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IMPROVING THE HARMONIC COMPOSITION OF OUTPUT VOLTAGE IN MULTILEVEL INVERTERS UNDER AN OPTIMUM MODE OF AMPLITUDE MODULATION

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Одним із найважливіших параметрів багаторівневих інверторів є синусоїдальність вихідної напруги. Існує досить багато різних алгоритмів модуляції, які дозволяють отримати різні показники синусоїдальності вихідної напруги та різний вміст вищих гармонік. Представлено універсальний алгоритм модуляції, який дозволяє отримати форму вихідної напруги багаторівневого інвертора з будь-якою кількістю ступенів, оптимізовану за вмістом вищих гармонік, а саме за мінімумом коефіцієнта гармонічних спотворень. Запропонований алгоритм дозволяє отримати мінімально можливий THD для будь-якої рівневої напруги. Перевагою запропонованого алгоритму у порівнянні з аналогічними алгоритмами оптимізації є забезпечення менших гармонічних спотворень та його відносна простота. Представлений алгоритм базується на амплітудній модуляції синусоїдального сигналу з 25 % перемодуляцією відносно найвищої дискретності. Представлено аналітичні вирази, що дозволяють визначити час (кут) вмикання кожного ступеня вихідної напруги для формування мінімуму середньоквадратичного значення вищих гармонік. Для підтвердження аналітичної точки оптимуму в програмному середовищі Matlab/Simulink було розроблено ряд багаторівневих інверторів напруги, які формують п'яти-, семи-, дев'яти- та одинадцятирівневу форми вихідної напруги. Проведені дослідження показали, що точки оптимуму для всіх форм багаторівневих напруг досягаються при одному й тому ж коефіцієнті амплітудної модуляції. Показано, що запропонований алгоритм модуляції можливо також застосовувати для регулювання амплітуди та частоти вихідної напруги в багаторівневому інверторі. Представлено регулювальну характеристику вихідної напруги багаторівневого інвертора при амплітудно-імпульсній модуляції

Ключові слова: амплітудна модуляція, коефіцієнт гармонічних спотворень, оптимум синусоїдальності вихідної напруги інвертора

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1. Introduction

Many industries, such as alternative power sources, electric drives in the oil extraction sector, and others, actively employ single-phase, three-phase and multiphase multilevel voltage source inverter (MVSI) [1, 2]. Some of the most common types of MVSI are the cascade inverters (Fig. 1) [3, 4].

Each phase of the cascade MVSI consists of the n number of connected in series single-phase bridges (cells). In the cascade MVSI, each shunt has its individual constant-voltage power supply [5, 6].

In this case, the cascade MVSI can employ both the two-level and three-level single-phase bridges. The advantage of using three-level bridges is that they make it possible, at the same number of independent power sources, to obtain a larger quantity of the output voltage levels and, consequently, higher sinusoidality [7, 8].

One of the basic requirements for MVSI is to ensure the highly sinusoidal output voltage and output current. The requirements for the shape of output voltage are particularly important for the converters operating as a power supply for own electric network [9, 10].

The sinusoidality of output voltage in multilevel inverters is typically assessed based on the total harmonic distortion (*THD*), which is an integrated indicator of the sinusoidality determining the rms content of the higher harmonics [11, 12]:

$$THD_u = \frac{\sqrt{\sum_{h=2}^{\infty} U_h^2}}{U_1}, \qquad (1)$$

where U_1 is the rms of the first harmonic; U_h is rms of the h-th harmonic.

