Methods of Pulse Width Modulation in Cascaded High Voltage Frequency Converters

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Abstract – ***Purpose.** The aim of this work is to compare the effectiveness of various methods for correcting cell failures in cascade high voltage frequency converters. These methods provide the smallest voltage drop on the motor, the least loads and oscillation of electromagnetic torque in an accident modes, and evaluate the effectiveness of pulse width modulation (PWM) methods with the injection of third harmonic and space-vector PWM in normal and emergency modes. Methodology. We use mathematical and geometrical interpretation of all analysed methods – Sinusoidal PWM (SPWM), Balanced sinusoidal PWM (BSPWM), Balanced PWM with injected 3rd harmonic (THPWM) and Balanced Space Vector PWM (SVPWM). Results. The method of balancing the phase-to-phase voltages by to such a shift of the zero point and rotation of the phase vectors, in which the amplitude of the phase-to-phase voltage decreases to the minimum possible value. Injection of the 3rd harmonic allows you to further increase the utilisation factor of power supplies in terms of voltage. But the violation of the symmetry of the phase voltages leads to the need to reduce the voltage amplitude to exclude saturation of the power supplies, which reduces this coefficient compared to the theoretically possible 15.6%. A distinctive feature of the method of balanced Space Vector PWM is that the amplitude of the 1st harmonic is always greater than the radius of the circle by 15.6%. Comparison of methods of space vector PWM (SVPWM), balancing of phase-to-phase voltage with the injection of the 3rd harmonic (THPWM) with sinusoidal PWM shows that SVPWM is the best method. Despite the more complex mathematical software for the implementation of this method, it provides the best performance in all considered emergency modes of 3…6 cascade converters. The Table of indicators for all methods are presented in the article. The use of a balanced SVPWM in combination with field oriented control makes it possible to obtain an electric drive in which, in the event of an accident, there are practically no shock mechanical and electromagnetic processes. After damage of cells the currents, electromagnetic torque and motor speed change along the required trajectory.*

***Key words:** Cascaded High Voltage Frequency Converter, 3rd Harmonic injection PWM, Balanced Space Vector PWM.*

I. INTRODUCTION

The development of high-power converters and medium-voltage (MV) drives started in the mid-1980s when 4500-V gate turn off (GTO) thyristors became commercially available.

The GTO was the standard for the MV drive until the advent of high-power insulated gate bipolar transistors (IGBTs) and gate commutated thyristors (GCTs) in the late 1990s. These switching devices have rapidly progressed into the main areas of high-power electronics due to their superior switching characteristics, reduced power losses, ease of gate control, and snubberless operation. The MV drives cover power ratings from 400 kW to 40 MW at the medium voltage level of 2.3 kV to 13.8 kV. The power rating can be extended to 200 MW. However, the majority of the installed MV drives are in the 1- to 4-MW range with voltage ratings from 3.3 kV to 6.6 kV based on Rockwell Automation information.

In the 1990s several researchers published articles that have reported experimental results for four-, five-, and six-level neutral point diode-clamped converters and a flying-capacitor-based inverter for such uses as static var compensation, variable speed motor drives, and high-voltage system interconnections.

But main structure of multilevel converter in industrial applications is the cascaded H-bridges. The cascaded inverter could also serve as a rectifier/charger for the batteries of an electric vehicle while the vehicle was connected to an ac supply as shown in Fig. 1. Advantages: the number of possible output voltage levels is more than twice the number of dc sources (m = 2s + 1); the series of H-bridges makes for modularized layout and packaging – this will enable the manufacturing process to be done more quickly and cheaply [1, 2, 3].

