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Comparison of PWM Methods for Compensating for H-Cell Damage in Cascaded High-Voltage Frequency Converters

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Abstract

The work compares methods for controlling power switches of a multilevel cascade converter in normal and emergency modes when one or more H-modules fail. It is shown that the phase-to-phase voltage balancing method, in which, in the event of an accident of individual cascades, the rotation of the phase voltage vectors is carried out so as to preserve the spatial position and the same amplitude of the phase-to-phase voltage vectors, ensures a decrease or even the absence of motor torque jumps.

Conditions have been found for supplementing the carrier sinusoidal signal with a third harmonic, which ensure the most efficient use of power supplies when two or more modules are damaged, and increase the voltage of the first harmonic by 10...20% compared to sinusoidal pulse-width modulation. The modified method of space-vector modulation of basic vectors also ensures the minimization of shock loads by limiting the amplitude of the desired vector at the level of the radius of the circle inscribed in the hexagon formed by the vertices of the basic vectors with arbitrary amplitude and position. This method makes it possible to increase the coefficient of use of power sources by 15.6%, regardless of the number of damaged cells in each phase, which, compared to sinusoidal pulse-width modulation, increases the voltage of the first harmonic by 10...26%. The method is best when one or two cells are damaged and during normal operation of the converter, that is, in the most common cases.

KEY WORDS: *multi-level cascade frequency converter, pulse width modulation, sinusoidal pulse width modulation, pulse width modulation with the addition of a third harmonic, balanced space vector pulse width modulation method*

1. Introduction

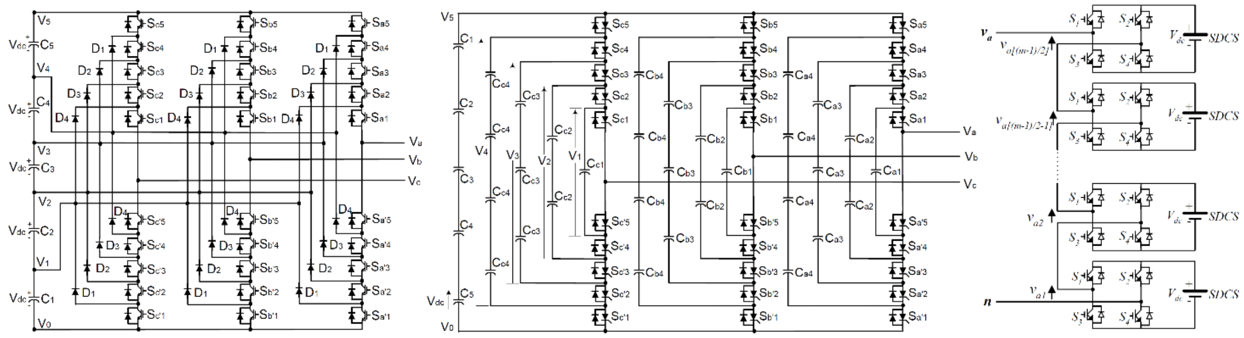
To set the research problem, it is necessary to characterize the current trends in topology and control methods of power switches in high-voltage multilevel frequency converters. High-power converters with increased voltage appeared in the mid-1980s with the appearance of high-power gate turn-off (GTO) thyristors with an operating voltage of 4500 V [1]. Although thyristors had a relatively low permissible switching frequency, they were widely used in medium-power electric drives. The appearance of high-power insulated-gate bipolar transistors (IGBTs) and fully controlled gate-commutated thyristors (GCTs) in the late 1990s was revolutionary [2, 3]. These power switches made possible the transition to medium and high power multi-level high voltage converters with incomparable power quality characteristics and minimal converter losses.

According to the leading manufacturers Rockwell Automation and ABB, the use of frequency converters for asynchronous and synchronous electric motors and soft starters for asynchronous motors with a nominal power from 400 kW to 40 MW and even up to 200 MW with a voltage of 2,3-13,8 kV is considered economically justified at the present time. But most industrial facilities use electric drives of this type in the power range of 1–4 MW with a voltage of 3,3–6,6 kV [4].

