Switching strategies for a multi-level inverter

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Abstract. The article examines the methods of switching the stages of a multi-level inverter in order to reduce the harmonic factor of the output voltage of the inverter. These methods use pulse-width modulation for switching, which is obtained by comparing a reference sinusoidal signal and a sequence of triangular pulses. The article describes the algorithms for obtaining the control sequence of pulses and simulates each of the strategies. The dependence of the nonlinear distortion factor on the frequency of the carrier wave for different switching strategies is obtained based on the simulation results. The influence of the LPF on the quality of the output voltage of the inverter is also investigated. In addition, an experimental study of a six-level inverter was carried out. The waveforms and spectrograms of the inverter were obtained using the Fluke 434-II electrical energy analyzer. The harmonics of the output voltage, which are distinguished by power from the entire spectrum, were identified.

1. Introduction
The topology of a multi-level inverter allows switching voltage levels. At the same time, in most cases, a particular topology differs only in the number of switching keys used, power supplies and other performance elements and does not allow obtaining a significant advantage in reducing the harmonic components. To reduce them, a certain strategy to select the switching time of each of the stages of a multi-level inverter was used. At the moment, there are various strategies used to implement a multi-level inverter [1-3]. Most of them are based on the use of pulse-width modulation [4-6].

The use of PWM is widely used to obtain a sinusoidal voltage at the output of a single-level inverter, where the pulse width of the carrier wave varies according to a sinusoidal law. But PWM can also be used for switching in a multi-level inverter [7-10] with the only difference that the carrier waves form each of the stages of the inverter separately.

It is proposed to investigate various strategies for reducing the harmonic factor basing on the topology of constructing a multi-level inverter presented in [11].

2. Switching Strategies
The PWM-based switching strategies discussed in this article are as follows:

- co-phased PWM strategy;
- antiphase PWM strategy;
- alternating antiphase PWM strategy;
- PWM strategy with superimposed carrier waves;
- PWM strategy with different frequency.
Let us consider a co-phased PWM stage switching strategy. \( U_s \) \( A \) sinusoid with an amplitude of 312 V and a frequency of 50 Hz was set as a modulating signal according to the law

\[
U_s = 312 \sin 100 \pi t.
\]

A triangular signal of a symmetrical shape shall act as a carrier wave, i.e. the growth duration of such a signal is equal to the duration of its downfall. The frequency of the carrier triangular signal will be constant but it must be several times greater than the frequency of the modulating sinusoidal signal. The amplitude of the triangular signal is selected depending on the amplitude of the multi-level inverter stage.

Let us introduce the concept of a frequency factor \( k_f \), which is equal to the ratio of the carrier wave frequency \( f_c \) to the modulating signal frequency \( f_s \).

\[
k_f = \frac{f_c}{f_s}
\]

Thus, it is possible to study the influence of this factor on the nonlinear distortion factor. Similarly, let us introduce the concept of the \( k_A \) amplitude factor, which will be calculated by the following formula

\[
k_A = \frac{n \cdot A_c}{f_s},
\]

where \( n \) is the number of inverter stages, \( A_c \) is the amplitude of the carrier wave, and \( A_s \) is the amplitude of the modulating signal.

Let us consider strategies based on a three-level inverter. Let the level of the stages be the same and conditionally equal to 1. In this case, the amplitude of the modulating signal is 3.

Figure 1a shows a diagram of the switching time selection according to the co-phased PWM strategy. For this case, the value of the frequency factor \( k_f \) is 20, i.e. the frequency of the carrier triangular signals is 20 times higher than the frequency of the sinusoidal wave. The amplitude factor \( k_A \) equals 1.
As can be seen from the figure, the carrier waves for each stage are in the same phase. The number of carriers required to obtain the switching time at each level is equal to the number of inverter stages multiplied by two. It should be noted that all carriers are of the same amplitude. According to this strategy, if the value of the carrier triangular wave for a given time is higher than the value of the sinusoidal signal, then a high-level value is formed, otherwise a low-level value is formed. Thus, the commuting pulse is generated whenever the triangular pulse of the stage is greater than the sinusoid.

