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Research paper

Advanced space vector modulation with “fractional” power cells

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ABSTRACT

The paper develops a model and studies various operating modes of a 5-phase multi-level cascade inverter as part of high-voltage powerful variable-frequency drives (VFD) with the most typical fan load for this type of electric drives. The aim of the work is to test the efficiency of the balanced spatial-vector pulse-width modulation method in a multi-phase high-voltage multi-level inverter in emergency modes by simulating the electric drive in the MATLAB/SIMULINK/Simscape Electrical environment.

The paper studies the features of using the balanced spatial-vector pulse-width modulation method in a five-phase frequency converter in normal and emergency modes and, especially, the differences from a three-phase inverter with a similar control principle. The model with a 5-phase synchronous motor from the MATLAB ac8_example.slx database is taken as a basis, which allows us to consider the simulation results reliable. The rules for calculating phase voltages in normal and emergency modes are formulated and the corresponding blocks of the inverter control system model are prepared - a block for calculating basic vectors and a block of spatial vector pulse-width modulation (PWM). The output signals of this block are used for further processing in the modules for controlling power cells with 2- or 3-level PWM. Such a model for a 5-phase electric drive has been built for the first time, which is a scientific novelty of the work.

Calculations of transient processes showed the absence of any oscillations, shocks when the system switches from normal to emergency mode and vice versa. That is, the proposed method of balanced spatial vector modulation preserves the symmetry of electromagnetic fields in the engine when individual H-bridges are damaged. It is shown that in normal mode, a 5-phase inverter using the spatial vector modulation method allows increasing the utilization factor of voltage sources by 23.1%. When individual power cells in phases fail, the utilization factor may decrease, but in any case it remains greater than 1. The method ensures compensation for emergency damage even in the event of a short circuit of one or two inverter phases. This significantly increases the service life of the electric drive, which is especially important in critical mechanisms and technological processes, where such complex inverters are actually used.

The study found that when using the proposed method in a 5-phase VFD, unlike a 3-phase one, the current balance in the load is disrupted, which leads to increased heating of individual phases of both the motor and the power section of the inverter. The second point of scientific novelty of the work is that in order to reduce this negative effect, it is proposed to improve the algorithm for calculating the output coordinates of the regulator by using the so-called “fractional” power cells with a voltage that is not a multiple of their rated voltage. This leads to a smooth change in phase shifts and asymmetry when individual H-bridges and even one or two phases are damaged. This, in turn, reduces the current imbalance and the corresponding overheating from 2...3 to 12...15%, which gives confidence in the efficiency of using this improvement. It is also important to note that such a change

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in the control algorithm does not require any changes in the circuit and does not increase the requirements for the computing power of the processors used.

1. Introduction

The application of high-voltage variable frequency drives (VFD) in powerful electromechanical systems (for example, such as ship propulsion devices, traction electric drives of trains, powerful electric drives in the metallurgical industry) ensures a multiple reduction in the consumption of electrical materials, primarily copper, a reduction in the weight of electric machines and cables, and also improves energy indicators THD (Total Harmonic Distortion), EEDI (Energy Efficiency Design Index) and EEOI (Energy Efficiency Operational Index) [1–3]. The basic structure of a multilevel VFD for such industrial applications is cascaded H-bridges, also called power cells. Despite the larger number of power transistors and the need to use a transformer with a large number of secondary windings, such a VFD topology has indisputable advantages: the number of possible output voltage levels is more than two (for H-bridges with two levels $-U$, $+U$: $m = 2N + 1$) or three (for 3-level $-U$, 0, $+U$: $m = 3N + 1$) times the number of direct current sources, where N is the number of H-bridges in one phase, each of which has a certain nominal voltage U; the sequence of H-bridges provides a modular arrangement and packaging, which allows to speed up and reduce the cost of both the manufacturing process and repair [4]. In powerful electric drives with increased requirements for reliability and torque smoothness, for example, in marine engines with a constant step, 5-phase synchronous motors and, accordingly, 5-phase VFDs are used, for example SIEMENS – Sinamics SL150 (SM150) [5,6]. Multilevel High Voltage VFDs use different types of power semiconductor components (IGBT, GTO, IGCT) [7] controlled by pulse width modulation (PWM) [8] and can have 3 or 5 and, even, 6 phases (Fig. 1).

2. Problem analysis

The reaction to the failure of one or more power cells is the most critical action of a cascade VFD [9–16]. A general short circuit of damaged elements leads to an imbalance of interphase voltages, currents, as well as shock loads in the mechanical part of the drive. To reduce these consequences in emergency situations, various correction methods are used. The basic method of reconfiguration consists in the fact that when a malfunction of the power cell in one of the phases is detected, the power cell of the other phases, similar in topology, are taken out of operation. At the same time, the phase voltages fall $(N-1)/N$ multiples. The second method is equalization (balancing) of the phase-to-phase voltage, which is carried out by changing the interphase angles and shifting the zero point [17–19]. The use of this method allows to reduce losses by 6...18% [20]. And space-vector modulation with bal-

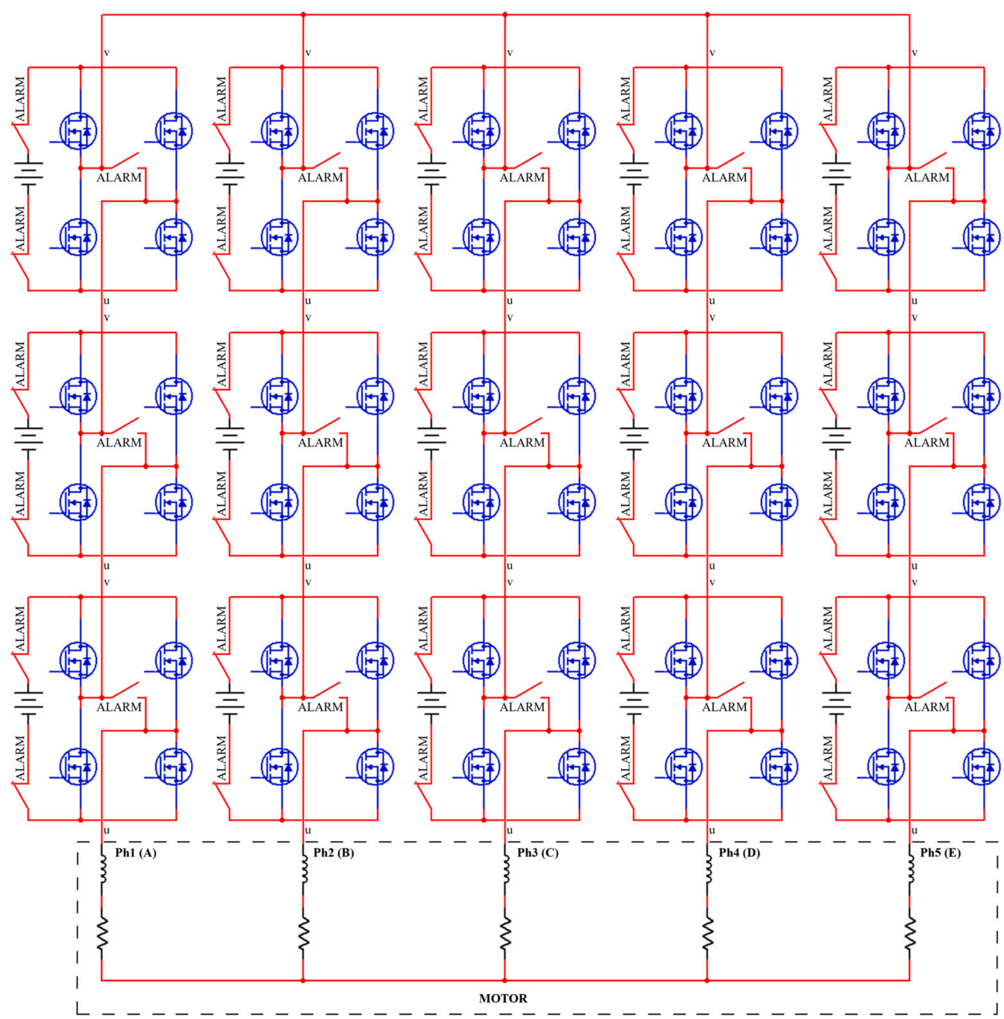
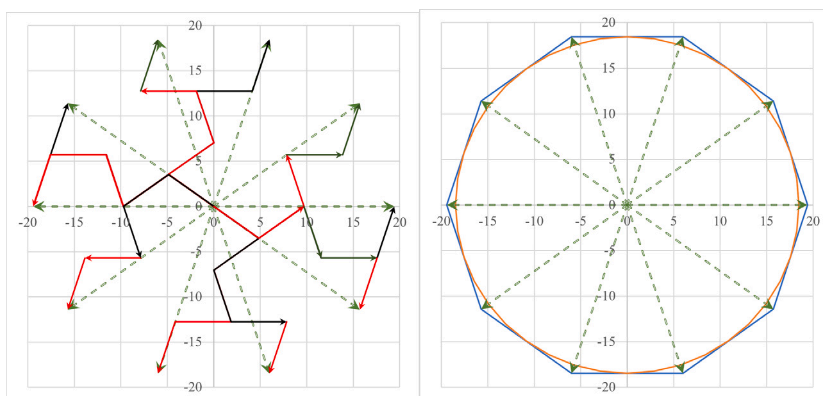


