Evaluation of SVM modulation methods for indirect two-level three-phase frequency converter and direct frequency converter

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Abstract. In current practice, indirectly structured frequency converters are popular because of the simple switch and control circuit diagram, and pulse width modulation (PWM) can be used to control the semiconductor switches. The PWM method has the advantage of a simple control circuit but has large switching losses and generates a common-mode voltage that causes motor damage. The development of the space vector modulation (SVM) method takes advantage of the PWM method, reducing the switching loss of the switches and reducing the harmonic at the output of the inverter. With direct converters, there are many types depending on the circuit structure and semiconductor key structure, including matrix frequency converters which are widely studied. The classical modulation method according to the duty-cycle matrix approach for matrix converter has disadvantages such as complex computational algorithms, which require many trigonometric calculations. Based on the PWM and SVM modulation algorithms for indirect converters, a space vector modulation method for matrix converters will be developed. Compared with the indirect converter, the SVM modulation method for the matrix converter will be based on two separate modulation principles: control the input current vector and control the output voltage vector. The relationship between current and voltage at the converter input is closely related to the voltage and current at the output. The relationship between current and voltage at the converter input is closely related to the voltage and current at the output. Make sure at the input of the converter, the power factor \( \cos \phi = 1 \) and can be adjusted, it has the quality of sine input and outputs current and the exchange power in two directions.

1. Introduction

Technology to control frequency converters is growing, so the study and improving the structure of the converter, the control algorithms are important tasks in the manufacture of frequency converters. The study of modulation techniques is an important step to ensure the quality of input and output
parameters and compliance with matching devices. Indirect frequency converter with a voltage source inverter (VSI), as shown in Figure 1, the rectifier circuits and inverter isolated transition sided circuit consisting of 2 elements L, C. The rectifier circuit uses unmanaged diodes; the inverter circuit uses managed keys IGBT modules, so management is easily done using the PWM and SVM methods [1]. The disadvantage of the indirect frequency converter is the presence of a diode s in the rectifier circuit. Because of them, harmonics appear in the network; it is not possible to regulate the input voltage of the inverter circuit; when working with a regenerative braking load, the energy will not return to the grid, but dissipated at the discharge resistor.

Direct frequency converter (AC-AC) is a AC direct converter in a variable frequency and variable voltage. Matrix converter (MC) is a direct converter based on semiconductor modules with with bidirectional switch [1, 2]. The block diagram of the electric drive with a matrix frequency converter is shown in fig. 2.

The main advantages of matrix converter are the possibility of bilateral exchange of energy, the regulation of the form of the input current, ensuring sinusoidal input current and voltage regulation, power factor $\cos \varphi = 1$ [3]. The main problem of the use of MC is more complex than the indirect converter structures, modulation control systems, as well as more complex methods of modification of the modulation system [4]. Currently, there are several types of modulation control systems for matrix converters: Venturini - Alesina method; scalar modulation method; space vector modulation. However, the modulation system Venturini - Alesina has disadvantages such as the algorithm requires complex calculations; the algorithm requires several trigonometric transformations; the algorithm requires continuous measurement of the input voltage with high accuracy [5]. The Scalar modulation system is simpler, but it has the main drawback, which will consist in the high dependency of control quality on the accuracy of computational and measuring operations [6, 7]. In the article, the strategy of controlling matrix transformation via DC virtual link is given. This DC link is not physically present, but the switches are divided into the virtual rectifier and virtual inverter in figure 2. The control of these two converters circuits has provided a platform for analyzing and derive several extends PWM strategies. On the basis of the PWM and SVM methods for indirect converters, a space vector
modulation method for matrix transformations will be developed by separate control for virtual rectifier circuits and virtual inverters [8, 9, 10].

2. Methods

2.1. SVM modulation principle in the indirect two-level three-phase frequency converter

Method SVM inherits the principle of the method the pulse-width modulation PWM and applies the theory of spatial vectors. SVM is a method of bundling closed states of semiconductor switches in which the value of the vector modulated output voltage close to the value of the vector of the desired output voltage [11, 12, 13].

