are six voltage effective vectors and two zero vectors, in which the upper and lower switch tubes of the three bridge arms of the inverter stage can be represented by numbers 1 and 0. For the same bridge arm, number 1 means that the upper switch tube is on, and number 0 means that the lower switch tube is on.

![Current Vector Modulation](image1.png) ![Voltage Vector Modulation](image2.png)

**Figure 3.** Modulation strategy of rectifier stage and inverter stage

Fig. 4 shows the cooperative control of the rectifier stage and inverter stage of space vector modulation. The commutation mode of USMC inverter stage selects zero current commutation, that is, when the two effective vectors of rectifier stage are switched, the inverter stage outputs different zero vectors on the basis of reducing commutation times, such as when $I_{ref}$ and $U_{ref}$. When both are in the first sector, their switching modulation states are shown in Fig. 4. In the picture $S_a$, $S_b$, $S_c$. They are three-phase bridge arm control signals of rectifier stages a, b and c, $S_{pX}(X=A,B,C)$ is the control signal of the three-phase upper bridge arm of the inverter stage, $S_{nY}(Y=A,B,C)$ is the control signal of the three-phase lower bridge arm of the inverter stage, and the shaded part indicates that the switch is on. With regard to the direct zero vector is used instead of the traditional zero vector to improve the voltage transmission ratio, that is, without changing the total action time of the traditional zero vector, its average sextuples are inserted into the switching commutation time.

![Coordinated Control of USMC Switch](image3.png)

**Figure 4.** Coordinated control of USMC switch
4. Analysis of voltage transmission ratio

Let the three-phase input phase voltage be:

\[
\begin{align*}
    u_a &= U_{im} \cos(\omega t) \\
    u_b &= U_{im} \cos(\omega t - \frac{2\pi}{3}) \\
    u_c &= U_{im} \cos(\omega t + \frac{2\pi}{3})
\end{align*}
\]

where $U_{im}$ is the input phase voltage amplitude, $\omega$ is the input line voltage angular frequency. Because the new USMC rectifier stage adopts double effective current vector modulation, when the current vector $I_{ref}$. Located in the first sector, the average current of three-phase input $i_a$, $i_b$, $i_c$ and DC current average $I_{dc}$. The duty cycle has the following relationship:

\[
\begin{align*}
    \overline{I}_a &= (d_{ab} + d_{ac})I_{dc} \\
    \overline{I}_b &= -d_{ab}I_{dc} \\
    \overline{I}_c &= -d_{ac}I_{dc}
\end{align*}
\]

where $d_{ab}$, $d_{ac}$ They are vectors respectively $I_{ab}$, $I_{ac}$ The duty cycle of. And satisfy:

\[
I_{ab} + I_{ac} = 1
\]

That is, the average value of DC voltage in a carrier period is:

\[
U_{dc} = d_{ab}u_{ab} + d_{ac}u_{ac} = \frac{3U_{im}^2}{2\cos\theta_i}, \quad \cos\theta_i = \max[|\cos\theta_{a1}|,|\cos\theta_{a2}|,|\cos\theta_{a3}|]
\]

The new USMC inverter stage adopts zero vector modulation. According to volt-second law and trigonometric sine theorem, the duty ratio of space vector is:

\[
\begin{align*}
    d_a &= m_s \sin\left(\frac{\pi}{3} - \omega t\right) \\
    d_b &= m_s \sin(\omega t) \\
    d_c &= 1 - d_a - d_b
\end{align*}
\]

where $m_s$ is the space vector pulse width modulation coefficient. Derived from the local average value of the output line voltage:

\[
\begin{bmatrix}
    \overline{U}_{AB} \\
    \overline{U}_{BC} \\
    \overline{U}_{CA}
\end{bmatrix} = \sqrt{3}U_{im} \begin{bmatrix}
    \cos(\omega_0 t + \phi_0 + 30') \\
    \cos(\omega_0 t + \phi_0 - 90') \\
    \cos(\omega_0 t + \phi_0 + 150')
\end{bmatrix}
\]

