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MULTI-LEVEL INVERTER SWITCHING STRATEGIES

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Abstract

In the article, the methods of switching stages of a multi-level inverter are studied. These techniques use pulse-width modulation for switching, which is obtained by comparing a reference sinusoidal signal and a sequence of triangular pulses. The article describes algorithms for obtaining a control sequence of pulses and examines how a particular strategy can reduce the coefficient of harmonic components of the output voltage of the inverter. To do this, Simulink simulates each of the strategies for different frequencies. Based on the simulation results, the dependence of the coefficient of nonlinear distortion on the frequency of the carrier oscillation for different switching strategies is obtained. The simulation was performed without filtering the output voltage of the inverter, and with the use of a low-pass filter. In addition, an experimental study of a six-level PWM inverter was performed. Using the Fluke 435-II electrical energy analyzer, oscillograms and spectrograms of the inverter are obtained. Harmonics of the output voltage are detected that differ in power from the entire spectrum.

Key words: multi-level inverter, PWM, switching angle, nonlinear distortion coefficient, sinusoidal voltage.

СТРАТЕГИИ КОММУТАЦИИ МНОГОУРОВНЕВОГО ИНВЕРТОРА

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Аннотация

В данной статье исследованы методики коммутации ступеней многоуровневого инвертора. Данные методики используют широтно-импульсную модуляцию для коммутации, которая получается путем сравнения эталонного синусоидального сигнала и последовательности треугольных импульсов. В статье описаны алгоритмы получения управляющей последовательности импульсов и исследовано как та или иная стратегия позволяет уменьшить коэффициент гармонических составляющих выходного напряжения инвертора. Для этого в среде Simulink произведено моделирование каждой из стратегий для различных частот. На основе результатов моделирования получена зависимость коэффициента нелинейных искажений от частоты несущего колебания для разных стратегий коммутации. Моделирование производилось без фильтрации выходного напряжения инвертора, и с использованием ФНЧ. Помимо этого произведено экспериментальное исследование шестиуровневого ШИМ-инвертора. При помощи анализатора электрической энегии Fluke 435-II полученны осциллограммы и спектрограммы инвертора. Выявлены гармоники выходного напряжения выделяющиеся по мощности из всего спектра.

Ключевые слова: многоуровневый инвертор, ШИМ, угол коммутации, коэффициент нелинейных искажений, синусоидальное напряжение.

КӨП ДЕҢГЕЙЛІ ИНВЕРТОРДЫҢ КОММУТАЦИЯ СТРАТЕГИЯЛАРЫ

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Аңдатпа

Бұл мақалада көп деңгейлі инвертор сатыларының коммутация әдістері зерттелді. Бұл әдістемелер эталондық синусоидалды сигналды және үшбұрышты импульстардың тізбегін салыстыру арқылы алынатын коммутация үшін кеңдік-импульстік модуляцияны пайдаланады. Мақалада импульстардың басқару тізбегін алу алгоритмдері сипатталған және сол немесе басқа стратегия инвертордың Шығыс кернеуінің гармоникалық құрауыштарының коэффициентін азайтуға мүмкіндік береді. Бұл үшін Simulink ортасында әртүрлі жиіліктер үшін стратегиялардың әрқайсысын модельдеу жасалған. Қазіргі кезде, бұл модельдеудің нәтижелері негізінде коммутацияның әр түрлі стратегиялары үшін салмақ түсетін тербелістің жиілігіне сызықты емес бұрмалау коэффициентінің тәуелділігі алынған. Модельдеу инвертордың Шығыс кернеуін сүзусіз және төмен жиіліктегі фильмдерді қолдану арқылы жүргізілді. Бұдан басқа алты деңгейлі КИМ-Инверторды Эксперименталды зерттеу жүргізілді. Fluke 435-II электр энегиясын талдағыштың көмегімен осциллограммалар мен инвертордың спектрограммалары алынды. Барлық спектрден қуат бойынша бөлінетін Шығыс кернеуінің гармониктері анықталды.

Түйінді сөздер: көп деңгейлі инвертор, КИМ, коммутация бұрышы, сызықты емес бұрмалау коэффициенті, синусоидалды кернеу.