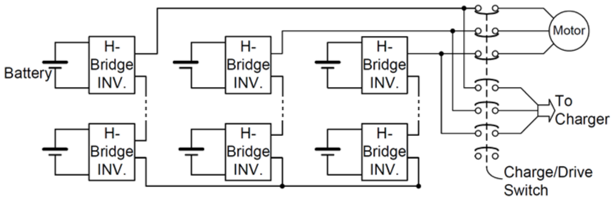


Fig. 1. The cascaded H-bridge converter for electric vehicle motor drive with battery charging

II. ANALISYS OF THE PROBLEM

Multilevel high-voltage frequency converters (HVFC) use the different types of power semiconductor components (IGBT, GTO, IGCT, SGCT) [4] and three Pulse Width Modulation (PWM) methods [5–7] (fig. 2):

- Sinusoidal PWM (SPWM) (fig.2, a);
- Third Harmonic injection PWM (THPWM) (fig. 2, b);
- Space Vector PWM (SVPWM) (fig. 2, c).

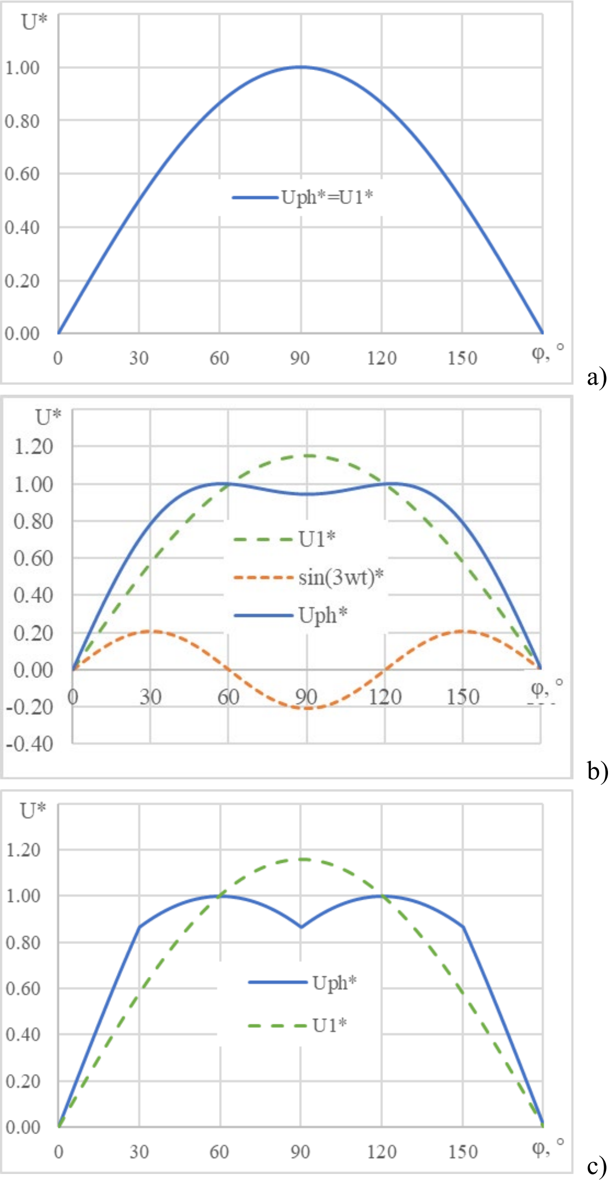


Fig. 2. Pulse Width Modulation methods

Response to the breakdowns of one or more modules is the most critical action of cascaded HVFC [8]. Common short circuit of the damaged cells results disbalance of phase-tophase voltages, currents, mechanical shock loads in mechanical part [9–11]. Thus, different correction methods are applied.

Base method: if fault is detected in one of the phases, the “like” cells in two other phases are closed [12]. In this case, voltage drops by $(N-1)/N$ times. The following method: balancing of phase-to-phase voltage is applied by changing the interphase angles and the shift of zero point [13, 14]. The use of this method allows to reduce losses by 6...18 % [15, 16]. Injection of third harmonic increases the efficiency of the dc power supply by 15.6%. Similar results are provided by the method of balancing SVPWM [17].

The purpose of this work is to compare the effectiveness of various methods for correcting cell failures in cascade converters.