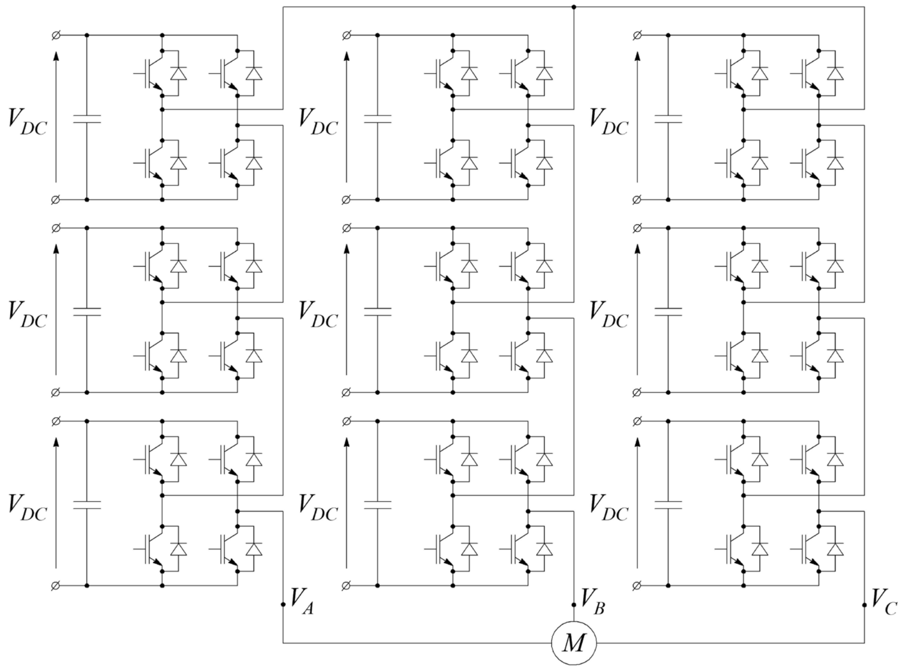


Fig. 1. Scheme of a cascade multilevel inverter

The *THD* parameter reflects the percentage of the higher harmonics relative to the first harmonic's voltage signal. In turn, the higher harmonics cause a series of negative effects in the power supply systems and various loads, which include the faster aging of insulation, electromagnetic interference with communication systems, as well as additional power losses in the active resistance of power supply systems and windings of induction motors [13].

According to [13, 14], the dependence of the relative value of additional power losses on the value of total harmonic distortion is shown in Fig. 2, in which 100 % denotes the loss caused by the principal harmonic or, for a DC network, the constant component of current.

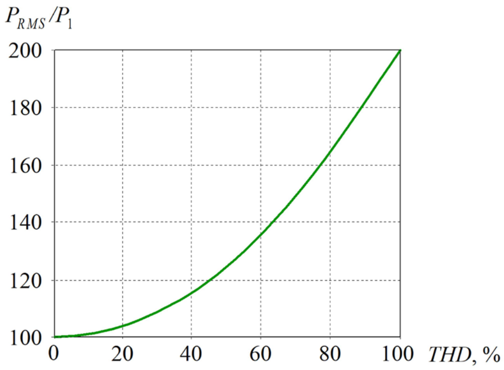


Fig. 2. Dependence of the value of relative additional power losses in the active resistance of power systems on the total harmonic distortion in the network current

In addition to physical phenomena related to an increase in the additional losses of power in active resistance, the higher harmonics of supply voltage in electrical networks must be destroyed to the levels specified by the international standards IEEE-519, IEC 61000-3-2, IEC 61000-4-3.

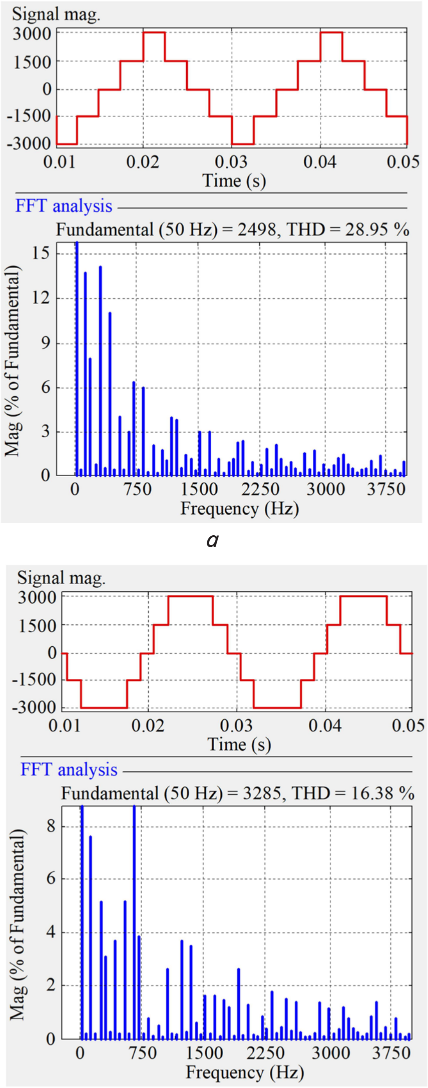
2. Literature review and problem statement