Introduction

The topology of building a multi-level inverter allows switching voltage levels. However, in most cases, a particular topology differs only in the number of switching keys, power supplies, and other execution elements used, and does not allow you to get a significant advantage in reducing the harmonic components. To reduce them, a specific strategy is used for choosing the switching time of each of the stages of a multi-level inverter. At the moment, there are various strategies used for implementing 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 oscillation varies according to the sinusoidal law. But PWM can also be used for switching in a multi-level inverter [7-10] with the only difference that the carrier vibrations form each of the stages of the inverter separately.

Based on the topology of building a multi-level inverter, presented in [11], we investigate how various strategies can reduce the coefficient of harmonic components, and determine the optimal one.

The method of switching

The PWM-based switching strategies discussed in this article are listed below:

- common-mode PWM strategy;
- antiphase PWM strategy;
- alternating antiphase PWM strategy;
- PWM strategy with the imposition of carrier oscillations;
- PWM strategy with different frequency.

Consider a common-mode PWM strategy for switching stages. The modulating signal U_s is a sine wave with an amplitude of 312 V and a frequency of 50 Hz according to the law

$$U_s = 312\sin 100\pi t.$$

A triangular signal of symmetrical shape will act as a carrier oscillation, i.e. the duration of growth of such a signal is equal to the duration of its decline [12]. The frequency of the carrier triangular signal will be unchanged, but it must be several times higher than the frequency of the modulating sinusoidal signal. The amplitude of the triangular signal is selected depending on the amplitude of the stage of the multi-level inverter.

We introduce the concept of a frequency coefficient k_f, which is equal to the ratio of the frequency of the carrier oscillation f_c to the frequency of the modulating signal f_s.

$$k_f = \frac{f_c}{f_s}$$

Thus, we can investigate the effect of this coefficient on the coefficient of nonlinear distortion. Similarly, we introduce the concept of the amplitude coefficient k_A, which will be calculated using the formula

$$k_A = \frac{n \cdot A_c}{f_s},$$

n is the number of stages of the inverter, A_c is the amplitude of the carrier oscillation, and A_s is the amplitude of the modulating signal.

Consider strategies based on a three-level inverter [13]. Let the level of the steps be the same and conditionally equal to 1. In this case, the Amplitude of the modulating oscillation is equal to 3.

Figure 1A shows the diagram of switching time selection for the common-mode PWM strategy. For this case, the value of the frequency coefficient k_f is 20, i.e. the frequency of the carrier triangular signals is 20 times higher than the frequency of the sinusoidal oscillation. The value of the amplitude coefficient k_A is 1.

As you can see from the picture, the carrier vibrations 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 have the same amplitude. According to this strategy, if the value of the carrier triangular oscillation 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 larger than the sine wave.