In parallel with the development of power electronic devices, the structure of the power section of the converters also changed. The neutral-point converter proposed by Nabae, Takahashi, and Akagi in 1981 was essentially a 3-level latching diode inverter [5]. In the 1990s, experimental results were reported for 4-, 5-, and 6-level converters of this type (Fig. 1, a) for static compensation of reactive power, motor speed control, high-voltage system connections [6-10]. Each of the three phases of the inverter has a common DC bus, which is divided by capacitors into several levels. Advantages: all phases share a common DC bus, minimizing converter capacitance requirements; capacitors can be pre-charged in one group. Disadvantages: active power flow is difficult to control as intermediate DC levels tend to vary due to charge/discharge; the number of clamping diodes depends squarely on the number of levels.

Maynard and Foch presented an inverter based on floating capacitors in 1992, where capacitors are used instead of latching diodes (Fig. 1, b) [11]. Advantages: it is possible to balance capacitor voltage levels and control active and reactive power flows; a large number of capacitors allows the inverter to compensate for short-term outages and deep voltage drops. However, the capacitors cause the main disadvantages of such a converter: it is difficult to monitor the voltage levels for all capacitors and perform preliminary charging of all capacitors to the same level; capacitors are more expensive and significantly exceed the dimensions of clamping diodes [12].

That is why, as soon as the mass production of power switches began and they became cheaper, industrial multilevel converters began to be built according to a cascade structure with so-called H-bridges [10, 12]. The structure of one phase of the cascade inverter is shown in Fig. 1, c. This topology provides an increase in the number of possible levels of output voltage m more than twice the number of direct current sources s: m = 2s + 1; each H-bridge is a separate module, which ensures acceleration and cost reduction of both production and maintenance as well as repair of the converter. A significant disadvantage of the topology is the increase in the number of power switches and the need for a separate direct current source for each H-bridge, which causes the presence of a large number of secondary windings in the converter of a complex transformer.

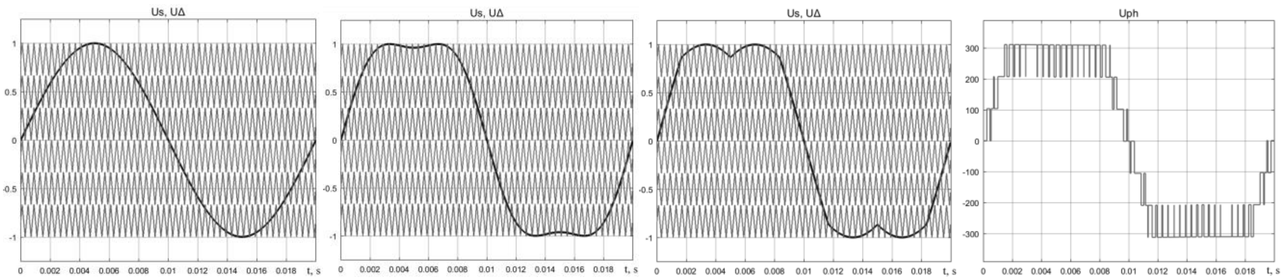


a b c

Fig. 1 Topology of high-voltage multilevel frequency converters: a – with clamping diodes; b – with floating capacitors; c – with cascade connections of H-bridges

But the most important advantage of cascaded multi-level converters with H-bridges is the possibility of continuing the work of the converter in case of failure of one or more modules. Short circuits of a damaged module lead to an imbalance of phase-to-phase voltage in the phases and a corresponding imbalance of currents, which in turn leads to electrical and electromechanical shock loads and a threat to the safety of the mechanism and personnel. In cascade converters, it is possible to switch the outputs of a defective module with a simultaneous change of control algorithms of other modules, which are based on balancing the linear voltage in phases.

Pulse-width modulation (PWM) strategies used in a conventional inverter can be modified for use in multilevel converters. Fig. 2 illustrates three main carrier-based methods: sinusoidal PWM (SPWM), third-harmonic PWM (THPWM), and space-vector PWM (SVPWM) [12, 13].



a b c d

Fig. 2 Comparison of typical PWM methods in multilevel frequency converters: a – sinusoidal PWM; b – PWM with the addition of the third harmonic; c – space-vector PWM -U_s carriers and multi-level triangular U_Δ signals; d – output phase voltage U_{ph}

In industrial application, it is sinusoidal PWM that is the main method, which is characterized by the simplest control algorithms both in regular and emergency modes when individual modules are damaged [12].