Fig. 1. Functional diagram of a 5-phase 3-cascade VFD with two-level H-bridges.

Step *i*	q1 (Ua)	q2 (Ub)	q3 (Uc)	q4 (Ud)	q5 (Ue)
1	1	1	-1	-1	-1
2	1	1	1	-1	-1
3	-1	1	1	-1	-1
4	-1	1	1	1	-1
5	-1	-1	1	1	-1
6	-1	-1	1	1	1
7	-1	-1	-1	1	1
8	1	-1	-1	1	1
9	1	-1	-1	-1	1
10	1	1	-1	-1	1
1	1	1	-1	-1	-1

(a)



(b) (c)

Fig. 2. Phase switching sequence, space vectors and inscribed circle in the normal mode of a 5-phase 6-cascade inverter.

ancing (SVPWM) additionally increases the efficiency of using a direct current source by 15.6% in a three-phase and by 23.1% in a five-phase converter [21–24]. Since accidental damage of H-bridges [25,26] most often occurs during the transient processes of starting or braking, when the currents increase, however, the frequency and the required amplitude of the supply voltage may be lower than the nominal one. Then the failure of individual power cells may not lead to phase asymmetry, but the diagnostic system, detecting damage, will initiate the transition of the control system to work with parameters that correspond to a balanced system. In three-phase converters, this is not reflected in the operation of the motor itself [27,28], it only changes the algorithms of the inverter phases [29,30]. But in 5-phase converters [31], when the basic space vectors are balanced, an imbalance of the phase currents occurs and, accordingly, the heating conditions of not only the converter, but also the motor change.

The purpose of the work is to improve the method of balanced space-vector pulse width modulation [32] in multiphase high-voltage multilevel VFD by using the so-called "fractional H-sections" [33] in emergency modes and to verify the method on models in MATLAB/SIMULINK/Simscape Electrical.

To achieve this goal, it will be developed an improved method of balanced space-vector modulation for a 5-phase VFD precisely so that there is an opportunity to use reliable models in MATLAB [34,35]. Simscape Electrical provides model examples of complete electric drives for 3-phase and 5-phase electric machines only. The mathematical model of the electric machine corresponds to the description presented in [36]. But the main ideas and algorithms that will be proposed in the work can be used for electric drives with an arbitrary number of phases.

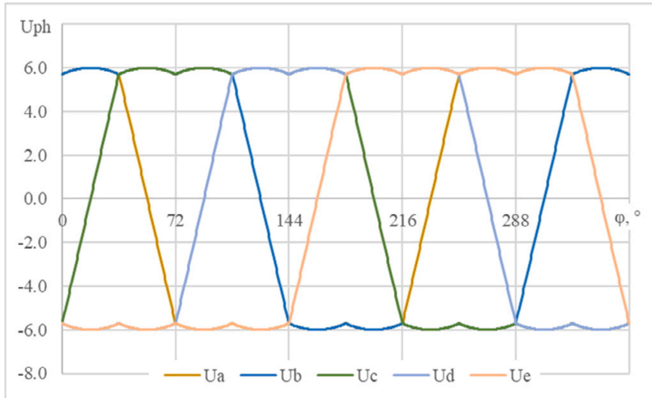
3. Method of balanced space-vector modulation in a 5-phase frequency converter

The idea of space-vector pulse-width modulation is based on sequential switching of phases with relative amplitude $U_{ph} = N_A = N_B = N_C = N_D = N_E = N$ on "+" or "–" of a direct current source, as shown in Fig. 2, a, which leads to the formation of 10 space (so-called basic) total voltage vectors with the following coordinates for each step i (Fig. 2 b) and the corresponding angles φ_i and angles between adjacent pairs $\varphi_{i,i+1}$:

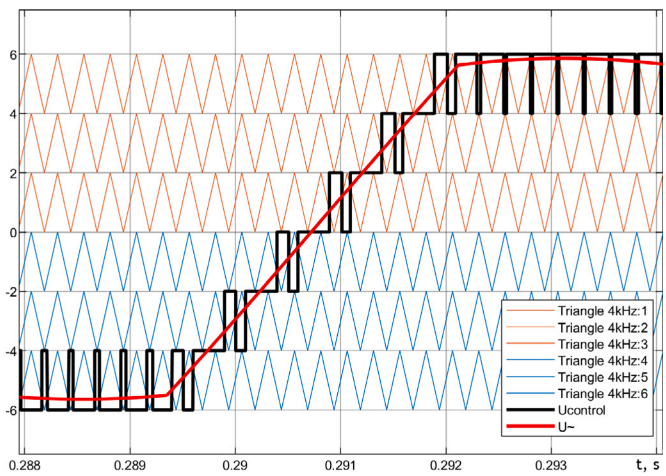
$$
\begin{gathered}
x_i = \sum_{j=1}^{5} q_{i,j} N_j \cos\left(\varphi_0 - (j-1)\frac{2\pi}{5}\right), \\
y_i = \sum_{j=1}^{5} q_{i,j} N_j \sin\left(\varphi_0 - (j-1)\frac{2\pi}{5}\right), \\
\varphi_i = \arctan\frac{y_i}{x_i}, \\
\varphi_{i,i+1} = \arccos\frac{x_i x_{i+1} + y_i y_{i+1}}{\sqrt{x_i^2 + y_i^2}\sqrt{x_{i+1}^2 + y_{i+1}^2}}.
\end{gathered}
\tag{1}
$$

The vectors describe the vertices of a polygon into which a circle of radius R can be inscribed. In the normal mode $R = 3.07768N$ (Fig. 2 c).

Matrix methods find a combination of switching on inverters to achieve a given position of the vector, taking into account the efficiency of individual inverters. But to create an electromagnetic torque without rotating pulsations, the voltage vector must be rotated within this circle. Matrix methods often do not take this limitation into account.



(a)



(b)

Fig. 3. Nominal phase voltage in normal mode at $N = 6$ (a); the principle of generating control signals for 2-level H-bridges (b).

With scalar control, it is necessary to set the angular frequency of rotation (the integral of which corresponds to the spatial position of the voltage vector) and the corresponding amplitude of the vector, with field-oriented control, the vector is formed by the corresponding regulators, but it is also characterized by two parameters – amplitude υ and angular position φ.