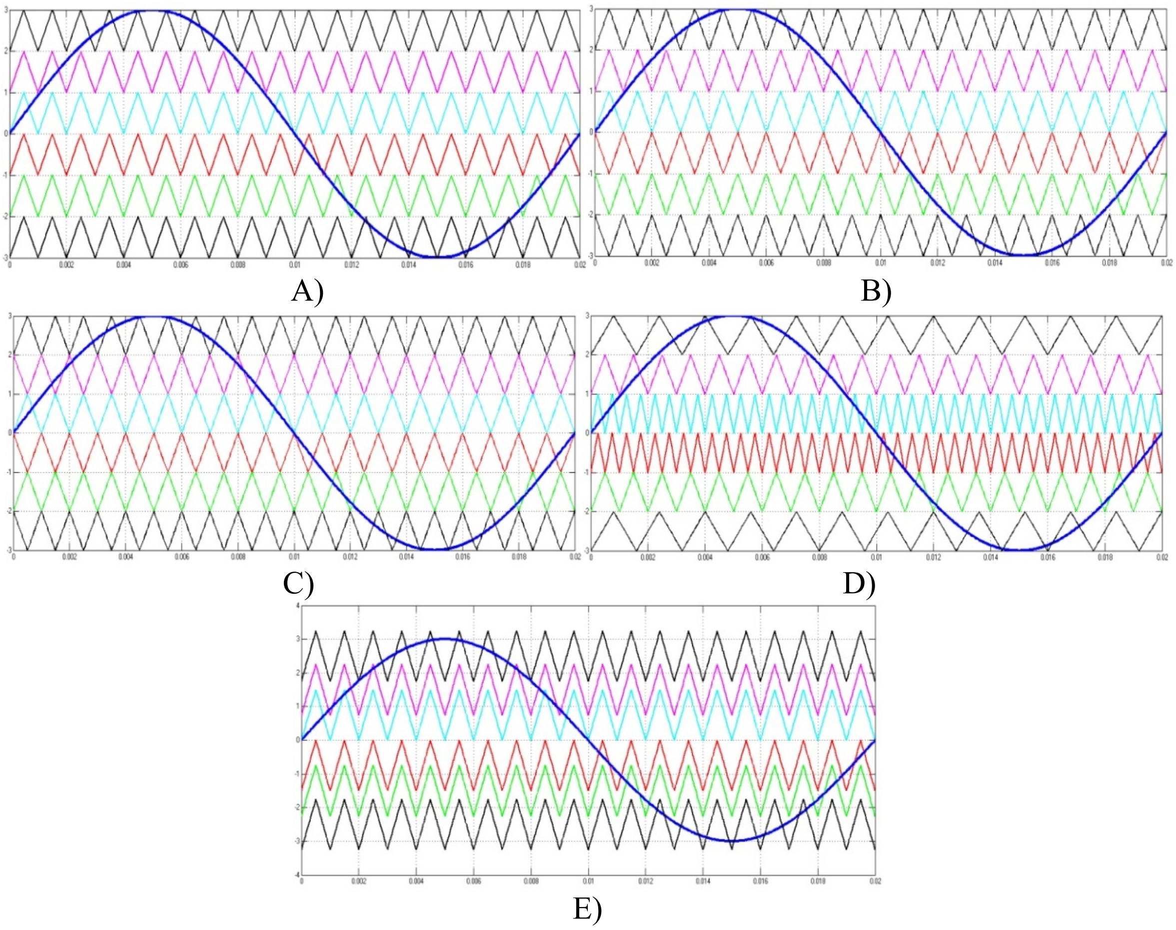


Figure 1 diagrams of the position of carrier vibrations for various strategies of the strategy

According to the principle of the formation of the control pulses according to the law of reversed-phase shim strategy all bearing vibrations of positive half-wave are in the same phase relative to each other and all the supporting negative half-cycle fluctuations are also in phase but in opposite phase with the carrier oscillations of positive half-wave (Figure 1B).

For an alternating antiphase PWM strategy, the carrier vibrations of the same amplitude are in the opposite phase relative to the neighboring 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 positive and negative half-waves in the same way, which is very convenient.

Since the sine wave 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. In order to equalize the number of switches for all levels, you can use different frequencies for carrier vibrations. This is implemented in the PWM frequency strategy. The carrier position diagram for this strategy is shown in figure 1G ($k_{f1} = 40$, $k_{f2} = 20$, $k_{f3} = 12.5$, $k_A = 1$).

Using PWM with superimposed carrier vibrations, you can increase or decrease the duration of switching pulses and eliminate short-term bursts. This is achieved by increasing the amplitude of the carrier vibrations, as the triangular signals are cut off and become trapezoidal. The diagram of the position of the carrier vibrations for the PWM strategy with overlapping carrier vibrations is shown in figure 1E ($k_f = 20$, $k_A = 1.5$).

Modeling

To study the effect of switching strategies on the coefficient of harmonic components, we will build a special model in the Simulink visual modeling environment.

Figure 2 shows a model of a 6-level inverter for the study of switching techniques [14]. The Sine Wave block generates a sinusoidal oscillation with a frequency of 50 Hz and an amplitude of 312 V. the Repeating Sequence Block generates a triangular signal of the carrier oscillation. This signal is formed with a constant component from the Constant block, the value of which is adjusted depending on the stage of the multi-level inverter. The triangular and sinusoidal signals are compared by the relative Operator comparison operator, which sends the signal to the power key. If the Sinusoidal signal is larger than the triangular one, the operator generates a logical unit, otherwise it generates a logical zero. To investigate only the impact of a particular strategy, we will exclude the influence of IGBTs, which we will replace with conventional power keys, which are represented by Ideal Switch blocks [15].