III. METHOD OF SOLUTION

In the normal mode, the voltages of phases A, B, C with a relative amplitude $N_a = N_b = N_c = N$ (quantity of the H-bridge in one phase, base unit is equal to nominal voltage of H-bridge) form a three-phase system of phase-to-phase voltages with a relative amplitude $U_{p-p} = v_0 = \sqrt{3}N$ (here and below, we will not use the symbol "*" to denote relative values).

In emergency mode, with symmetrical disconnection of H-cells in phases, the voltage decreases to $v_0 = \sqrt{3}\min(N_a, N_b, N_c)$, as shown green triangle on fig. 3.

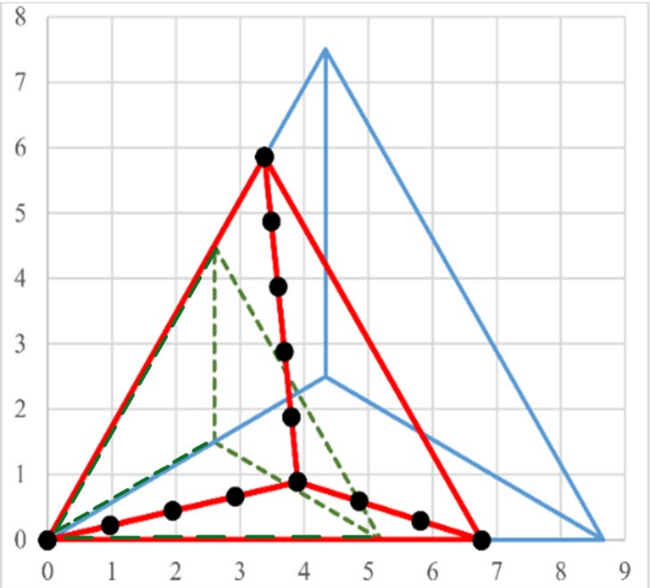


Fig. 3. Normal mode 5-5-5 (blue), symmetrical disconnection method 3-3-3 (green), balancing of phase-to-phase voltages 5-4-3 (red)

By balancing phase-to-phase voltage method to determine interphase angles in the emergency mode, it is required to meet the equality of the linear voltages to some unknown value L.

In the general case, if $N_a \neq N_b \neq N_c$, then system of equations may be solved only by iteration methods or by searching through possible solutions within the admissible ranges of value changes; the latter method is simpler to implement in microprocessor control systems.

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

As the analysis has shown, a calculation method based on the angle's selection turns to be rather slow as it is necessary to use two nested loops for two of the three angles with the searching through all the possible combinations.

$$\begin{cases} \alpha\downarrow_{\alpha_{\min}}^{\alpha_{\max}} \\ \beta\downarrow_{\beta_{\min}}^{\beta_{\max}} \end{cases} \Rightarrow L\ \forall\ L_{eq.1}\approx L_{eq.2}\approx L_{eq.3} \qquad (2)$$

Much faster solution is possible owing to a method based on Heron theorem with one loop of triangle square comparison [16].

$$\begin{cases} S_{\Delta ABC}=S_{\Delta AOB}+S_{\Delta BOC}+S_{\Delta COA},\\ S_{\Delta AOB}^2=\dfrac{2\left(N_A^2N_B^2+N_A^2L^2+N_B^2L^2\right)-N_A^4-N_B^4-L^4}{16},\\ S_{\Delta BOC}^2=\dfrac{2\left(N_B^2N_C^2+N_B^2L^2+N_C^2L^2\right)-N_B^4-N_C^4-L^4}{16},\\ S_{\Delta COA}^2=\dfrac{2\left(N_C^2N_A^2+N_C^2L^2+N_A^2L^2\right)-N_C^4-N_A^4-L^4}{16},\\ S_{\Delta ABC}=\sqrt{3}L^2/4. \end{cases} \qquad (3)$$

$$L\downarrow_{L_{\min}}^{L_{\max}} \Rightarrow L\ \forall\ S_{\Delta ABC}\approx S_{\Delta AOB}+S_{\Delta BOC}+S_{\Delta COA}. \qquad (4)$$

This method allows you to increase the voltage in the event of a fault of cells by several percent compared to the symmetrical method.