At each moment of time, the desired voltage vector is within one of the 10 sectors between two adjacent basic vectors (υ_1, φ_1), (υ_2, φ_2) and it can be formed by commutation of these vectors with duty cycles γ_1, γ_2, calculated by the theorem of sines:

$$\begin{aligned} &\upsilon \le \upsilon_{\max}, \varphi_1 \le \varphi \le \varphi_2, \\ \gamma_1 &= \frac{\upsilon}{\upsilon_1} \frac{\sin\left(\left(\varphi_2 - \varphi_1\right) - \left(\varphi - \varphi_1\right)\right)}{\sin\left(\pi - \left(\varphi_2 - \varphi_1\right)\right)}, \\ \gamma_2 &= \frac{\upsilon}{\upsilon_2} \frac{\sin\left(\varphi - \varphi_1\right)}{\sin\left(\pi - \left(\varphi_2 - \varphi_1\right)\right)}. \end{aligned} \tag{2}$$

Outside the sector, the duty cycles of these basis vectors are $\gamma_1 = 0$, $\gamma_2 = 0$, but the calculation continues for the next pair. During the circuit, the obtained values γ_1, γ_2 in each sector and the switching table $q_{i,j}$ of individual phases allow you to calculate the equivalent voltage values of each of the phases (Fig. 3 a):

Based on the comparison of these values with N-level triangular high-frequency signals (2-16 kHz), it is possible to generate control signals for transistors in H-bridges with 2-level (–U, +U) (Fig. 3 b) or 3-level (–U, 0, +U) output voltages. The use of calculated voltage signals of each of the phases allows you to implement asynchronous control of each inverter in phases, which is appropriate given the complex topology of the inverter and its design as a set of separate sections.

$$U_{ph\,j} = N_j \left(\sum_{i=1}^{10} \gamma_{1i} q_{i,j} + \gamma_{2i} q_{i+1,j} \right). \tag{3}$$

In the emergency mode, individual H-modules are short-circuited by electronic and/or electromechanical switch ALARM (Fig. 1) and the permissible voltage amplitude of the corresponding phase decreases. The symmetry of space vectors is broken. But, if to pay attention to formulas (1)–(3), then they are suitable for calculations at any voltage values of individual phases (this fact will be used later). Therefore, it can be calculated the coordinates of the vertices of the new polygon. It can be also inscribed a circle in it so that its diameter does not exceed the distance between the parallel sides. Fig. 4 shows a hypothetical case when the voltages of all phases are different $N_A = 2$, $N_B = 3$, $N_C = 4$, $N_D = 5$, $N_E = 6$ (we denote this case 2–3–4–5–6). If the amplitude of the desired vector does not exceed the radius of this circle, then the voltages of individual phases will be such that the symmetry of the magnetic fields of the stator windings of a 5-phase motor will not be disturbed [16]. The radius of this circle is also calculated based on the coordinates of the base vectors:

$$\begin{aligned} a_i &= \frac{y_{i+1} - y_i}{x_{i+1} - x_i}, \\ R_i &= \left| \left(y_i - a_i x_i \right) \sqrt{1 + a_i^2} \right|, \\ \upsilon_{\max} &= \min R_i, \quad i = 1 \ldots 5. \end{aligned} \tag{4}$$

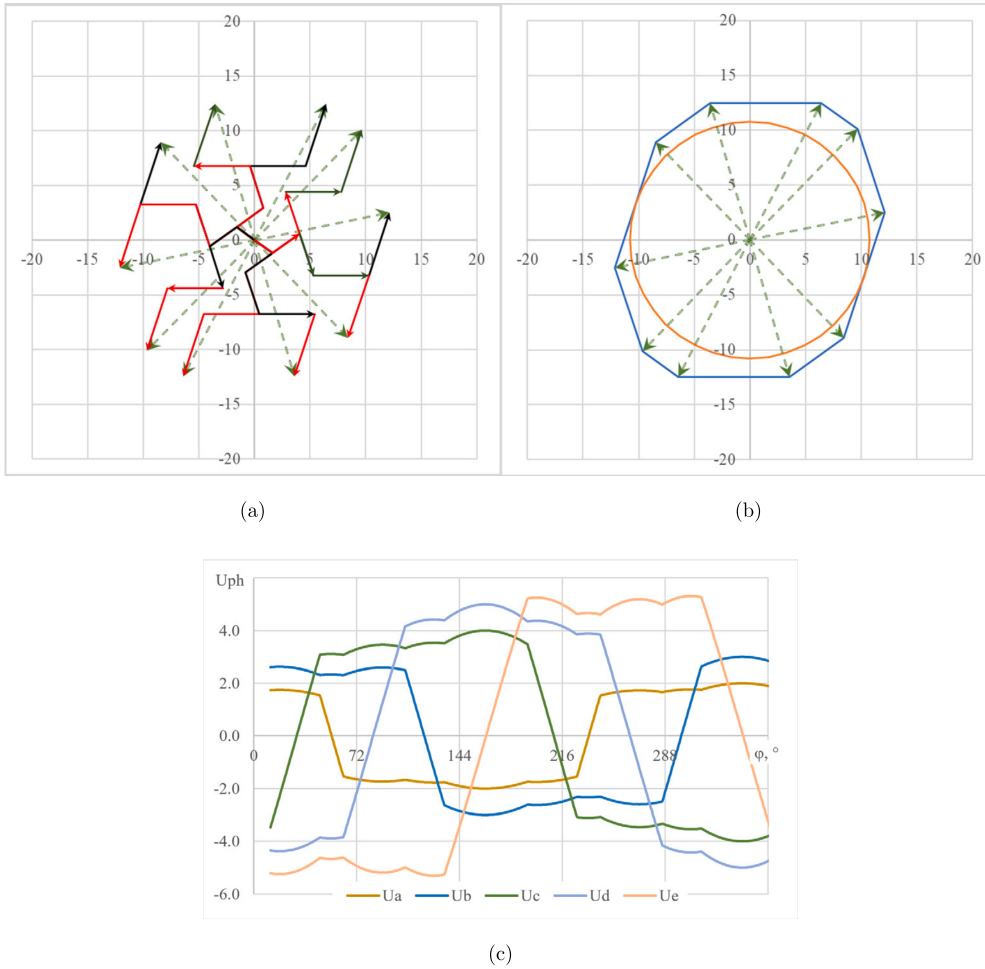


Fig. 4. Base vectors (a), inscribed circle (b) and phase voltages (c) in emergency mode 2-3-4-5-6.

In emergency modes, when one or even two phases of the converter fail completely, due to emergency switches of power cell, maintain conductivity, that is, they have a resistance close to zero. Therefore, currents can be supplied to the motor phases. The use of the method of balanced space-vector modulation allows maintaining the symmetry of the magnetic fields in the motor stator in these cases as well. Fig. 5 shows diagrams of phase voltages in modes 0-6-6-6-6 (voltage reduction compared to normal mode is 30.9%), 0-0-6-6-6 (voltage reduction – 50.0%) and 0-6-0-6-6 (voltage reduction – 61.8%).

4. Simulation of a 5-phase VFD using balanced space-vector modulation

To verify the obtained theoretical results, a model of an electric drive with a 5-phase 6-cascade VFD was developed, the control system of which works out the proposed algorithms of operation in emergency modes. The model is based on the example of a 5-phase complete electric drive with field-oriented control from the MATLAB/SIMULINK ac8_example.slx package and a mechanical load of the fan type, typical for many mechanisms using high-voltage powerful asynchronous electric drives, for example, thrusters on ships, and a model of a typical industrial 5-phase motor, which allows us to consider the simulation results to be quite reliable. Calculations in the model are carried out with a step of 2.5 μs, which is feasible in modern 32-bit microprocessors or industrial controllers.