But THPWM and SVPWM provide an increase in the efficiency of using a direct current power source due to the fact that the amplitude of the first harmonic becomes higher than the amplitude of the total signal by almost 15.6%.

The purpose of the work is to find a method of controlling high-voltage multilevel frequency converters that would ensure the smallest voltage drop on the motor with the smallest fluctuations of the electromagnetic moment in the event of damage to one or more H-modules in the inverter phases and to evaluate the effectiveness of using PWM with the third harmonic component and space-vector PWM in emergency modes.

2. Materials and Research Results

2.1. Phase-to-Phase Voltage Balancing Method with SPWM and THPWM

Phase-to-phase voltage balancing in the event of failure of a separate H-module can be carried out in various ways. For example, in Allen Bradley HV FC 6000 frequency converters, when a defect is detected in a module of one of the phases, "similar" modules in the other two phases are closed [14]. Then the voltage drops $(N-1)/N$ times, the triangle depicted by dashed lines in Fig. 3. In some cases, the linear voltage balancing method is applied by changing the interphase angles, as in the FC SIEMENS Robicon PERFECT HARMONY series [15] (voltage vectors of individual phases are depicted by lines with markers in Fig. 3). But of the mentioned converters, this method is used only for sinusoidal PWM.

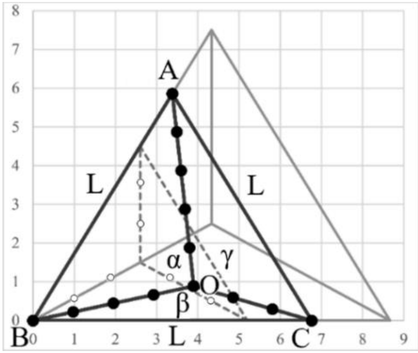


Fig. 3 Phase-to-phase voltage balancing by symmetrisation of the number of modules (dashed line) and rotating the phase vectors (dotted lines)

In case of failure of one or more H-bridges, it is necessary to find such angles between the voltage vectors of individual phases in order to maintain the spatial position and the same amplitude L of each of the phase-to-phase voltage vectors. For this, it is necessary to find a solution to the system of equations:

$$\begin{cases} N_A^2 + N_B^2 - 2N_A N_B \cos(\alpha) = L^2; \\ N_B^2 + N_C^2 - 2N_B N_C \cos(\beta) = L^2; \\ N_C^2 + N_A^2 - 2N_C N_A \cos(\gamma) = L^2; \\ \alpha + \beta + \gamma = 2\pi, \end{cases} \quad (1)$$

where $N_A, N_B, N_C, \alpha, \beta, \gamma -$ is the number of working H-modules in the phases and the angles between the phase vectors (Fig. 3).

The analytical solution of this system in its general form, if $N_A \neq N_B \neq N_C,$ has been found for the case of practical importance - when the point O is within the triangle ABC:

$$\left. \begin{aligned} &L = \sqrt{0.5\left(N_A^2 + N_B^2 + N_C^2\right) + 0.5\sqrt{3\left(N_A + N_B + N_C\right)\left(N_A + N_B - N_C\right)\left(N_A - N_B + N_C\right)\left(-N_A + N_B + N_C\right)}}; \\ &\alpha = \arccos\left(\frac{N_A^2 + N_B^2 - L^2}{2N_A N_B}\right), \beta = \arccos\left(\frac{N_B^2 + N_C^2 - L^2}{2N_B N_C}\right), \gamma = 2\pi - \alpha - \beta. \end{aligned} \right\} \quad (2)$$