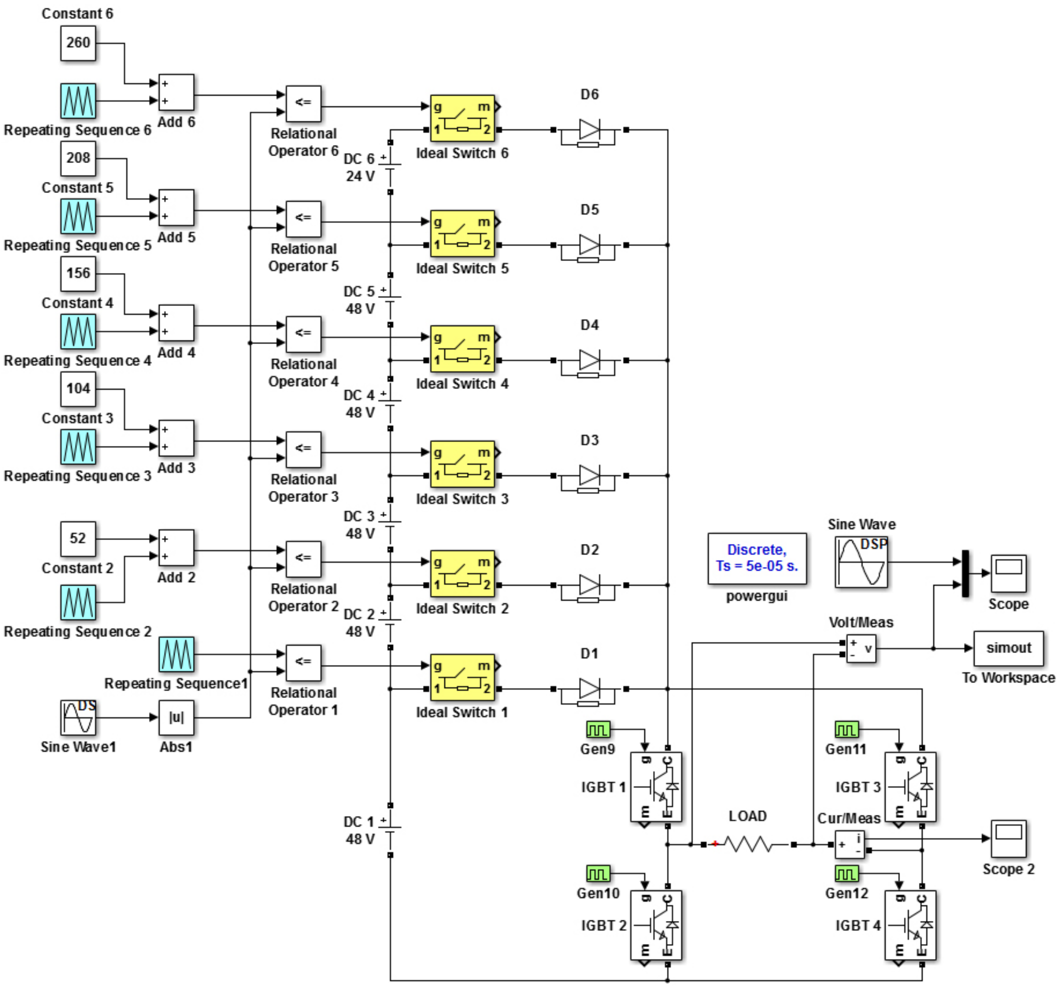


Figure 2 Model of a 6-level inverter for the study of switching techniques

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.