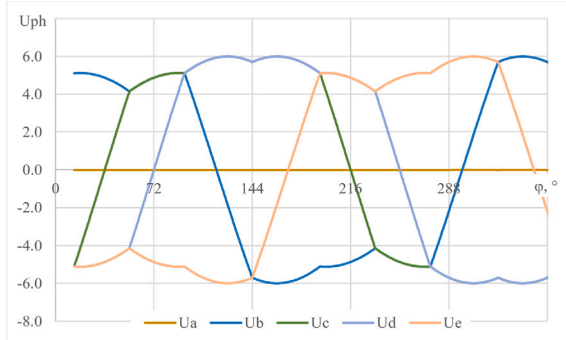
Since the switching methods of power cells in normal and emergency modes are tested, the control system is simplified to a scalar voltage and frequency control law.

The model consists of a block for generating the amplitude and position of the field vector according to the scalar control law, a subsystem for calculating the parameters of the basic vectors, a subsystem with 10 blocks for calculating the duty cycles and the relative voltage of the phases according to the commutation table. Next, the relative voltages are transmitted to the control pulse generation units for power cells. Depending on the selected type, 2- or 3-level modules can be used, which are already connected to the inverter phases and then – to the motor (Fig. 6 a).

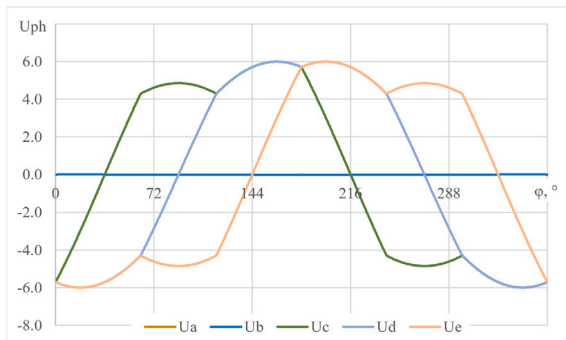
For further evaluation of the results, an ideal transient process was calculated under the condition of the formation of a 5-phase system of sinusoidal voltage with a linear increase in frequency and amplitude, load pattern for fan or pump application is selected, taking into account the nominal viscous damping and static friction in the engine (Fig. 6 b). The voltages and currents of the phases, the electromagnetic torque and the angular speed of the motor are displayed on the graphs. Also process of the integral heating of individual phases $\int_0^t i(t)^2\,dt$ is given.

In normal mode, when using space-vector modulation and 3-level H-bridges, identical graphs are obtained (Fig. 7). The voltage graphs calculated (red) and PWM signals (blue) are showed. It is clearly visible that the currents have a non-sinusoidal shape, but an electromagnetic torque identical to the reference one is created, and the actual values of the currents also coincide with the reference ones, as evidenced by graph of the integral heating process.

Next, the emergency modes will be analyzed by model in Fig. 6 a with Na_ = Na ... Ne_ = Ne. Fig. 8 a shows the results of calculations when using balanced space-vector modulation in the 6-3-4-5-6 mode, which starts from 0.1 s. It is clearly visible that the graphs of the electromag-



(a)



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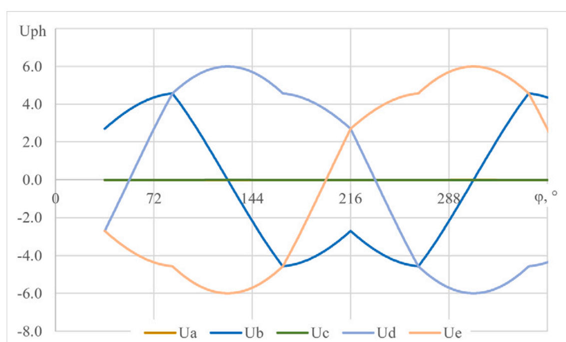


(c)

Fig. 5. Phase voltages in modes 0-6-6-6-6 (a), 0-0-6-6-6 (b), 0-6-0-6-6 (c).

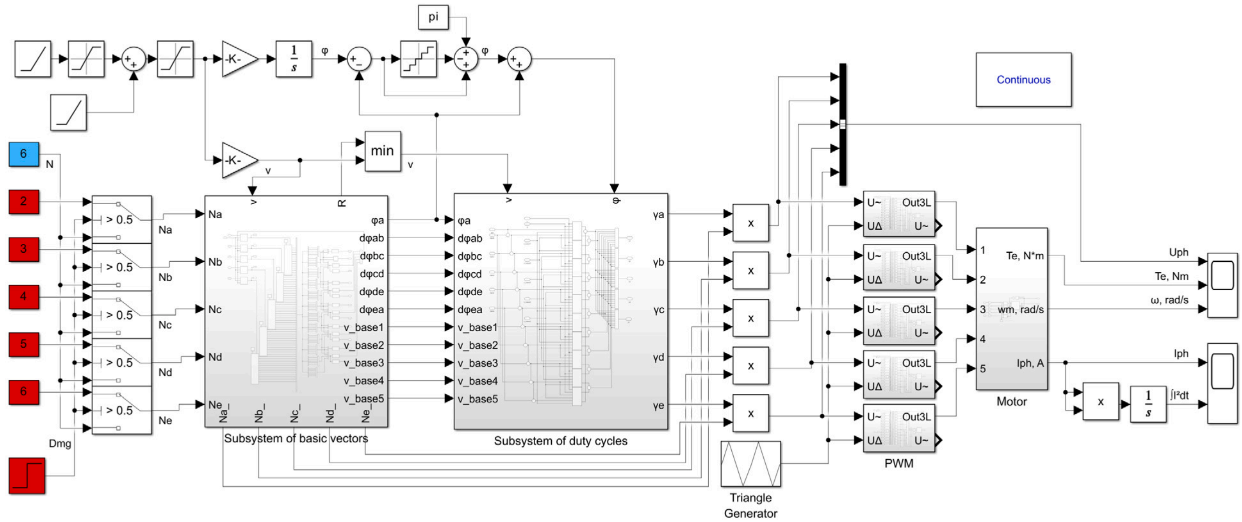
netic torque and speed practically coincide with Fig. 6 b and 7, any shocks and oscillations at the time of the accident are absent, which is evidence of the successful operation of the used balancing method. But a violation of the symmetry of the phase voltage leads to an asymmetry of the currents and, most significantly, to a change in the heating conditions of the phases: one phase heats up less, two phases heat up approximately the same as in normal mode, but the other two significantly overheat. At the end of the transient process, the sum of integral $\int_0^t i(t)^2\,dt$ estimates are $41100A^2s$, while in normal mode this value was $28200A^2s$, that is, the motor and individual phases of the converter will heat up more than in normal conditions. Fig. 8 b shows similar graphs with emergency mode 2-3-4-5-6, but with the set speed reduced by 25%. The engine successfully accelerates and decelerates. The integrated assessment of heating was $52300A^2s$ against $27400A^2s$ in regular mode.

Fig. 9 a shows the processes in the electric drive when one phase is damaged (emergency mode 0-6-6-6-6), and Fig. 9 b is the most difficult mode 0-6-0-6-6, but with a 25% reduced set speed.