The inverter is considered as a single unit with \(2^3=8\) distinct closed States from 0 to 7 (Figure 3), according to each closed switch state will receive 1 unchanging voltage vector (both direction and magnitude) listed in table 1.

![Status of keys in the inverter circuit](image)

Table 1. Voltage values for different closed states of keys

| Vector | Key | Phase voltage | Wire voltage |
|--------|-----|---------------|--------------|
|        | \(S_1\) | \(S_3\) | \(S_5\) | \(U_{An}\) | \(U_{Bn}\) | \(U_{Cn}\) | \(U_{AB}\) | \(U_{BC}\) | \(U_{CA}\) |
| \(U_0\) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| \(U_1\) | 1 | 0 | 0 | 2/3 | -1/3 | -1/3 | 1 | 1 | 1 |
| \(U_2\) | 1 | 1 | 0 | 1/3 | 1/3 | -2/3 | 0 | 1 | -1 |
| \(U_3\) | 0 | 1 | 0 | -1/3 | 2/3 | -1/3 | -1 | 1 | 0 |
| \(U_4\) | 0 | 1 | 1 | -2/3 | 1/3 | 1/3 | -1 | 0 | 1 |
| \(U_5\) | 0 | 0 | 1 | -1/3 | -1/3 | 2/3 | 0 | -1 | 1 |
| \(U_6\) | 1 | 0 | 1 | 1/3 | -2/3 | 1/3 | 1 | -1 | 0 |
| \(U_7\) | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |

We see that all of the vectors from the voltage \(U_1\) to \(U_6\) have the same value which is equal to \(2/3U_{dc}\), phase angles deviate to \(\pi/3\), other two vectors \(U_0, U_7\) have zero value. Of these standard pairs of boundary vectors, vector space is divided into 6 uniform sectors with the angle between the vectors is \(\pi/3\).
Any voltage vector of a vector space should be in one of the six sectors, as shown in Figure 4, and will be represented by the sum of two component vectors or standard boundary vectors of this sector [14-16]. If necessary to determine the output voltage when its vector is in sector 1, as \( U_s \) (\( U_A, U_B, U_C \)) then by the formula to calculate the vector sum we have: \( U_s = k \cdot U_1 + l \cdot U_2 \). \( U_1 \) is formed by closing the keys \( S_6, S_1, S_2\), and \( U_2 \) is formed by closing \( S_1, S_2, S_3 \). \( k, l \) is the closing coefficient of a cell in one pulse period. From here it is possible to develop a method of modulation of the vector \( U_s \), by closing the key \( S_6, S_1 \) and \( S_2 \) (vector \( U_1 \)) during time \( T_1(s) \), closing the valves \( S_1, S_2, S_3 \) (vector \( U_2 \)) within time \( T_2(s) \) period the hash pulses \( T_3(s) \) satisfy the condition: \( k = T_2/T_s \), \( l = T_1/T_s \). Since \( T_1, T_2 \leq T_s \), the values of \( k \) and \( l \) are in the range \((0,1)\). The remaining time \( T_0 = T_s - (T_1 + T_2) \) is the time for vector modulation. Thus, the formula for determining output voltage (which should be achieved by modulation) \( U_s \), depending on the standard vector of boundary voltages and the closing time of the key:

\[
U_s = \frac{T_1}{T_s} U_1 + \frac{T_2}{T_s} U_2 + \frac{T_0}{T_s} U_0
\]

According to the geometrical calculation formula to calculate values for \( T_1, T_2 \):

\[
T_1 = T_s \cdot m \cdot \frac{2}{\sqrt{3}} \sin\left(\frac{\pi}{3} - \theta\right)
\]

\[
T_2 = T_s \cdot m \cdot \frac{2}{\sqrt{3}} \sin(\theta)
\]

Where: \( m = \frac{|U_{dc}|}{U_{dc}} \) and \( T_s = \frac{1}{f_s} \).

After determining the times \( T_1, T_2, \) and \( T_0 \), the time of the closing all keys to the rack at work is determined. In each sector the switching time of each key is different and is described in [17-18].