The parametrs of the sinusoidality output voltage directly depend on the type of modulation. There are many different modulation algorithms to form the output voltage in multilevel inverters. The most common ones are the sinusoidal PWM, level-shifted PWM, level-phase-shifted PWM, space-vector PWM, amplitude modulation, etc. At the same time, all these algorithms predetermine different values for the sinusoidality output voltage and current, as well as varying components of power losses in an inverter. This is because the higher voltage harmonics cause the presence of the higher current harmonics, predetermining additional power losses in power lines and load [15]. Among the described algorithms, the best indicators of the sinusoidal output voltage are demonstrated by algorithms built on the basis of amplitude modulation. However, even under the mode of amplitude modulation, an MVSI can demonstrate quite different indicators of the sinusoidal output voltage (Fig. 3) [16, 17].

Various studies have been conducted to improve the harmonic structure in multilevel inverters. Paper [18] reports the results of studying a genetic algorithm for optimizing the output voltage of multilevel inverters. However, the disadvantage of the cited paper is the lack of full numerical data and a comparison of the sinusoidal shape of the output voltage in multilevel inverters before and after optimization by the genetic algorithm.

Work [19] describes a study of the method for the output voltage shape optimization in two-level voltage inverters. The disadvantage of the cited work is the lack of a description of the algorithm for optimizing a voltage shape; only the resulting shape is given. In addition, at a nine-level shape of the output voltage in a cascade inverter, the authors obtained THD_U_{out}=9.46 %.

Article [20] reports a study aimed at optimizing the shape of the output voltage in a cascaded multilevel inverter at different levels of supply voltage to each cell. The downside is that there are no numerical data in full.



a

b

Fig. 3. Possible shapes of output voltage in a five-level inverter: *a* – a THD shape of 28.95 %; *b* – a THD shape of 16.38 %

Paper [21] describes a method for optimizing the shape of output voltage in multilevel cascaded inverters. The method is based on the following approach. The duration of each stage in the shape of output voltage is set constant while the voltage degree amplitude is regulated. However, the disadvantage of a given method is that it requires additional control over voltage levels in each cell, that is, additional DC-DC converters are needed, which considerably increases the cost of the system. It is much simpler and cheaper, in order to optimize the shape, to regulate the time of enabling the levels rather than the magnitude of voltage stages [22, 23].

Thus, the above survey allows us to argue that the existing modulation algorithms in the control systems of multilevel inverters do not provide an optimum of the sinusoidal output voltage for the *THD* parameter. This circumstance necessitates the task of constructing a modulation algorithm that would implement the output voltage shape in multilevel inverters with a minimum *THD* parameter under the condition of the same number of voltage levels.

3. The aim and objectives of the study

The aim of this study is to improve the harmonic composition of output voltage in a multilevel inverter at maximum possible sinusoidality (minimal *THD*).

To accomplish the aim, the following tasks have been set:

– to construct and study the proposed algorithm of modulation, which ensures the shape of output voltage in multilevel voltage inverters with minimum *THD*;

– to define analytical expressions for calculating the time of switching stages in forming the optimal shape of output voltage;

– to investigate the *THD* of output voltage in multilevel voltage inverters with the proposed modulation algorithm through simulation in the MATLAB/Simulink.

4. The proposed modulation algorithm for the formation of an optimum of the sinusoidal staged output voltage in a multilevel inverter

The principle of forming an optimum sinusoidal staged output voltage in a multilevel inverter can be derived through the amplitude discretization of a bipolar sinusoidal signal [24, 25].

The effect of amplitude discretization implies the amplitude quantization of a sinusoidal signal into a stepped from [26, 27]. The output data are computed using the rounding method to the nearest value, created by an output signal, symmetrically relative to zero [28, 29]:

$$y = q \cdot \mathrm{round}\left(\frac{A_{\sin}}{q}\right), \tag{2}$$

where y is the output discrete signal; $A_{\sin}$ is the input sinusoidal signal of amplitude $A_{\sin.m}$; q is the amplitude quantization parameter, q=1.