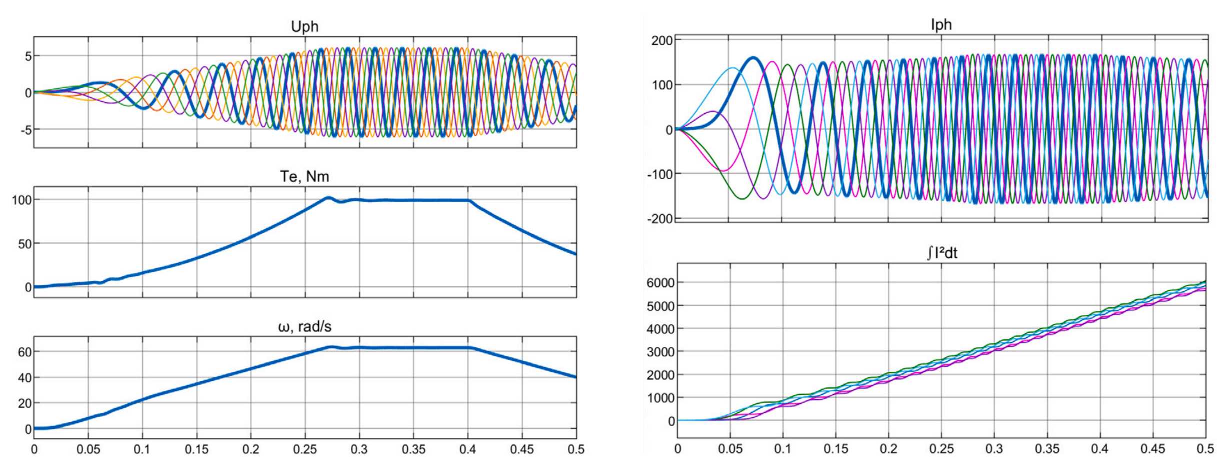
The obtained transient processes indicate that the engine is successfully accelerated and decelerated, the failure of individual phases of the converter is compensated for by using the method of balanced space-vector modulation. But the total integral heating estimates are $152,000A^2s$ for the 0-6-6-6-6 mode and $315,000A^2s$ for the 0-6-0-6-6 mode.

5. Balanced space-vector modulation with “fractional” power cells

The vector (υ, φ) calculated by the control system and the known parameters of the inverter make it possible to solve the inverse problem: to calculate the number of necessary power cells in each phase, taking into account the limitations caused by the failure of individual sections. Such a calculation can be performed by an integral regulator of the circle radius, which, based on a comparison of the desired amplitude of the vector υ and the radius calculated according to formulas (1) and (4)



(a)



(b)

Fig. 6. The model of high voltage cascaded VFD (a) and the ideal transient process with scalar control and sinusoidal voltage (b).

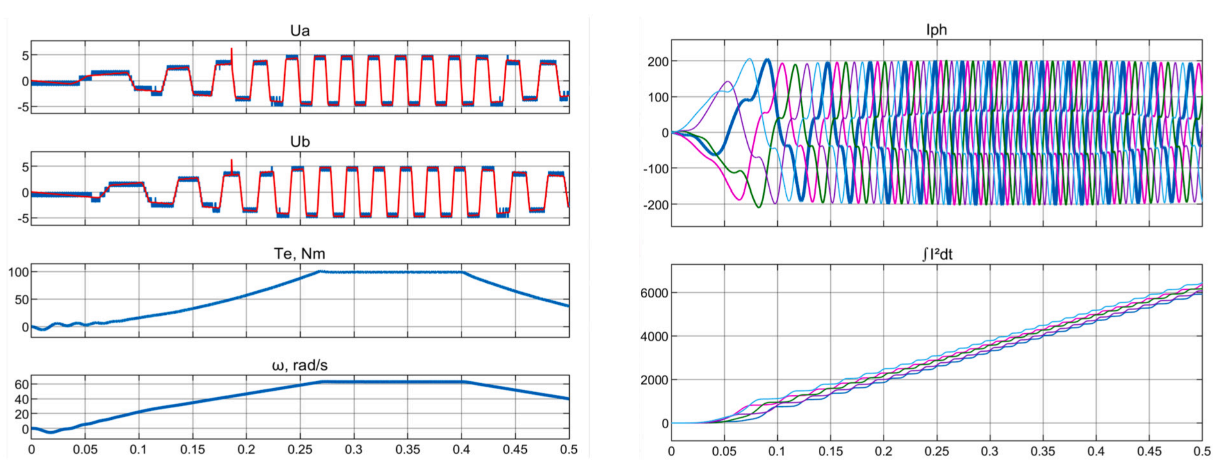
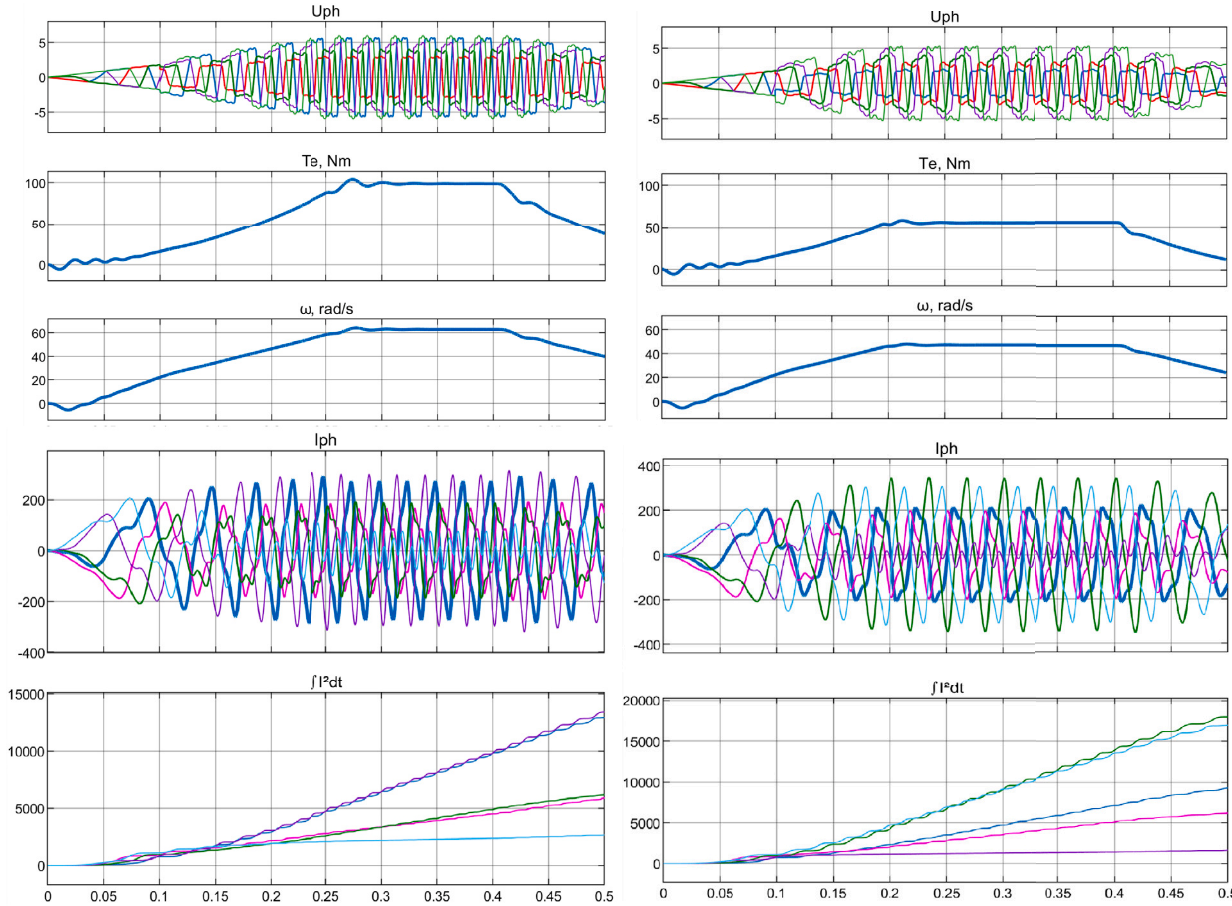


Fig. 7. Graphs of transient processes in regular mode 6-6-6-6-6 with space-vector modulation.