The THPWM method allows to additionally increase the voltage. However, due to the distortion of the shape of the phase voltages (fig. 4), the voltage increase cannot be 15.6%. In the final table k_{deform} shows how much the maximum allowable voltage should be reduced so that the total phase voltage does not exceed the source voltage. In a number of cases, THPWM becomes ineffective compared to balanced sinusoidal PWM (see cases 6-4-4, 4-3-2, 3-2-2 in Table 1).

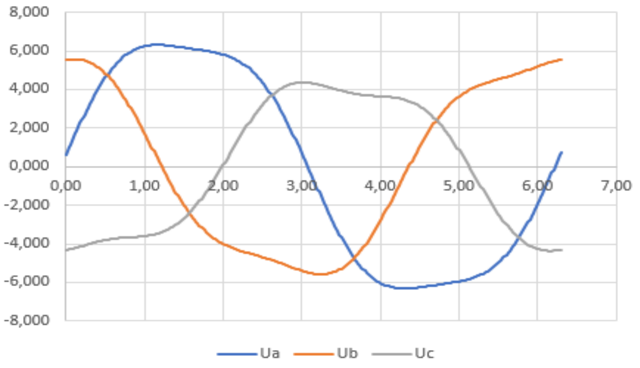


Fig. 4. Phase voltages in emergency mode 6-5-4 with THPWM without correction $1/k_{deform}$

The following method, SVPWM, in emergency mode allows you to build an asymmetric base vector system that fits into a circle (fig. 5). The radius of this circle determines the maximum allowable voltage [17];

$$\begin{aligned} &a_i=(y_{i+1}-y_i)/(x_{i+1}-x_i),\\ &R_i=abs\left((y_i-a_ix_i)\,sqrt\left(1+a_i^2\right)\right),\\ &v_{\max}=\min(R_i),\quad i=1...3, \end{aligned} \qquad (5)$$

when coordinates of vectors determine by formulas:

$$\begin{aligned} x_i&=\pm N_a\cos(\varphi_a)\pm N_b\cos\left(\varphi_a-\frac{2\pi}{3}\right)\pm N_c\cos\left(\varphi_a-\frac{4\pi}{3}\right),\\ y_i&=\pm N_a\sin(\varphi_a)\pm N_b\sin\left(\varphi_a-\frac{2\pi}{3}\right)\pm N_c\sin\left(\varphi_a-\frac{4\pi}{3}\right). \end{aligned} \qquad (6)$$