In this case, each level switch is determined when the sine crosses the amplitudes of 0.5; –0.5; 1.5; –1.5; 2.5; –2.5, etc.

The number of quantization stages is predetermined by the physical number of possible stages in the formation of output voltage in a multilevel inverter. The shape optimization is achieved by defining the amplitude $A_{\sin.m}$ value, at which the rms content of the higher harmonics is minimal [17].

An example of such a discretization in the formation of the seven-level output voltage is shown in Fig. 4. In this case, to form the five levels of output voltage shape, the sinus amplitude should be in the range from 2.5 to 3.5 [30, 31].

The concept of acquiring an optimal shape of the level-discrete voltage comes down to minimizing and balancing the area of higher harmonics relative to a one- fourth period of the output voltage shape [32, 33].

Thus, a given problem is reduced to the requirement for the equality of areas:

$$S_1 = S_2 + S_3. \tag{3}$$

The areas S_1, S_2, S_3, shown in Fig. 3, are determined from expressions [34, 35]:

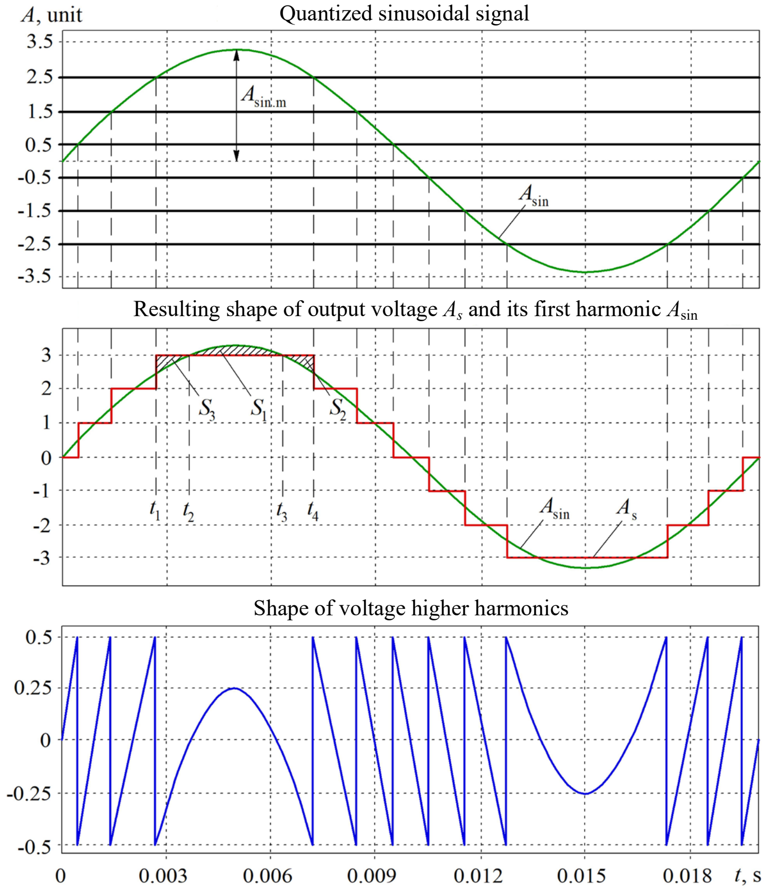


Fig. 4. The amplitude-level discretization for the formation of seven-level output voltage

$$S_1=\int_{t_2}^{t_3}\left(A_{\text{sin}}\cdot\sin(wt)-A_s\right)\cdot \mathrm{d}t; \tag{4}$$

$$S_2=\int_{t_1}^{t_2}\left(A_s-A_{\text{sin}}\cdot\sin(wt)\right)\cdot \mathrm{d}t; \tag{5}$$

$$S_3=\int_{t_3}^{t_4}\left(A_s-A_{\text{sin}}\cdot\sin(wt)\right)\cdot \mathrm{d}t, \tag{6}$$

where A_s is the constant, the amplitude of the maximum stage (level) of a quasi-sinusoidal shape at discretization, in Fig. 4 A_s=3; A_{sin} is the amplitude of a sinusoidal modulated signal.