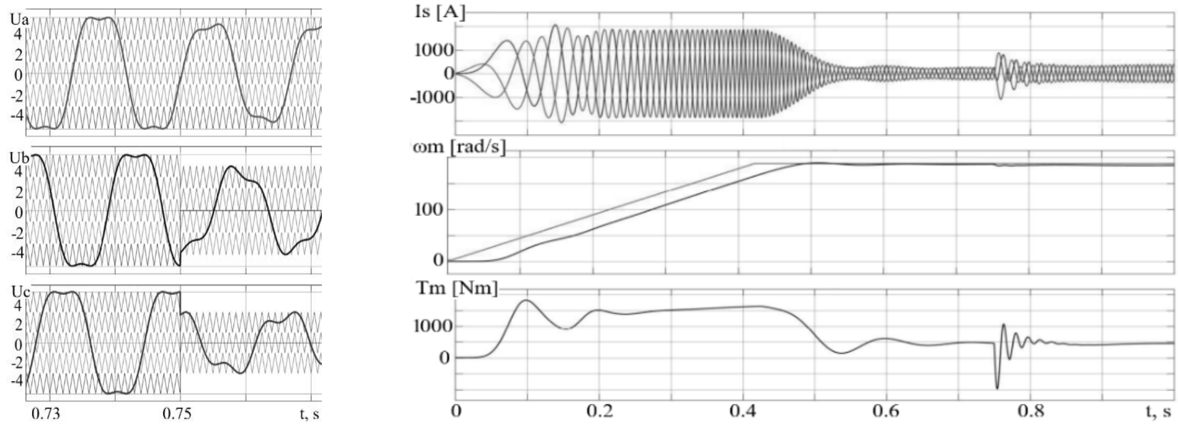
To preserve the spatial position of the linear voltage vectors, it is necessary to set the initial angles of rotation, which are also found in Fig. 2:

$$\alpha_0 = \frac{\pi}{3} + \arcsin\left(\frac{N_B}{L}\sin(\alpha)\right), \beta_0 = \alpha_0 + \alpha, \gamma_0 = \beta_0 + \beta.$$

The obtained expressions made it possible to find, without unnecessary computational costs, the polar coordinates of the phase voltage vectors to obtain the specified value of the phase-to-phase voltage in the normal and emergency modes of operation of the cascaded frequency converter with 3-6 H-modules in the phases, and to show that this method of balancing provides an increase in the voltage of the first harmonic by 7-17% compared to symmetrical disconnection of modules in phases.

In normal mode, the addition of the third harmonic with an amplitude of 1/6 of the main harmonic with a shift of 0° increases the efficiency of using power sources – the amplitude of the first harmonic can be greater than the voltage amplitude of the power source by 15.6%. But in the emergency mode, when balancing the line voltage with the rotation of the phase vectors and the asymmetric location of the third harmonic relative to the first one, the total amplitude can reach 116% of the amplitude of the first harmonic, which not only does not increase, but also requires a reduction of the task signal. The condition under which the most complete use of direct current sources is ensured when adding the third harmonic is its shift that coincides with the angle of the undamaged phase [16]. Then the asymmetry and excess voltage in the phases are minimal (Fig. 4). In this case, when using THPWM, the efficiency of the power source increases by 11-12%.

Fig. 4 shows graphs of transient processes, which show that in the event of damage to 5A-4B-3C (that is, 5 working modules remain in phase A, 4 in phase B, and 3 in phase C) the fluctuations of electromagnetic moments are the smallest possible thanks to both minimized voltage changes and preservation of the spatial position of linear voltage vectors.



a b

Fig. 4 Graphs of voltage in phases (a) and transient processes of current, speed and torque in the motor (b) in case of accident 5A-4B-3C (t = 0.75 s)

2.2. Balancing Method with Space-Vector PWM

Space vectors are formed by simultaneously connecting all phases of the motor through the converter keys to a constant voltage of the same magnitude, but with different polarity. In the event of an accident, in the general case, due to different voltage amplitudes in the phases, the basic vectors appear in parallel pairs, but of different lengths (Fig. 5).

If you draw the vectors v1 ... v6 from the origin of coordinates, their ends form a hexagon, the coordinates of the vertices of which are calculated according to the following formulas [16] for the location, as in Fig. 5:

$$\left.\begin{aligned} x_i &= \mp N_b \sin\left(\frac{2\pi}{3}\right) \mp N_c \sin\left(\frac{4\pi}{3}\right); \\ y_i &= \pm N_a \pm N_b \cos\left(\frac{2\pi}{3}\right) \pm N_c \cos\left(\frac{4\pi}{3}\right), \end{aligned}\right\} \tag{3}$$