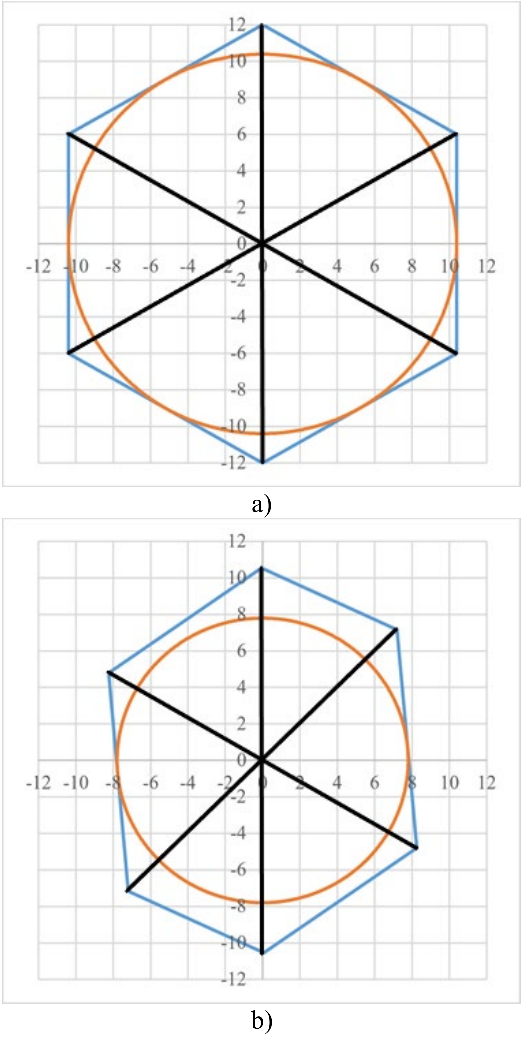
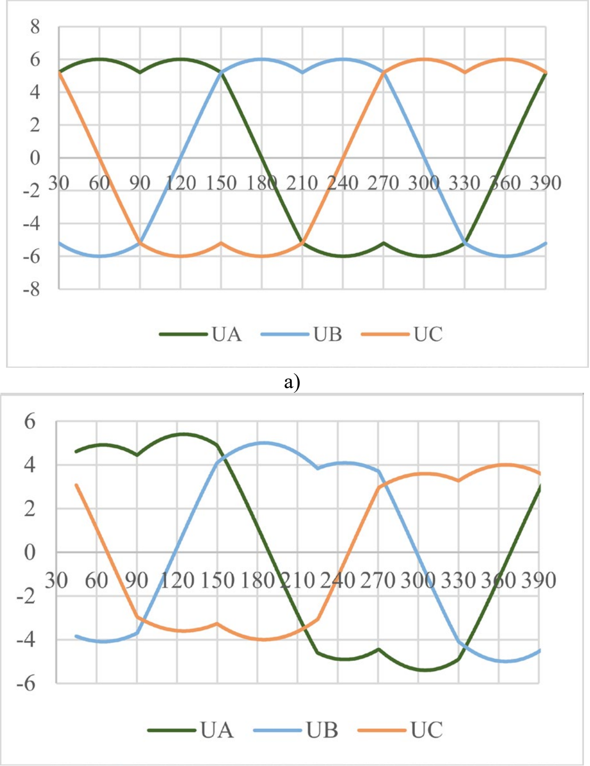


Fig. 5. Base vectors in normal (a) and emergency (b) modes with Spase Vector PWM

Fig. 6, a shows the shape of the phase voltages at the outputs of the inverter in normal mode. The same graphs are shown in the event of an accident, as a result of which 6, 5 and 4 H-modules remained operable in phases A, B, C, respectively (fig. 6, b).



b)

Fig. 6. Phase voltages in cases of 6–6–6 (a) and 6–5–4 (b) H-bridges in phases A, B, C

A distinctive feature of the method is that the amplitude of the 1st harmonic is always greater than the radius of the circle by 15.6%.

Based on the data obtained, the indicators of the generated voltage of the 1st harmonic for the considered methods for inverters with 3-6 H-bridges in each phase in normal and emergency modes are compared.

In emergency modes, the voltage of the first harmonic is compared with the voltage of the same converter in the normal mode with sinusoidal pulse-width modulation $v_{0\ \sin}^{*}$. The most informative indicator is $U_{p-p}^{*} - v_{0\ \sin}^{*}$, which shows how much the voltage at the output of the converter increases when using method of balanced phase-to-phase voltages with sinusoidal PWM and Third Harmonic PWM or method of balanced Space Vector PWM.