Substituting the areas in expression (2), we obtain:

$$\int_{t_2}^{t_3}\left(A_{\text{sin}}\cdot\sin(wt)-As\right)\cdot \mathrm{d}t= \\ =\int_{t_1}^{t_2}\left(A_s-A_{\text{sin}}\cdot\sin(wt)\right)\cdot \mathrm{d}t+ \\ +\int_{t_3}^{t_4}\left(A_s-A_{\text{sin}}\cdot\sin(wt)\right)\cdot \mathrm{d}t. \tag{7}$$

A feature of resolving this task is that equality is solved at the following value for the amplitude of a sinusoidal modulated signal for any number of degrees of output voltage [36, 37]:

$$A_{\text{sin}.m}=A_s+0.25. \tag{8}$$

Thus, the maximum sinusoidality (minimal *THD*) is achieved at a value for the level discretization by setting a sinusoidal signal of the following amplitude:

$$A_{\text{sin}.m}=\frac{N_L-1}{2}+0.25, \tag{9}$$

where N_L is the number of levels (stages) in the shape of output voltage in a multilevel inverter.

5. Analytical expressions to determine the timing of switching the levels to form an optimal shape of output voltage

The timing for switching the levels in order to form an optimal shape of output voltage for implementing a microprocessor control system [38, 39] is determined from expression:

$$t_i=\frac{\arcsin\left(\dfrac{i-0.5}{\dfrac{N_L}{2}-0.25}\right)}{360}\cdot T_{Uout}, \tag{10}$$

where i is the sequential number of switching in a quarter of the output voltage period; T_{Uout} is the frequency of output voltage; 0.5 is the first stage of switching.

Other moments of switching are formed symmetrically with respect to a one-fourth period of the stage voltage [40, 41].

For the nine-level shape of output voltage, the switching time at the first one-fourth of the period, taking into consideration an optimum value for the amplitude of a sinusoidal modulated signal $A_{\text{sin}.m}$=4.25, equals:

$$t_i=\frac{\arcsin\left(\dfrac{i-0.5}{4.25}\right)}{360}\cdot T_{Uout}. \tag{11}$$

For the nine-level shape, the switching times are

T_1=3.754·10^{-4} s, T_2=1.148·10^{-3} s,

T_3=2.002·10^{-3} s, T_4=3.08·10^{-3} s.

6. Simulation of cascade multilevel inverters with the proposed modulation algorithm

To confirm our theoretical study, the MATLAB/Simulink programming environment was employed to build the models of cascade multilevel inverters, which form 5, 7, 9, and 11 stages in the shape of output voltage (Fig. 5).

The spectrum of the higher harmonics of the output voltage in a multilevel inverter at the suggested modulation algorithm is shown in Fig. 6.

The dependences of *THD* and *RMS* shapes of the output voltage in multilevel inverters on a value of the modulated signal $A_{\text{sin}.m}$ amplitude are given in Table 1.

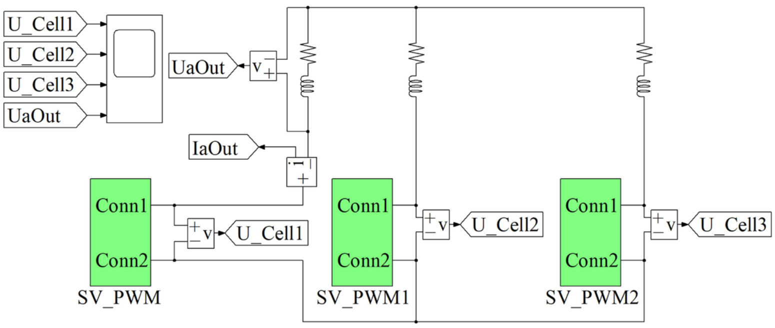
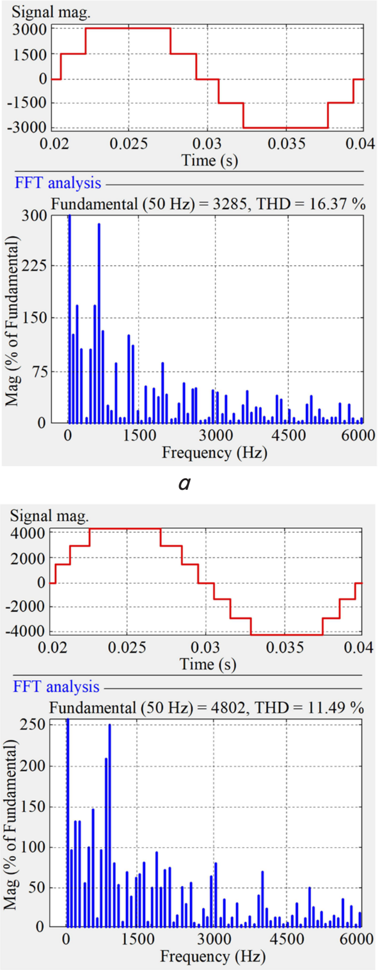