(a)

(b)

Fig. 8. Graphs of transient processes in the emergency mode with 0.1 s 6-3-4-5-6 (a) and 2-3-4-5-6 (b).

for arbitrary values N_j, increases or decreases precisely N_j taking into account the restrictions (Fig. 10).

Such regulators are connected to each phase of the "Subsystem of basic vectors" in Fig. 6 a. The result of the calculation in the general case is fractional, which is what determined the name of the improved method: "Balanced space-vector modulation with "fractional" power cells."

The result of the regulators is shown in Fig. 11 a, for emergency mode 6-3-4-5-6 and Fig. 11 b for emergency mode 2-3-4-5-6 with reduced speed.

The use of regulators leads to a gradual change in both the amplitude and the shifts of individual phases. Accordingly, the nature of transient processes of the electric drive changes. The total integral estimate of heating decreases from $41100A^2s$ to $36400A^2s$ (by 12%) due to the reduction of the current imbalance during not only the transient process, but also in the steady state. For mode 2-3-4-5-6, the integral heating estimate is $44,500A^2s$, which is 15% less than when using the basic method.

Fig. 12 shows the graphs of the transient processes of the calculated and PWM phase voltage signals, which show that the actual voltage levels have not changed, they remain multiples of whole numbers, but due to the regulators, there are no jumps and instantaneous changes in phase shifts.

The proposed method is multipurpose, it can be used in 3-phase VFDs. Fig. 13 it was compared the work in standard and emergency modes when using the method with "fractional" H-sections.

Table 1
Comparison of heating factor with different control methods.

Mode	Speed	Balanced SVPWM	Balanced SVPWM with "fractal" cells
6–6–6–6–6	100%	28,200	28,200
6–3–4–5–6	100%	41,100	36,400
6–6–6–6–6	75%	27,400	27,400
2–3–4–5–6	75%	52,300	44,500
0–6–6–6–6	75%	152,000	148,900
0–6–0–6–6	75%	315,000	307,100

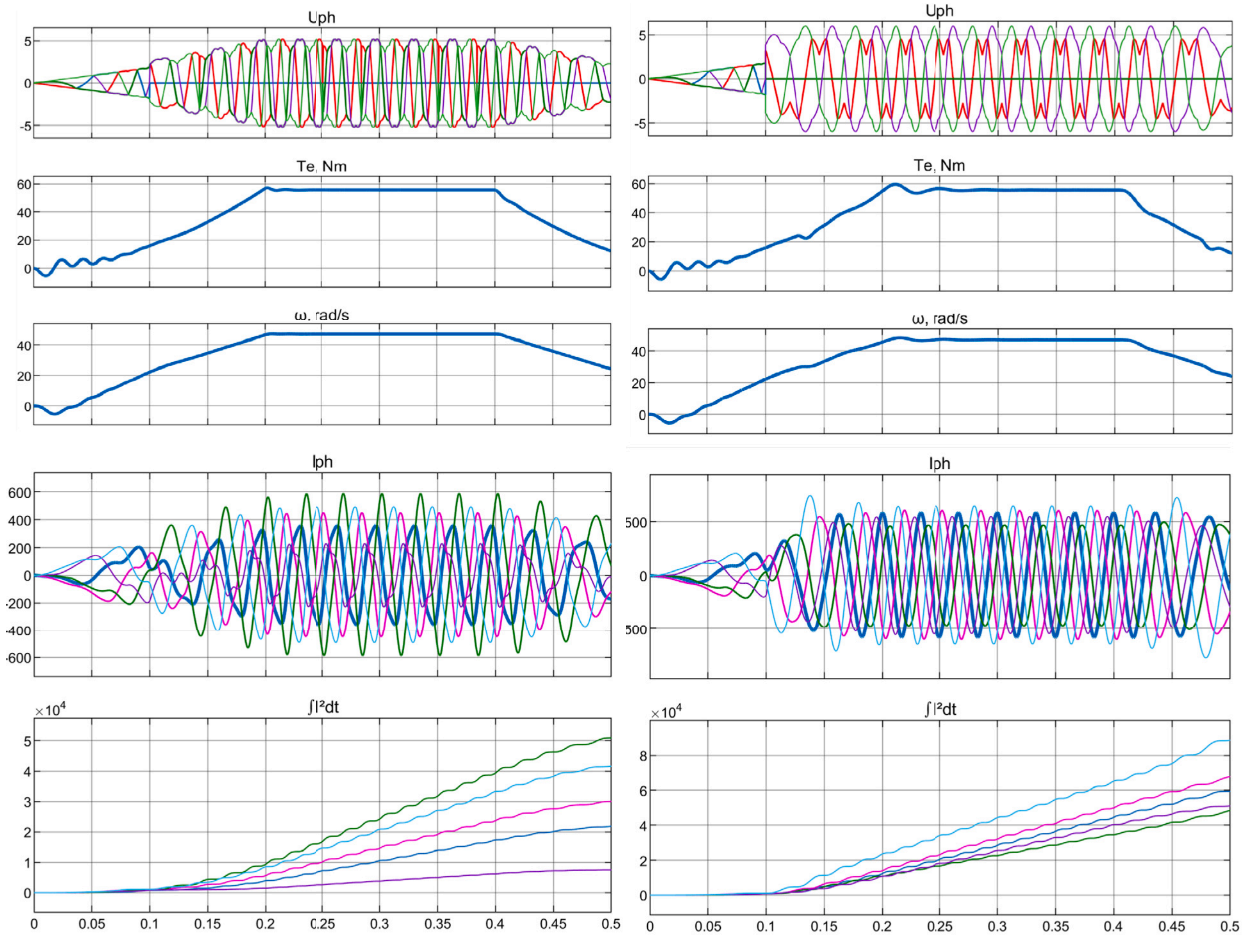
It can be seen from the graphs of the integral assessment of overheating that there is no current asymmetry in the 3-phase electric drive and the method does not have any effect.

It will be checked the efficiency of the method in case of damage to the phases of the 5-phase VFD. Fig. 14 shows the corresponding transient processes in emergency states 0-6-6-6-6 and 0-6-0-6-6.

In such emergency cases, the "fractional" H-bridge method reduces the heating of individual phases to a lesser extent, but the positive effect is also manifested: at high frequencies, the integral heating characteristic decreases by 2% and 2.5%, at a frequency twice as low – by 3.3%.

For a more visual comparison, the results of modeling processes using different control methods are summarized in Table 1.

Thus, in 5-phase cascade VFDs, a slight complication of only the calculation part of the control algorithm allows to reduce the imbalance of currents and, accordingly, to reduce the heating of the motor and the power part of the inverter in emergency modes, while using the effective method of balanced space-vector PWM.



(a) (b)

Fig. 9. Graphs of transient processes in emergency mode 0-6-6-6-6 (a) and 0-6-0-6-6 (b).