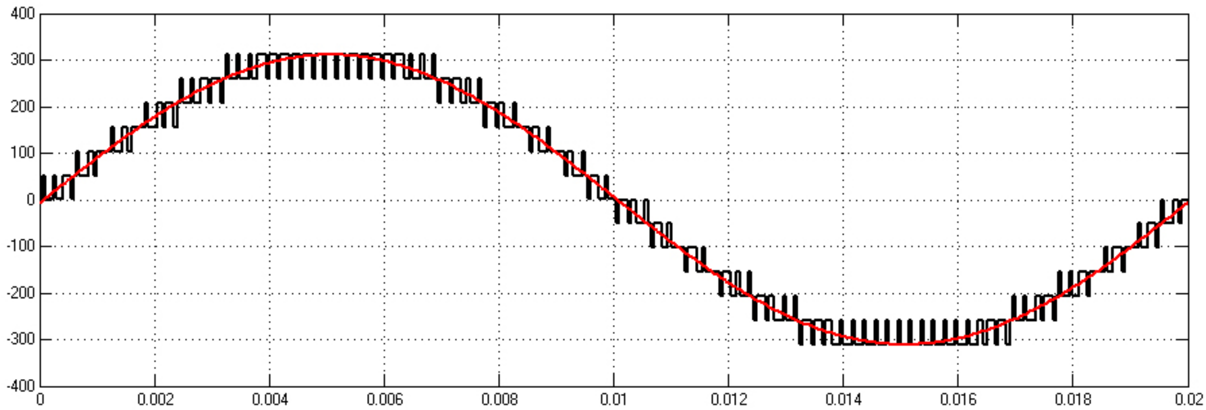


Figure 3 output voltage Waveform

To compare strategies, the value of the nonlinear distortion coefficient is important, which is automatically calculated using the powergui block by means of a fast Fourier transform. The data for the strategies are listed in table 1.as you can see, the coefficients of nonlinear distortion are quite large, due to the presence of high frequencies in the output voltage of the inverter. Therefore, these strategies are applied with a low-pass filter. In order not to distort low frequencies, it is necessary to select a filter with a smooth frequency response at the bandwidth frequencies [16, 17]. A typical third-order Butterworth filter with a cutoff frequency of 1000 Hz was used [18]. For modeling, the Butterworth filter is built using the Analog Filter Design block, where the filter order and cutoff frequency are set to 6283.2 rad/s.

Table 1 coefficients of nonlinear distortions of various methods

Period	Frequency	AP PWM		AAP PWM		PWM with ICO		PWM with DF	
		Without LFF	After LFF	Without LFF	After LFF	Without LFF	After LFF	Without LFF	After LFF
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

Based on the simulation results, a graph of the dependence of the coefficient of nonlinear distortion on the frequency of the carrier oscillation is constructed. In this graph, dashed lines show the results of strategy modeling without filtering, and solid lines show the results of modeling with LFF.