### 2.2. Modulation for direct frequency converter

This section presents a space vector modulation method for the matrix converter, the structure of the power circuit described in figure 2. For the synthesis system modulation control based on the methods of space vector modulation, it is necessary to consider the matrix converter as a converter indirect with an intermediate DC link. The division of the MC to the rectifier and the inverter gives the possibility to perform synthesis of modulation control with the formation of the output voltage and controlling the input current.

#### 2.2.1. Modulation of the spatial vector of the input current

The vector diagram of the MC input current is presented in Fig. 5. DC bus voltage and the input current can be represented as follows:

\[
\begin{bmatrix}
U_{dc+} \\
U_{dc-}
\end{bmatrix} =
\begin{bmatrix}
S_1 & S_4 & S_6 \\
S_2 & S_4 & S_6
\end{bmatrix}
\begin{bmatrix}
U_a \\
U_b \\
U_c
\end{bmatrix}
\]
The given vector of the input current of the rectifier (grid current) can be represented by the combination of the base vectors of the two active vectors, between which there is a specified vector of the input current and the zero vector:

\[ I_i = d_\gamma I_\gamma + d_\delta I_\delta + d_{0i} I_0 \]

Where \( d_\gamma, d_\delta, d_{0i} \) - interval modulation coefficients, which determine the duration of the base vectors of the current in the loop modulation.

**Figure 5.** Vector input current diagram

**Figure 6.** Output voltage vector diagram

Current modulation factor is calculated as follows:

\[ m_i = \frac{|I_i|}{I_{dc}} \]

The interval modulation coefficients of the current are calculated as follows:

\[ d_\gamma = m_i \sin \left( \frac{\pi}{3} - \Delta_i \right) \]
\[ d_\delta = m_i \sin (\Delta_i) \]
\[ d_{0i} = 1 - d_\gamma - d_\delta \]

2.2.2. Modulation of the space vector of the output voltage

The vector diagram of the MC output voltage is presented in Fig.7. Direct current and output voltage can be represented as follows:

\[
\begin{bmatrix}
  I_a \\
  I_b \\
  I_c
\end{bmatrix} =
\begin{bmatrix}
  S_1 & S_2 & I_{dc+} \\
  S_3 & S_4 & I_{dc-} \\
  S_5 & S_6 & I_{dc-}
\end{bmatrix}
\]

The specified output voltage vector inverter a (load voltage) can be represented by a combination of base vectors as follows:

\[ U^*_0 = d_a U_a + d_\beta U_\beta + d_{0a} U_0 \]

Where \( d_a, d_\beta, d_{0a} \) - interval modulation coefficients, which determine the duration of the base vector in the voltage in the modulation cycle.

The voltage modulation factor is calculated as follows:
Interval coefficients of the modulation voltage are calculated as follows:

\[ m_u = \frac{|U_0|}{U_{dc}} \]

\[ d_\alpha = m_u \sin \left( \frac{\pi}{3} - \Delta \right) \]

\[ d_\beta = m_u \sin (\Delta) \]

\[ d_{\alpha\delta} = 1 - d_\alpha - d_\beta \]

### 2.2.3. Formation of switching functions using the indirect method

To ensure the symmetry of the input current and the output voltage in the modulation period, it is necessary to provide a certain switching sequence in the right mode \((\gamma - \delta - 0)\) with the switching of the inverter \((\alpha - \beta - 0)\). Therefore, the modulation should provide the following switching sequence:

\[ \alpha \gamma \rightarrow \beta \gamma \rightarrow \beta \delta \rightarrow \alpha \delta \]

Modulation factor for each stage:

\[ d_{\alpha \gamma} = d_\alpha d_\gamma \]

\[ d_{\alpha \delta} = d_\alpha d_\delta \]

\[ d_{\beta \gamma} = d_\beta d_\gamma \]

\[ d_{\beta \delta} = d_\beta d_\delta \]

\[ d_0 = 1 - (d_{\alpha \gamma} + d_{\alpha \delta} + d_{\beta \gamma} + d_{\beta \delta}) \]