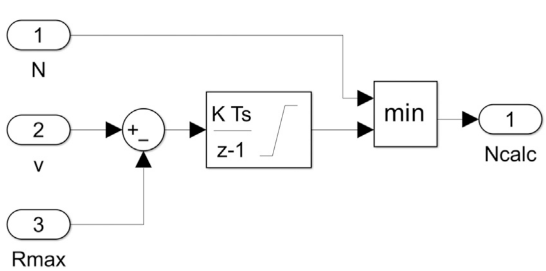


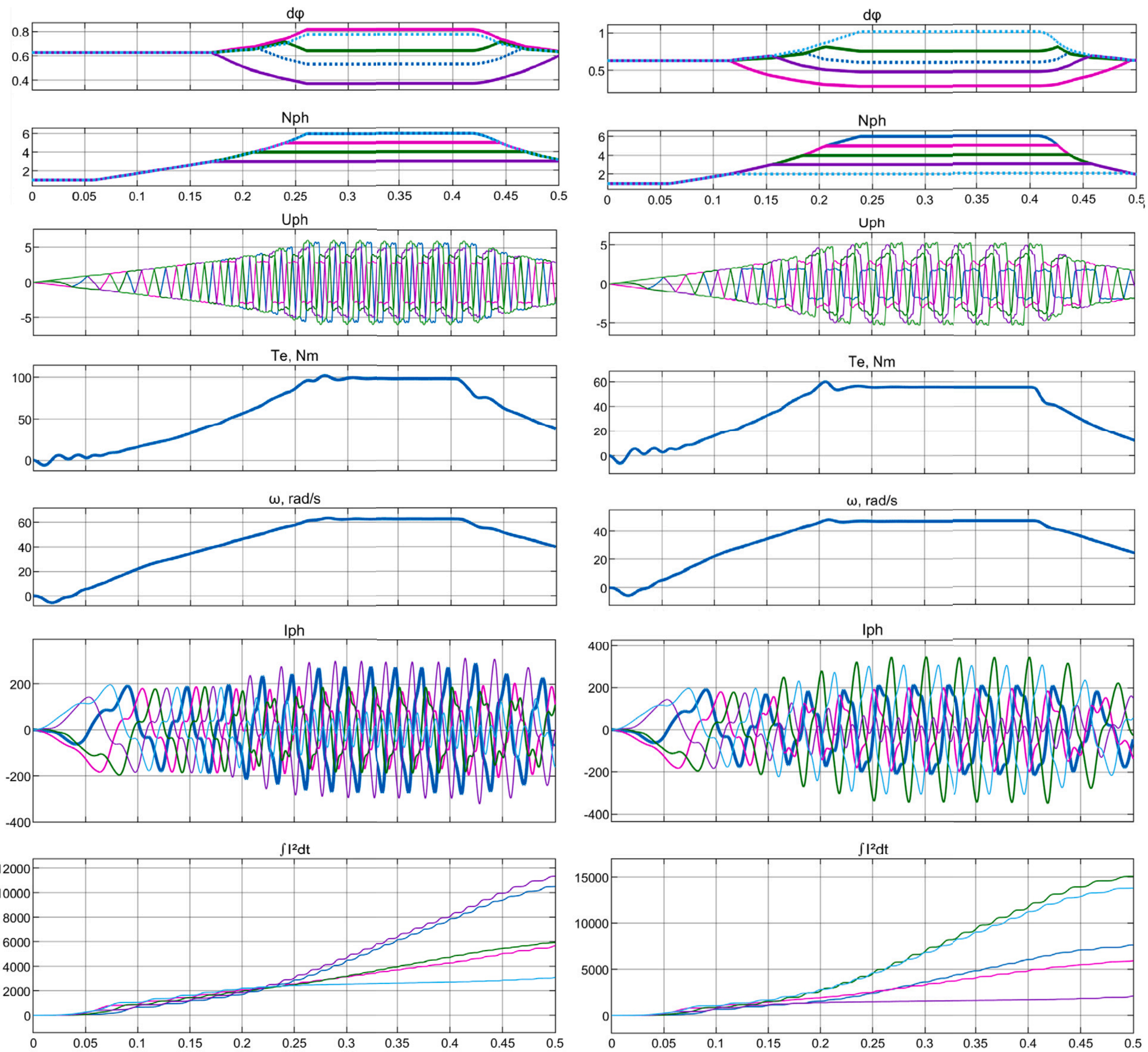
Fig. 10. Integrated phase voltage regulator.

6. Conclusions

The paper investigates the possibilities of using the method of balanced space-vector pulse-width modulation in a 5-phase high-voltage multilevel VFD in normal and emergency modes, taking into account the mathematical and geometric interpretation of the motor stator as a symmetrical 5-phase load. To check the efficiency of the method, a model with a 5-phase synchronous motor from the MATLAB/SIMULINK/Simscape Electrical database was used as a basis, which allows considering the research results as reliable. The rules for calculating phase voltages in regular and emergency modes have been formulated and the corresponding blocks of the model of the inverter control system have been prepared. These values are used for further processing in power cells control modules with 2- or 3-level pulse-width modulation.

Calculations of transient processes showed the absence of any oscillations, shocks when the system transitions from normal mode to emergency mode and vice versa. That is, the proposed method of balanced space-vector modulation preserves the symmetry of electromagnetic fields in the engine when individual H-bridges are damaged. It is shown that in regular mode, a 5-phase inverter using the space vector modulation method allows to increase the utilization factor of voltage sources by 23.1%. If individual power cells in the load phases fail, the utilization factor may decrease, but in any case, remains greater than 1. The method provides compensation for emergency damages even in case of short-circuiting of one or two phases of the inverter. This significantly increases the durability of the electric drive, which is especially important in responsible mechanisms and technological processes, where, in fact, such complex inverters are used.

However, when using the proposed method, in a 5-phase VFD, unlike a 3-phase one, the balancing of currents in the load is disturbed, which leads to increased heating of individual phases of both the motor and the power part of the inverter. To reduce this negative effect, in this paper is proposed to improve the algorithm for calculating the output coordinates of the regulator by using so-called fractional H-bridges with a voltage not multiple of their nominal voltage. In addition, the method does not require complex calculations and therefore does not increase the requirements for the computing power of microcontrollers and can be implemented without changing the electronic and electrical circuits. This leads to a smooth change of shifts and asymmetry of phases in case of damage to individual H-bridges and even phases. This, in turn, re-



(a) (b)

Fig. 11. The result of the operation of the “fractional” H-bridge regulators during start-up and braking in emergency modes 6-3-4-5-6 (a) and 2-3-4-5-6 (b).

duces the imbalance of currents and the corresponding overheating from 2...3 to 12...15%, which gives confidence in the effectiveness of using this improvement. At the same time, the method of balancing phase-to-phase voltages is completely free from this drawback. Therefore, further research can be aimed at finding a method that combines the advantages of balancing phase-to-phase voltages and balanced space vector modulation, supplemented by the method of “fractional” power cells.

Since the input coordinate in the model is a voltage vector with a given position and amplitude, the obtained results can be used in the synthesis of not only scalar, but also more complex control systems, including those with field-oriented control. We also plan to use the obtained results for the synthesis of fractional-order ID controllers, which are most effective in complex nonlinear systems with changing parameters, to improve transient processes in 5-phase electric drives [37].

The work contains calculation formulas, diagrams explaining the principles of operation in normal and emergency situations, some of the most important blocks of the model that can be used in the design of a microprocessor control system for power elements of the inverter.

CRediT authorship contribution statement

Victor Busher: Writing – review & editing, Project administration, Conceptualization. **Anatoliy Shestaka:** Conceptualization. **Lubov Melnikova:** Resources. **Vitaliy Kuznetsov:** Software, Methodology. **Oleksii Mykhailenko:** Visualization. **Viktor Kovalenko:** Resources. **Viktor Kutyk:** Formal analysis. **Dmytro Osadchyi:** Resources. **Iryna Osypenko:** Validation. **Samer Abdel Gawad:** Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

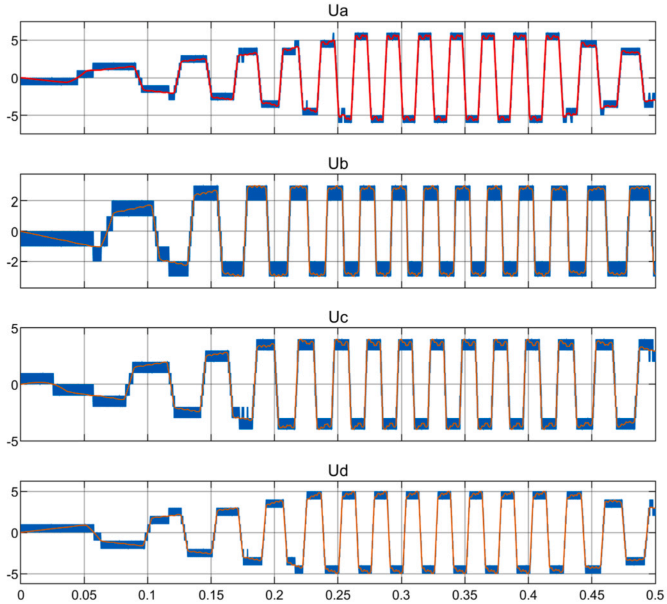


Fig. 12. Calculated and PWM phase voltages when using the “fractional” H-bridge method.