Fig. 5. A model of the cascade multilevel inverter that forms five stages of output voltage



a

b

Fig. 6. A spectrum of the higher harmonics of the output voltage in a multi-level inverter at the proposed modulation algorithm: *a* — for five-stage voltage; *b* — for seven-stage voltage

Table 1

Dependences of *THD* and *RMS* of the shape of the output voltage in multilevel inverters on a value of the modulated signal $A_{\sin.m}$ amplitude

5 levels in voltage			7 levels in voltage			9 levels in voltage			11 levels in voltage		
$A_{\sin.m}$	*THD*	U_{rms}, kV	$A_{\sin.m}$	*THD*	U_{rms}, kV	$A_{\sin.m}$	*THD*	U_{rms}, kV	$A_{\sin.m}$	*THD*	U_{rms}, kV
1.5	31.2	0.92	2.50	17.71	1.65	3.50	12.41	2.37	4.50	9.57	3.09
1.6	28.5	1.21	2.6	17.37	1.89	3.6	12.45	2.59	4.6	9.66	3.28
1.7	24.2	1.32	2.7	15.62	1.99	3.7	11.47	2.69	4.7	9.04	3.38
1.8	21.1	1.39	2.8	14.12	2.07	3.8	10.59	2.76	4.8	8.45	3.46
1.9	18.9	1.44	2.9	13	2.13	3.9	9.88	2.82	4.9	7.94	3.52
2	17.6	1.49	3	12.24	2.18	4	9.37	2.88	5	7.57	3.58
2.1	16.8	1.52	3.1	11.73	2.22	4.1	9.05	2.92	5.1	7.34	3.63
2.2	16.4	1.55	3.2	11.53	2.26	4.2	8.88	2.97	5.2	7.25	3.66
2.25	16.37	1.56	3.25	11.49	2.27	4.25	8.88	2.99	5.25	7.25	3.69
2.3	16.45	1.58	3.3	11.56	2.29	4.3	8.92	3.01	5.3	7.27	3.72
2.4	16.7	1.60	3.4	11.7	2.32	4.4	9.08	3.04	5.4	7.43	3.75
2.49	17.1	1.62	3.49	12.1	2.35	4.49	9.33	3.07	5.49	7.65	3.79

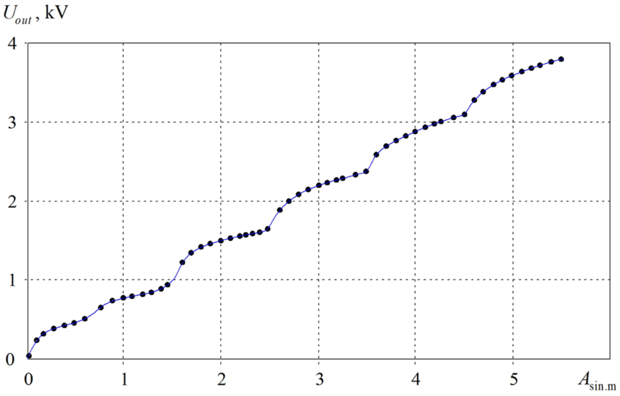


Fig. 7. Dependence of the rms value of output voltage on the amplitude of the sinusoidal modulated signal $A_{\sin.m}$ in an eleven-level voltage shape

Table 1 shows that an optimum shape of the output voltage in a multilevel inverter is achieved at the modulation amplitude $A_{\sin.m}$ from expression (8). In addition, one can see that by adjusting the amplitude of the modulated sinusoidal signal $A_{\sin.m}$ it becomes possible to rather effectively regulate the output voltage magnitude in a multilevel inverter.