Table 1. Comparative characteristics of correction methods for 3-6-level HVFC

State of H-bridges			Symmetrical SPWM	Balanced phase-to-phase voltages						Balanced Space Vector PWM			
				SPWM			THPWM						
Na	***Nb***	***Nc***	$v_{0\,\sin}^*$	U_{p-p}	U_{p-p}^*	$U_{p-p}^*-v_{0\,\sin}^*$	U_{p-p}^*	k_{deform}	$U_{p-p}^*-v_{0\,\sin}^*$	v_{max}	v_{max}^*	U_{p-p}^*	$U_{p-p}^*-v_{0\,\sin}^*$
6	**6**	**6**	**1**	**10.392**	**1**	**0.000**	**1.156**	**1.000**	**0.156**	**10.392**	**1**	**1.156**	**0.156**
6	6	5	**0.833**	9.78	0.942	**0.109**	1.088	1.050	**0.154**	9.526	0.917	1.060	**0.226**
6	5	5	**0.833**	9.2	0.885	**0.052**	1.023	1.068	**0.078**	8.666	0.833	0.963	**0.130**
6	5	4	**0.667**	8.54	0.821	**0.154**	0.950	1.106	**0.150**	7.794	0.75	0.867	**0.200**
6	4	4	**0.667**	7.84	0.755	**0.088**	0.872	1.173	**0.041**	6.928	0.667	0.771	**0.104**
5	**5**	**5**	**1**	**8.666**	**1**	**0.000**	**1.156**	**1.000**	**0.156**	**8.666**	**1**	**1.156**	**0.156**
5	5	4	**0.8**	8.05	0.93	**0.130**	1.075	1.058	**0.167**	7.794	0.9	1.040	**0.240**
5	4	4	**0.8**	7.45	0.86	**0.060**	0.994	1.086	**0.071**	6.928	0.8	0.925	**0.125**
5	4	3	**0.6**	6.77	0.78	**0.180**	0.902	1.134	**0.157**	6.062	0.7	0.809	**0.209**
4	**4**	**4**	**1**	**6.928**	**1**	**0.000**	**1.156**	**1.000**	**0.156**	**6.928**	**1**	**1.156**	**0.156**
4	4	3	**0.75**	6.31	0.91	**0.160**	1.052	1.070	**0.185**	6.062	0.875	1.012	**0.262**
4	3	3	**0.75**	5.7	0.82	**0.070**	0.948	1.115	**0.059**	5.196	0.75	0.867	**0.117**
4	3	2	**0.5**	4.96	0.72	**0.220**	0.832	1.183	**0.170**	4.333	0.625	0.723	**0.223**
3	**3**	**3**	**1**	**5.196**	**1**	**0.000**	**1.156**	**1.000**	**0.156**	**5.196**	**1**	**1.156**	**0.156**
3	3	2	**0.667**	4.56	0.88	**0.213**	1.017	1.089	**0.222**	4.333	0.833	0.963	**0.297**
3	2	2	**0.667**	3.92	0.75	**0.083**	0.867	1.173	**0.037**	3.464	0.667	0.771	**0.104**

Obviously, in all cases, the Space Vector PWM with the proposed base vector balancing method the best indicators of the use of the bridge power supplies.

The use of a balanced SVPWM in combination with field oriented control makes it possible to obtain an electric drive in which, in the event of an accident, there are practically no shock mechanical and electromagnetic processes. On fig. 7 shows graphs of transients in an electromechanical system with a fan load. At 1.1 s, an accident occurs – the 5-5-5 mode changes to 5-4-3. This is clearly seen in the phase voltage graphs. However, the currents, electromagnetic torque and motor speed change along the required trajectory.