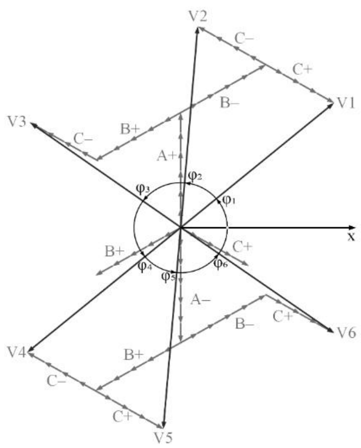


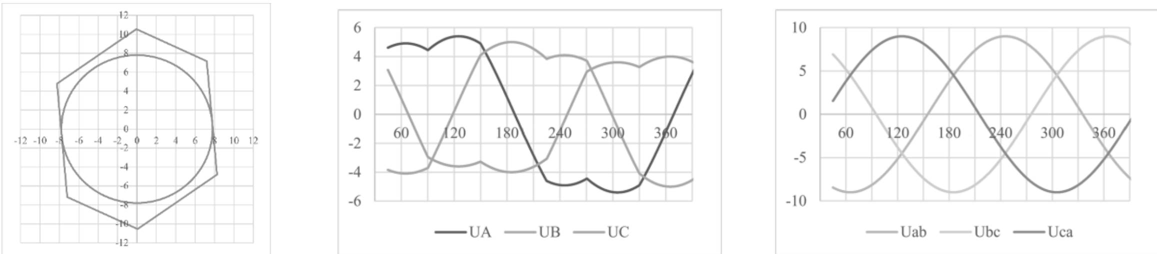
Fig. 5 Basic vectors in case of damage to modules 6A-5B-4C

And a circle with a v_{max} radius defined as the smallest distance from the origin of the coordinates to the sides of the hexagon can be inscribed in the formed hexagon:

$$a_i = (y_{i+1} - y_i)/(x_{i+1} - x_i); \qquad R_i = abs\left((y_i - a_i x_i)\,sqrt\left(1 + a_i^2\right)\right); \qquad v_{max} = min(R_i); \qquad i = 1...3. \tag{4}$$

Then, considering the sector between two basic vectors with amplitudes of v_1, v_2 and angles of rotation φ_1, φ_2, to obtain the desired vector v with an amplitude of no more than v_{max}, located between the basic vectors with an angle φ, according to the theorem of sines, it is possible to determine the rules of pulse-width modulation of these vectors γ_1, γ_2 and, accordingly, the voltage in the phases (Fig. 6):

$$\gamma_1 = \frac{v}{v_1}\frac{\sin(\varphi_2 - \varphi)}{\sin(\pi - (\varphi_2 - \varphi_1))}; \qquad \gamma_2 = \frac{v}{v_2}\frac{\sin(\varphi - \varphi_1)}{\sin(\pi - (\varphi_2 - \varphi_1))}. \tag{5}$$



a b c

Fig. 6 Hexagon of base vectors (a), voltage in phases (b) and phase-to-phase voltage (c) in case of failure of H-modules 6-5-4

It can be seen from Fig. 6 that the linear voltage is sinusoidal, with the same amplitude and the necessary shifts between U_{ab}, U_{bc}, U_{ca}, despite the nonlinearity and asymmetry of the voltage in the phases. In addition, Fourier series analysis showed that in symmetrical and asymmetrical modes, the amplitude of the 1st harmonic exceeds the signal amplitude by 15.6%, that is, the power source is used with the greatest efficiency.

2.3. Comparison of Voltage Balancing Methods in Case of Damage to H-Modules

The results of calculations for the analyzed balancing methods are shown in Table. As the basic method, the method of symmetrical shutdown of H-modules with sinusoidal PWM (SPWM) was chosen. To evaluate the efficiency of the methods, the amplitude of the linear voltage of the undamaged converter with SPWM is taken as the basic value (therefore, in the states 6-6-6, 5-5-5, 4-4-4, 3-3-3 $v_{0\ sin}^* = 1$) and the difference $\Delta U^* = U_{p-p}^* - v_{0\ sin}^*$ is shown for the other three methods – linear voltage balancing with sinusoidal PWM (BSPWM), linear voltage balancing with the addition of the 3rd harmonic (THPWM), balanced space-vector PWM (SVPWM).