The dependence of rms value of output voltage on the amplitude of the sinusoidal modulated signal $A_{\sin.m}$ in an eleven-level voltage shape is shown in Fig. 7.

Thus, amplitude modulation can be effectively used to regulate the amplitude of the output voltage.

The proposed algorithm could be used for other topologies of multilevel voltage inverters: MVSI with fixed diodes; MVSI with floating capacitors; cascade MVSI; modular MVSI.

The proposed algorithm for optimizing the shape of output voltage can be implemented for any topology of single-phase multilevel voltage inverters.

7. Discussion of results of studying the method for forming an optimum of the sinusoidal stage output voltage

This paper reports our study of the proposed modulation algorithm, which ensures forming a shape of the output voltage in multilevel voltage inverters at the lowest possible *THD* indicator. The proposed algorithm is based on the amplitude-level modulation at the assigned level of a sinusoidal modulated signal. The obtained results are explained by the fact that we achieved the minimization of an rms value for the signal of higher harmonics, which in turn is achieved by balancing and minimizing the signal noise area under condition $S_1=S_2+S_3$. The special feature of a given method for forming the shaping of output voltage is that the duration of each stage is different. Thus, the spectrum of the higher harmonics of such a shape of the output voltage would have its own peculiarities regarding a spatial-vector PWM when the duration of each stage is the same.

The reported analytical expressions make it possible to determine the time to switch the levels in order to form the optimal shape of output voltage. The formulae take into consideration the number of output voltage levels and the required output frequency. The resulting formulae are useful for implementing a microprocessor control system for multilevel inverters.

The proposed theoretical provisions for minimizing the *THD* of output voltage in multi-level inverters when applying the proposed modulation algorithm were confirmed by simulation in the MATLAB/Simulink programming environment. The proposed algorithm, when compared with known algorithms, makes it possible to obtain the improved indicators of the THD shape of output voltage; for example, in comparison with work [19], which reported a method for improving the shape of output voltage in semiconductor voltage inverters. In the cited work, a 9-level shape of the output voltage in a cascade inverter yielded THD_U_{out}=9.46 %. In comparison, the algorithm proposed in this paper makes it possible to obtain, at the same number of levels of the output voltage, THD_U_{out}=8.88 %.

The limitation and disadvantage of our study are that the proposed method is used provided that the amplitudes of each voltage level are the same. That is, when each cell is powered by different levels of voltage, the proposed method could not provide for an optimum shape.

Further research will be aimed at constructing a method for optimizing the shape of output voltage in multilevel inverters at different power amplitudes for individual bridges. In addition, it is necessary to further study the features in the spectrum of higher harmonics, as well as a possibility to apply a given algorithm for other topologies of multilevel inverters.

8. Conclusions

1. We have proposed, for multi-level voltage inverters, a modulation algorithm, which makes it possible to rather simply implement the minimum mode of the content of the higher harmonics of output voltage in forming the output voltage at any number of levels. The proposed algorithm is based on the amplitude-level modulation at a predetermined level of the sinusoidal modulated signal.

2. Mathematical expressions have been given that make it possible to determine the time to switch the transistors in order to form an optimal shape of output voltage. Their use could greatly simplify the microprocessor implementation of the proposed algorithm. The mathematical expressions are based on the arcsine functions, which make it possible to determine at what point of time a modulating sinusoidal function at the desired amplitude reaches the specified thresholds of switching 0.5, 1.5, 2.5, ... The difference between the suggested mathematical expressions and existing expressions for calculating the time of switching in a space-vector PWM for multi-level inverters [42–44] is that the existing expressions require a preliminary spatial-vector transformation of the *abc* coordinates to αß, and are then built on the ratio of two sinusoidal functions and, thus, are more complex and require more CPU resources.

3. The MATLAB/Simulink software was employed to simulate the operation of five-, seven-, nine-, and eleven-level inverters when implementing the proposed modulation algorithm. The obtained simulation results have confirmed the implementation of a minimum total harmonic distortion in the shape of output voltage in multi-level inverters. When implementing the proposed algorithm of modulation, five levels in the shape of output voltage in a multilevel inverter form *THD*=16.37 %; seven levels form *THD*=11.49 %; nine levels form *THD*=8.88 %; eleven levels form *THD*=7.25 %.

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