The coefficients of the modulation can be represented as follows:

\[ d_\gamma d_\alpha = \frac{2|U_0|}{\sqrt{3}|U_i|} \sin \left( \frac{\pi}{3} - \Delta \right) \sin \left( \frac{\pi}{3} - \Delta_i \right) \]

\[ d_\delta d_\alpha = \frac{2|U_0|}{\sqrt{3}|U_i|} \sin (\Delta_i) \sin \left( \frac{\pi}{3} - \Delta_i \right) \]

\[ d_\gamma d_\beta = \frac{2|U_0|}{\sqrt{3}|U_i|} \sin \left( \frac{\pi}{3} - \Delta_i \right) \sin (\Delta) \]

\[ d_\delta d_\beta = \frac{2|U_0|}{\sqrt{3}|U_i|} \sin (\Delta) \sin \left( \frac{\pi}{3} - \Delta_i \right) \]

These coefficients can be calculated for all phases of the MC. From the presented equations it can be concluded that the maximum voltage gear ratio for MC is equal to \(\sqrt{3}/2 = 0.866\).

The sequence of formation of the base current vectors MFC should be constructed as follows:

- For rectifier:

\[ I_\gamma \rightarrow I_\delta \rightarrow I_0 \rightarrow I_\delta \rightarrow I_\gamma \]

- For inverter:

\[ U_\alpha \rightarrow U_\beta \rightarrow U_0 \rightarrow U_\beta \rightarrow U_\alpha \]

In MC output voltages should be formed in nine steps:

- If the sum of \(N_\gamma + N_\delta\) is odd value then:

\[ \gamma \gamma - \beta \gamma - \beta \delta - \alpha \delta - 0 - \alpha \delta - \beta \delta - \gamma \gamma; \]

- If the sum of \(N_\gamma + N_\delta\) is even:

\[ \beta \gamma - \alpha \gamma - \alpha \delta - 0 - \beta \delta - \alpha \delta - \gamma \gamma - \beta \gamma. \]

The order of formation of the output voltage vectors for all sectors of the phase plane (Fig.5 and Fig.6) is presented in Table 2.
Table 2. The order of formation of the vector of the output voltage of the Matrix converter

| Voltage and current sector $N_v$ | Switch combination | Switching order |
|-------------------------------|-------------------|-----------------|
| $U_1$-$I_1$                   | abb abb aac acc acc ccc | $\alpha\gamma\beta\gamma\alpha\delta - \alpha\delta - \alpha\delta - \beta\delta - \beta\gamma\alpha\gamma$ |
| $U_2$-$I_1$                   | bab bab aac cac cac ccc | $\beta\gamma\alpha\gamma\alpha\delta - \alpha\delta - \beta\delta - \alpha\delta - \beta\gamma\alpha\gamma$ |
| $U_3$-$I_6$                   | bab baa cca cac ccc ccc | $\alpha\gamma\beta\gamma\beta\delta - \beta\delta - \alpha\delta - \delta\gamma\beta\gamma$ |
| $U_4$-$I_6$                   | bba baa cca cca ccc ccc | $\beta\gamma\alpha\gamma\alpha\delta - \beta\delta - \alpha\delta - \beta\delta - \alpha\delta - \beta\gamma\alpha\gamma$ |
| $U_5$-$I_6$                   | bba aba cca cca ccc ccc | $\alpha\gamma\beta\gamma\beta\delta - \beta\delta - \alpha\delta - \delta\gamma\beta\gamma$ |
| $U_6$-$I_6$                   | abb aba cca acc ccc ccc | $\beta\gamma\alpha\gamma\alpha\delta - \beta\delta - \alpha\delta - \delta\gamma\beta\gamma$ |
| $U_7$-$I_1$                   | aac acc bcc bbb bbb bbb | $\gamma\beta\gamma\alpha\delta - \beta\delta - \alpha\delta - \delta\gamma\beta\gamma$ |
| $U_8$-$I_1$                   | cac acc cbc bbb bbb bbb | $\gamma\beta\gamma\alpha\delta - \beta\delta - \alpha\delta - \delta\gamma\beta\gamma$ |
| $U_9$-$I_1$                   | cca cca ccb bbb bbb bbb | $\gamma\beta\gamma\alpha\delta - \beta\delta - \alpha\delta - \delta\gamma\beta\gamma$ |
| $U_10$-$I_1$                  | ccb ccb bab aab aab aab | $\gamma\beta\gamma\alpha\delta - \beta\delta - \alpha\delta - \delta\gamma\beta\gamma$ |
| $U_11$-$I_1$                  | bba bba cca cca ccc ccc | $\gamma\beta\gamma\alpha\delta - \beta\delta - \alpha\delta - \delta\gamma\beta\gamma$ |
| $U_12$-$I_1$                  | cba cba ccb bbb bbb bbb | $\gamma\beta\gamma\alpha\delta - \beta\delta - \alpha\delta - \delta\gamma\beta\gamma$ |
| $U_13$-$I_1$                  | aab aab aac acc ccc ccc | $\gamma\beta\gamma\alpha\delta - \beta\delta - \alpha\delta - \delta\gamma\beta\gamma$ |
| $U_14$-$I_1$                  | bab bab aac acc ccc ccc | $\gamma\beta\gamma\alpha\delta - \beta\delta - \alpha\delta - \delta\gamma\beta\gamma$ |
| $U_15$-$I_1$                  | cca cca ccb bbb bbb bbb | $\gamma\beta\gamma\alpha\delta - \beta\delta - \alpha\delta - \delta\gamma\beta\gamma$ |