Where $U_{im} = \frac{\sqrt{3}}{2}m_s B U_{ac} \cos \phi _i$ . From this, a new USMC voltage transmission ratio $M$ can be obtained as:

\[
M = \frac{\sqrt{3}}{2}m_s B
\]

According to equation (16), the source transmission ratio B is proportional to $M$, and B can be obtained from equation (6) and related with $\gamma_i$. At the same time, due to $1 \leq \gamma_i \leq 2$ that is, when $\gamma_i$ falling within this range, the voltage transmission ratio increases instead.
Because the inverter stage adopts zero vector modulation, which satisfies: \( d_a + d_\beta + D_{ST} \leq 1 \) Combining equations (6) and (16), it can be drieved as:

\[
m_v \leq 1 - \frac{D_{ST}}{\gamma_T} = \left( \gamma_T - 1 + B \right) / B \gamma_T
\]

(18)

It can be obtained from equations (17) and (18):

\[
m_v \leq \sqrt[3]{m_v} / 2M + \left( 2M - \sqrt[3]{m_v} \right) / 2M \gamma_T
\]

(19)

According to equation (19), The value of \( m_v \) is raterd with \( M \) and \( \gamma_T \). When \( M \) is constant, in the value range of \( \gamma_T \), the maximum value of \( m_v \) is increased as \( \gamma_T \) decreases.

Finally, complete content and organizational editing before formatting. Please take note of the following items when proofreading spelling and grammar:

Simulation verification

In this paper, Matlab/Simulink is used to verify the correctness and feasibility of the proposed topology. The simulation parameters are set as shown in the following table:

| Table 1. Simulation parameters |
|-------------------------------|
| parameter                     | value | parameter | value |
| Input voltage amplitude /V    | 311   | Load R/Ω  | 20    |
| mains frequency f/Hz          | 50    | Load L/mH | 10    |
| switching frequency f/Hz      | 20K   | transformation ratio \( \gamma_T \) | 1.25 |
| Direct duty cycle D_{ST}      | 0.1   | Capacitance C/μF | 470 |

Under the condition that the basic parameters remain unchanged, the output voltage and current waveforms of the traditional USMC and the new USMC with Γ source are simulated and compared. Fig. 5 shows the three-phase voltage input waveforms of the rectifier stage under two topologies.

Fig. 5. Three-phase voltage input to rectifier stage

Fig. 6(a) shows DC voltage waveform of the rectifier stage in the new USMC, and its value fluctuates between the half amplitude of the input line voltage and its amplitude, and the waveform is good. Fig. 6(b) shows the voltage waveform of the inverter stage input after the Γ source. Compared with the output of the rectifier stage, the voltage amplitude has increased significantly.
Fig. 6. DC Link Voltage Waveform of New USMC

Fig. 7(a) shows the output line voltage waveform of ordinary USMC, and its fundamental amplitude is 465.64V, while Fig. 7(b) shows the output line voltage waveform of the new USMC, which has a fundamental amplitude of 580.05V. It can be seen that by changing the transformation ratio of the transformer in the $\Gamma$ source, the voltage transmission ratio can reach 1.0, which can effectively improve the voltage transmission ratio of the USMC.

Fig. 8 show the output phase current and FFT analysis diagram with the two topologies. It can be seen that although the output current distortion rate of the new USMC has increased, it is still in a small range, and both are low.
5. Conclusion
Aiming at the problem that the traditional USMC voltage transmission is relatively low, this paper proposes a new USMC topology with a Γ source. It is verified by Matlab/Simulink simulation that the topology can make its voltage transmission ratio less than that without changing the modulation strategy. Reaching 1.0 and above, it can simply and effectively improve the USMC voltage transfer ratio, and can be flexibly adjusted by adjusting the voltage transfer ratio of the boost circuit, which breaks through the limitation of the traditional USMC voltage ratio lower than 0.866, and has the same good input and output waveform as the traditional topology.

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