According to the principle of forming control pulses according to the law of antiphase PWM strategy, all the carrier waves of the positive half-wave are in the same phase relative to each other and all the carrier waves of the negative half-wave are also in the same phase, but in the opposite phase to the carrier waves of the positive half-wave (figure 1b).

For an alternating antiphase PWM strategy, the carrier waves of the same amplitude are in antiphase relative to the neighbouring ones (figure 1c). In fact, this and the previous strategies are convenient from the point of view of application, since a phase shift of 180° shifts the carriers so that the positive and negative half-waves are in the same position relative to the carriers. Thus, the pulses are formed for the positive and negative half-waves equally, which is very convenient.

Since the sinusoid has a characteristic steepness, the number of switches for the lower levels of the inverter is less than the number of switches for the upper levels. Different frequencies for the carrier waves can be used in order to equalize the number of switches for all levels. This is implemented in the PWM strategy with frequency. The carrier position diagram for this strategy is shown in figure 1d ($k_{f1} = 40$, $k_{f2} = 20$, $k_{f3} = 12.5$, $k_A = 1$).

Using PWM with superimposed carrier waves allows increasing or decreasing the duration of switching pulses and eliminate short-term bursts. This can be achieved by increasing the amplitude of the carrier waves, as the triangular signals are cut off and become trapezoidal. The carrier wave position diagram for the PWM strategy with carrier wave superposition is shown in figure 1e ($k_f = 20$, $k_A = 1.5$).

3. Simulation

In order to study the effect of switching strategies on the harmonic factor, let us build a special model in the Simulink visual simulation environment.

Figure 2 shows a model of a 6-level inverter for the study of switching methods [12].

![Figure 2. Model of a 6-Level Inverter for the Study of Switching Methods.](image-url)
The output voltage obtained from the simulation differs from the usual step voltage by the presence of pulse-width modulation (figure 3). It should be noted that the closer the pulses are to the border of the transition to a high level, the wider the pulses and vice versa.

![Figure 3. Output Voltage Waveform.](image)

To compare strategies, there can be used the nonlinear distortion factor, which is automatically calculated using the powergui block by means of a fast Fourier transform. The data for the strategies are shown in table 1. Conspicuously, the nonlinear distortion factors are quite big due to high frequencies in the output voltage of the inverter. Therefore, these strategies are applied with a low-pass filter. In order not to distort the low frequencies, it is necessary to choose a filter with a smooth amplitude-frequency response at the passband frequencies [13,14]. A typical third-order Butterworth filter with a cutoff frequency of 1000 Hz was used.