2.3. Results and analysis
To study the effectiveness of the use of the indirect method of modulation of matrix Converter, simulations were carried out in Matlab. The simulation model has the following parameters: input voltage 220(V), 50(Hz), load resistance $R = 2\Omega$, inductance $L = 10$mH.
2.3.1. Two-level inverter VSI Simulation

![SVM modulation results](image)

**Figure 7.** SVM modulation results, (a) VSI load current, (b) the output voltage (f = 50 Hz)

![Fundamental (50Hz) = 84.18, THD= 5.45%](image)

**Figure 8.** Output voltage total harmonic distortion (THD=5.45%) of the PWM method

![Fundamental (50Hz) = 127.1, THD= 3.15%](image)

**Figure 9.** Output voltage total harmonic distortion (THD=3.15%) of the SVM method

2.3.2. Results when using a matrix converter

![The voltage and current at MC](image)

**Figure 10.** The voltage and current at MC, (a) input MC, (b) output MC
The modulation method SVM for VSI shows the better output voltage and current than the PWM method (Fig.8 and Fig.9) because the SVM method creates a continuous shift of equivalent to a space vector voltage of the inverter on a circular path. With a uniform displacement of the spatial vector on a circular path, the higher harmonics are removed. There is a possibility to prepare SVM to optimize switching or optimization of harmonics depending on the choice of modulation standard boundary voltages. However, the quality of voltage and current still has the disadvantages of the VSI Converter. With modulation method SVM for matrix converter (Fig 10-12) the results show that the phase of the input current almost coincides with the phase of the input voltage, no voltage surge, the output voltage has a sinusoidal form. At the entrance there are no harmonics of voltage, indicating the correctness of the control logic switching.

3. Conclusion
The Based on the theoretical analysis and simulation of PWM and SVM modulation methods for indirect frequency converters, a space vector modulation method for 3x3 matrix converters has been developed. This modulation method has divided the bidirectional valves into two virtual rectifiers and virtual inverters to control the current vector and voltage vector separately. This ensures that in each cycle, it is only necessary to determine the phase angle of the voltage at the input with the time when the source voltage passes to the value of 0 without regard to the instantaneous value of the voltage. The output voltage is determined by the required frequency and the desired modulation factor. This will minimize the steps of calculating the modulation factor so the anti-interference is good, is a direct energy converter in two directions. The paper reviews the method of controlling semiconductor valves in indirect converters to develop methods of controlling two directions valves in matrix frequency converters, with the desire to develop the advantages of matrix converters in the electric drive control system.

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