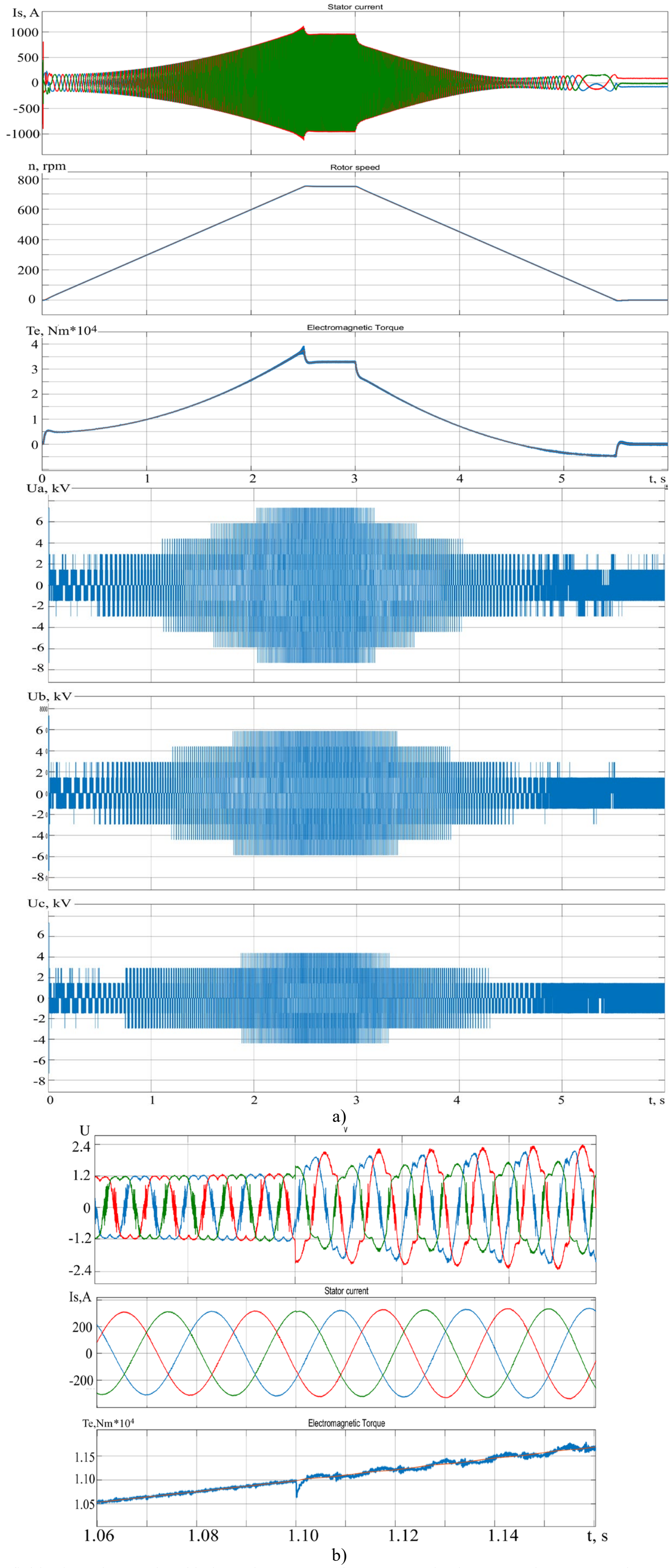


Fig. 7. Transients in HVFC with field oriented control and balanced SVPWM (the 5-5-5 mode changes to the 5-4-3 mode at 1.1 s) (a), enlarged fragment at the time of the accident (b)

IV. CONCLUSION

The paper compares a four control method for a cascaded high-voltage frequency converter with H-bridges – symmetrical disconnection of cells with sinusoidal PWM; balancing of phase-to-phase methods with sinusoidal and 3-rd harmonic injection PWM; balanced Space Vector PWM.

Table 1 summarizes efficiency indicators of HVFC with 3…6 H-bridges in each phase in normal and accident modes.

The method of balancing the phase-to-phase voltages by to such a shift of the zero point and rotation of the phase vectors, in which the amplitude of the phase-to-phase voltage decreases to the minimum possible value. Injection of the 3rd harmonic allows you to further increase the utilization factor of power supplies in terms of voltage. But the violation of the symmetry of the phase voltages leads to the need to reduce the voltage amplitude to exclude saturation of the power supplies, which reduces this coefficient compared to the theoretically possible 15.6%.

A distinctive feature of the method of balanced Space Vector PWM is that the amplitude of the 1st harmonic is always greater than the radius of the circle by 15.6%. Comparison of methods of space vector PWM (SVPWM), balancing of phase-to-phase voltage with the injection of the 3rd harmonic (THPWM) with sinusoidal PWM shows that SVPWM is the best method. Despite the more complex mathematical software for the implementation of this method, it provides the best performance in all considered emergency modes of 3…6 cascade converters.