Table

Comparative characteristics of balancing methods

State of the inverter			Symmetrical sinusoidal PWM - SPWM	Phase-to-phase voltage balancing					Space-vector PWM			The optimal method
				BSPWM			THPWM		SVPWM			
N_A	N_B	N_C	$v_{0\ sin}^*$	L	U_{p-p}^*	ΔU^*	U_{p-p}^*	ΔU^*	v_{max}	U_{p-p}^*	ΔU^*	
6	**6**	**6**	**1**	**10.392**	**1**	0.000	**1.156**	**0.156**	**10.392**	**1.156**	**0.156**	SVPWM
6	6	***5***	0.833	9.78	0.94	0.107	1.030	**0.197**	9.526	1.060	**0.226**	SVPWM
6	***5***	***5***	0.833	9.2	0.88	0.047	0.951	**0.118**	8.666	0.963	**0.130**	SVPWM
6	***5***	***4***	0.667	8.54	0.82	0.153	0.856	**0.189**	7.794	0.867	**0.200**	SVPWM
6	***4***	***4***	0.667	7.84	0.75	**0.083**	0.738	0.071	6.928	0.771	**0.104**	SVPWM
5	**5**	**5**	**1**	**8.666**	**1**	0.000	**1.156**	**0.156**	**8.666**	**1.156**	**0.156**	SVPWM
5	5	***4***	0.8	8.05	0.93	0.130	1.009	**0.209**	7.794	1.040	**0.240**	SVPWM
5	***4***	***4***	0.8	7.45	0.86	0.060	0.915	**0.115**	6.928	0.925	**0.125**	SVPWM
5	***4***	***3***	0.6	6.77	0.78	0.180	0.795	**0.195**	6.062	0.809	**0.209**	SVPWM
4	**4**	**4**	**1**	**6.928**	**1**	0.000	**1.156**	**0.156**	**6.928**	**1.156**	**0.156**	SVPWM
4	4	***3***	0.75	6.31	0.91	0.160	0.976	**0.226**	6.062	1.012	**0.262**	SVPWM
4	***3***	***3***	0.75	5.7	0.82	0.070	0.850	**0.100**	5.196	0.867	**0.117**	SVPWM
4	***3***	***2***	0.5	4.96	0.72	**0.220**	0.703	0.203	4.333	0.723	**0.223**	SVPWM
3	**3**	**3**	**1**	**5.196**	**1**	0.000	**1.156**	**0.156**	**5.196**	**1.156**	**0.156**	SVPWM
3	3	***2***	0.667	4.56	0.88	0.213	0.928	**0.313**	4.333	0.963	0.297	THPWM
3	***2***	***2***	0.667	3.92	0.75	**0.083**	0.738	0.071	3.464	0.771	**0.104**	SVPWM

The given data indicate that the best method in terms of the efficiency of using power sources in undamaged converters or with one/two damaged H-modules is the method of space-vector PWM. Only in one case (3–3–2) balancing with the addition of the 3rd harmonic provides a better result.

3. Conclusions

The work analyzes the methods of controlling a multi-level cascaded frequency converter in normal mode and in case of an accident, when one or more H-modules in different phases fail.

The phase-to-phase voltage balancing method minimizes shock loads during the transition from normal to emergency mode due to such displacement of the zero point and rotation of the phase vectors, in which the amplitude of the phase-to-phase voltage is reduced to the minimum possible value, the spatial position of the linear vectors remains unchanged. The conditions for the optimal addition of the 3rd harmonic have been found, which increases the efficiency of using power sources by 7...20% compared to symmetrical sinusoidal PWM. But in some accidents (6-4-4, 4-3-2, 3-2-2) the addition of the 3rd harmonic turns out to be ineffective. The basic vector balancing method provides the same conditions and an increase in the utilization factor of power sources by 15.6%, regardless of the number of damaged modules, which increases the amplitude of the 1st harmonic in the event of accidents by 10...26% compared to sinusoidal PWM. A comparison of methods of space-vector PWM (SVPWM), linear voltage balancing with the addition of the 3rd harmonic (THPWM) with sinusoidal PWM shows that SVPWM is the best method when one or two modules are damaged and during normal operation of the converter (only with the exception configuration 3-3-2), i.e. in the most common cases.

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