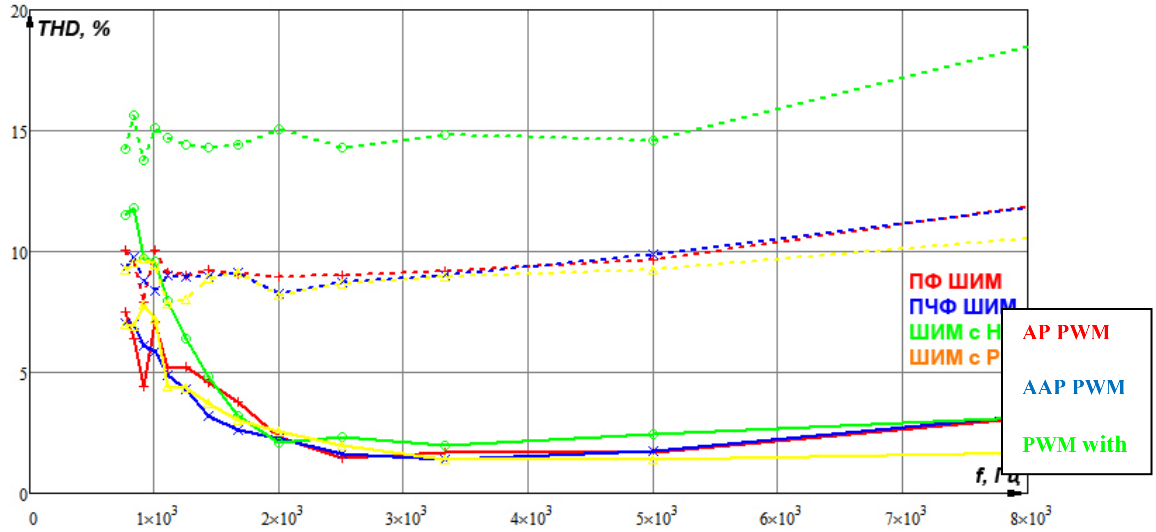
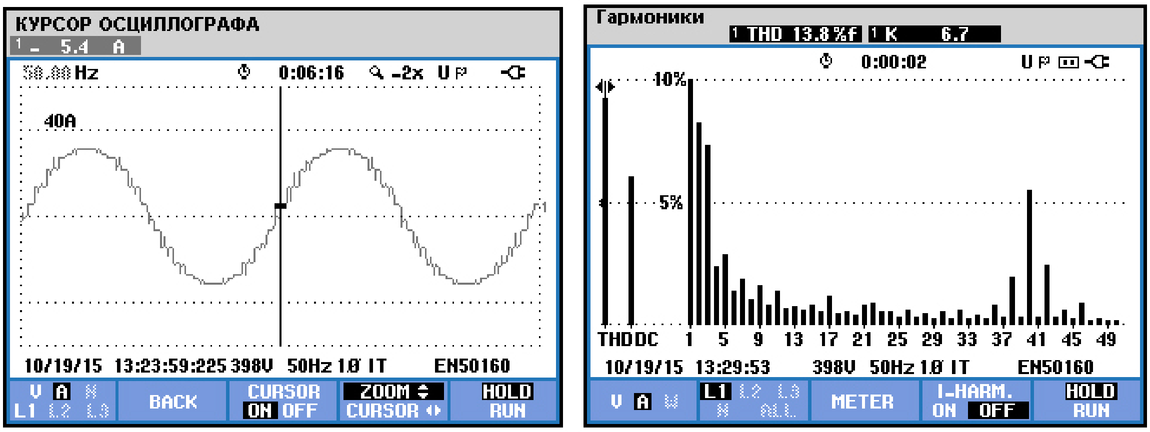


Figure 4 Graph of the dependence of the coefficient of nonlinear distortion on the frequency of the carrier oscillation

As can be seen from figure 4, for all strategies, at low values of the frequency coefficient k_f, a high value of the nonlinear distortion coefficient is observed, and with increasing carrier frequency, this coefficient decreases to a certain minimum and then increases slightly. At the same time, the lowest coefficient of nonlinear distortion is observed when using a PWM-based switching strategy with RF. When implementing a power inverter, however, you should not choose a higher frequency, since the frequency increases the energy loss for transients. It should also be borne in mind that switching is performed by power keys, such as IGBT or MOSFET, transients in which at a high switching frequency can disable them [19, 20].

Experiment

An experimental study of a six-level PWM inverter was performed. The resulting waveforms and spectrograms of inverters are shown in figure 5. Figure 5A shows the waveform, and figure 5B shows the output voltage spectrogram for a six-level PWM inverter.



A) B)

Figure 5 Waveform and spectrogram of the output voltage of a six-level inverter with PWM strategy

As you can see from figure 5, the shape of the output voltage of the inverter has spikes on each of the stages, but it is visually close to the sine wave. The output voltage spectrograms of inverters are of particular interest. You can see 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 slice frequency. This filter is lighter and more compact in comparison with a conventional LFF, and is very simple in design.

Conclusion

The article deals with methods of switching stages of a multi-level inverter based on pulse-width modulation. Based on the results of Simulink simulation, the dependence of the nonlinear distortion coefficient on the frequency for various strategies without filtering the output voltage of the inverter, and with the LPF is obtained. It was found that the lowest coefficient of nonlinear distortion can be obtained when using a switching strategy based on PWM with different frequencies for stages. An experimental study of a six-level inverter with the proposed switching strategy was performed.

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