The use of a balanced SVPWM in combination with field oriented control makes it possible to obtain an electric drive in which, in the event of an accident, there are practically no shock mechanical and electromagnetic processes. After damage of cells the currents, electromagnetic torque and motor speed change along the required trajectory.

REFERENCES

[1] Urbaniak M, Kardas-Cinal E and Jacyna M 2019 Optimization of Energetic Train Cooperation *Symmetry* 11(9), 1175; https://doi.org/10.3390/sym11091175

[2] Burdasov B K, Nesterov S A and Fedotov Yu B 2015 Frequency converters for high-voltage AC drives *APRIORI Series Natural and technical sciences* 4 pp 2–15

[3] Malinowski M, Gopakumar K, Rodriguez J and Pérez M A 2010 A Survey on Cascaded Multilevel Inverters I*EEE Transactions on Industrial Electronics* 57 7 pp 2197–2206

[4] Manimala V, Geetha N and Renuga P 2011 Design and simulation of five level cascaded inverter using multilevel sinusoidal pulse width modulation strategies *IEEE 3rd International Conference on Electronics Computer Technology* 2 pp 280–283. https://ieeexplore.ieee.org/document/5941701

[5] McGrath B P and Holmes D G 2002 Multicarrier PWM strategies for multilevel inverters I*EEE Transactions on Industrial Electronics* 49 4 pp 858–867

[6] Grahame D 2003 Pulse width modulation for power converters. *Principles and practice* (New Jersey: John Wiley & Sons, Inc.) p 724

[7] Kolpakov A 2009 Multilevel Converter Control Algorithms *Silovaya Elektron.* 2 pp 57–65. https://power-e.ru/wp-content/uploads/2009_2_57.pdf

[8] High voltage frequency converters series N5000 // http://www.tekhar.com/Programma/HYUNDAI/index_V_V_invert.html

[9] Frequency converters VEDADRIVE 315–25000 kVA // www.danfoss.ru/VLT

[10] Krishnapriya S and Unnikrishnan L 2015 Multilevel Inverter Fed Induction Motor Drives, *International Journal of Research in Engineering and Technology (IJRET)* 04 09 pp 60–64

[11] Rudyk T, Szczepański E, Jacyna M 2019 Safety factor in the sustainable fleet management model. *Archives of Transport*, 49(1), 103-114. DOI: https://doi.org/10.5604/01.3001.0013.2780

[12] PowerFlex 6000 Medium Voltage Variable Frequency Drive Firmware, Parameters, and Troubleshooting Manual Catalog Number 6000G // *Publication 6000-TD004E-EN-P* – September 2019. http://www.rockwellautomation.com/support

[13] High voltage frequency converters Robicon PERFECT HARMONY 225 kW–120 MW // www.siemens.com/robicon-perfect-harmony

[14] Puchkov A P and Osipov O I 2018 Correction of the Control System of a Multilevel Converter with a Defect in the Power cell of its Inverter *Electrotechnical Systems and Complexes* 3 40 pp 42–46

[15] Gorodny A, Dymerets A, Kut Y, Denisov Y, Natalia D 2020 Generalized method of commutation processes calculation in high-frequency switched-mode power converters *Advances in Intelligent Systems and Computing* 1019 pp 71–80

[16] V Busher et al 2020 *IOP Conf. Ser.: Mater. Sci. Eng*. 985 012021. https://doi.org/10.1088/1757-899X/985/1/012021

[17] V. Busher, A. Shestaka, O. Chornyi, O. Glazeva, L. Melnikova and V. Tytiuk, "Method of Space Vector Pulse Width Modulation in High Voltage Cascaded Frequency Converter with Damaged H-cells," 2021 IEEE International Conference on Modern Electrical and Energy Systems (MEES), 2021, pp. 1-5, https://doi.org/10.1109/MEES52427.2021.9598782