### Table 1. Nonlinear Distortions Factors of Various Methods.

| Period, sec | Frequency, Hz | AP PWM without LPF | AP PWM after LPF | AAP PWM without LPF | AAP PWM after LPF | PWM with SC without LPF | PWM with SC after LPF | PWM with DF without LPF | PWM with DF after LPF |
|-------------|----------------|--------------------|------------------|----------------------|-------------------|------------------------|----------------------|------------------------|----------------------|
| 0.0013      | 769.2          | 9.3                | 7.04             | 10.05                | 7.51              | 14.24                  | 11.49                | 9.27                   | 6.98                 |
| 0.0012      | 833.3          | 9.75               | 6.95             | 9.6                  | 6.42              | 15.65                  | 11.8                | 9.54                   | 6.93                 |
| 0.0011      | 909.1          | 8.78               | 6.08             | 7.91                 | 4.44              | 13.8                   | 9.69                | 9.7                    | 7.8                  |
| 0.001       | 1000           | 8.38               | 5.85             | 10.08                | 7.1               | 15.12                  | 9.6                  | 9.46                   | 7.23                 |
| 0.0009      | 1111.1         | 8.99               | 4.88             | 9.15                 | 5.17              | 14.73                  | 7.98                | 7.86                   | 4.44                 |
| 0.0008      | 1250           | 8.98               | 4.33             | 9                    | 5.26              | 14.39                  | 6.37                | 8                      | 4.38                 |
| 0.0007      | 1428.6         | 8.94               | 3.21             | 9.22                 | 4.59              | 14.3                   | 4.84                | 8.92                   | 3.75                 |
| 0.0006      | 1666.7         | 9.14               | 2.63             | 9.08                 | 3.79              | 14.4                   | 3.19                | 9.12                   | 3.05                 |
| 0.0005      | 2000           | 8.27               | 2.28             | 8.98                 | 2.31              | 15.05                  | 2.11                | 8.19                   | 2.54                 |
| 0.0004      | 2500           | 8.71               | 1.65             | 9.01                 | 1.43              | 14.29                  | 2.35                | 8.65                   | 2                    |
| 0.0003      | 3333.3         | 9.01               | 1.4              | 9.17                 | 1.67              | 14.8                   | 2                   | 8.96                   | 1.38                 |
| 0.0002      | 5000           | 9.86               | 1.74             | 9.64                 | 1.7               | 14.6                   | 2.47                | 9.22                   | 1.37                 |
| 0.0001      | 10000          | 13.1               | 4.18             | 13.3                 | 4.09              | 21.11                  | 3.63                | 11.42                  | 1.85                 |

A graph of the dependence of the nonlinear distortion factor on the frequency of the carrier wave is constructed based on the simulation results. In this graph, the dashed lines show the results of simulation strategies without filtering, and the solid lines show the simulation with the LPF.
As can be seen from figure 4, a high value of the nonlinear distortion coefficient can be observed for all strategies with low values of the frequency factor, and with an increase in the carrier frequency, this factor decreases to a certain minimum and then increases slightly. At the same time, the lowest factor of nonlinear distortion is observed when using a switching strategy based on PWM with DF. When implementing a power inverter, however, a higher frequency should be chosen, since the frequency increases the energy loss for transients. The fact that switching is carried out by power switches, such as IGBT or MOSFET, transients in which at a high switching frequency can disable them [15,16], should also be taken into account.

4. Experiment
An experimental setup was assembled in the MATLAB environment after checking the correctness of the diagram. Figure 5a shows the block diagram of the inverter, and figure 5b shows the experimental setup. The inverter consists of a 6-channel switch, an H-bridge and a control system built on an ATmega32A microcontroller.

Waveforms and spectrograms of the output voltage were obtained as a result of the experimental study. Figure 6a shows the waveform, and figure 6b shows the output voltage spectrogram for a six-level PWM inverter.
As can be seen from figure 6a, the shape of the output voltage of the inverter has spikes at each of the stages, but it is visually close to sinusoidal. Of particular interest are the spectrograms of the output voltage of inverters. It can be noted that the 37th, 39th, 41st and 43rd harmonics, whose frequencies are 1850, 1950, 2050 and 2150 Hz, respectively, are expected to stand out in power from the entire spectrum. This is naturally related to the pulse frequency of the pulse width modulation stages. Harmonics at this frequency are very convenient to filter since the filter is set to high harmonics, i.e. with a higher cutoff frequency. Such a filter is lighter and more space-saving than a conventional LPF and is very simple in design.

5. Conclusion
The dependences of the nonlinear distortion factor on the frequency for various strategies without filtering the output voltage of the inverter, and with the low-frequency filter are obtained based on the results of the Simulink simulation. It was found that the lowest factor of nonlinear distortion can be obtained by using a switching strategy based on PWM with different frequencies for the stages. The results of the experimental study confirmed the presence of harmonics at the carrier frequency, which can be eliminated using a low-pass filter.

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