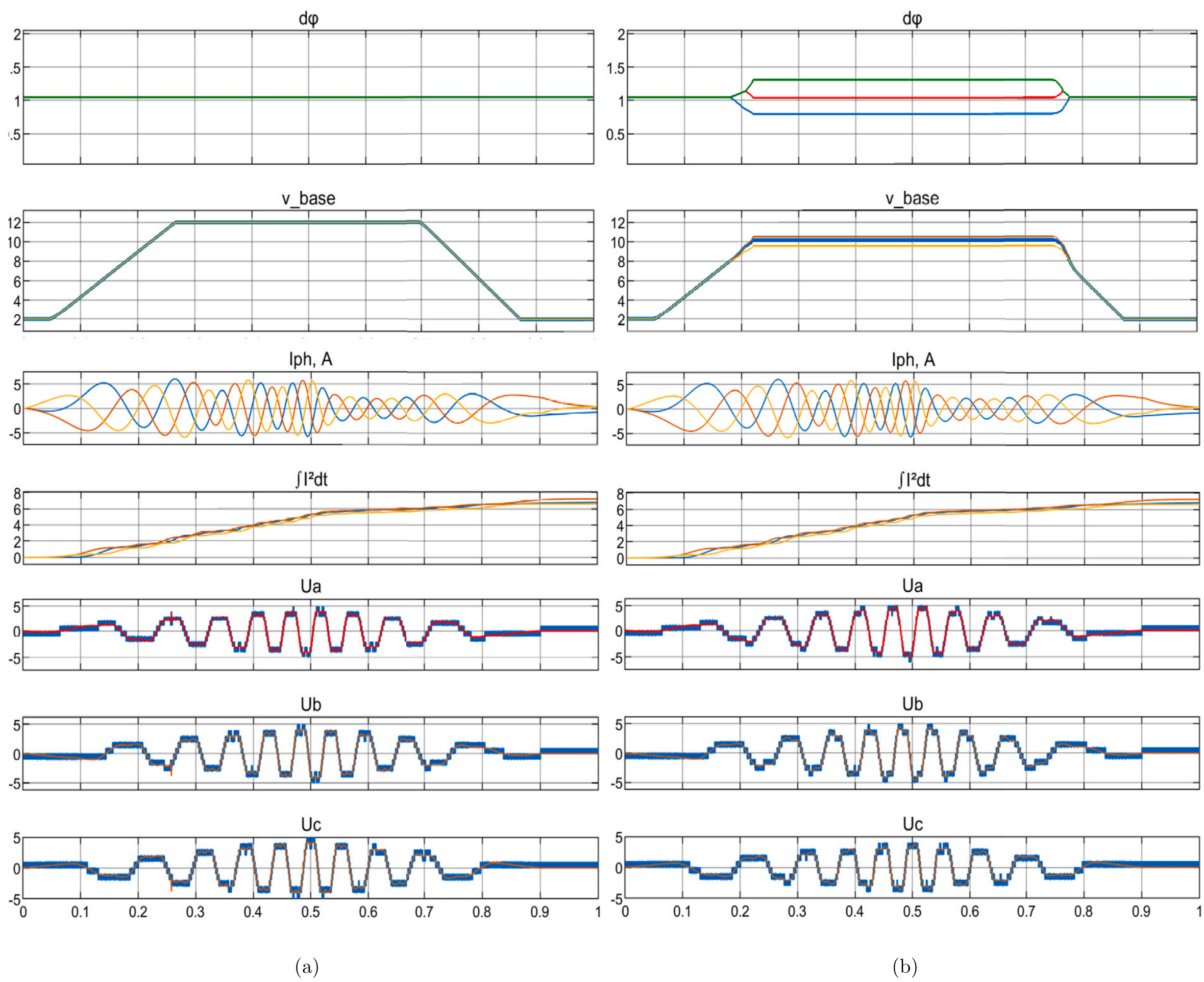


Fig. 13. Graphs of transient processes in a 3-phase inverter in normal mode (a) and accidents 6-5-4 (b).

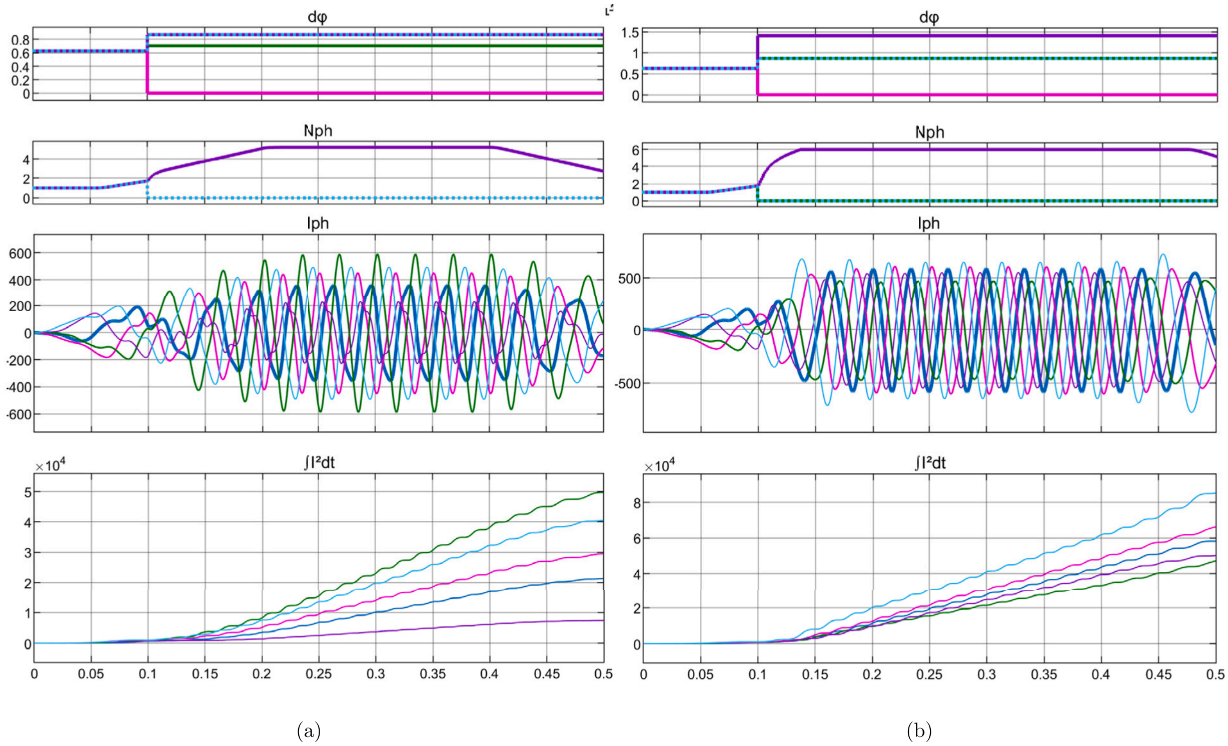


Fig. 14. Graphs of transient processes in accidents 0-6-6-6-6 (a) and 0-6-0-6-6 (b).

References

[1] M. Urbaniak, E. Kardas-Cinal, M. Jacyna, Optimization of energetic train cooperation, Symmetry 11 (9) (2019) 1175, https://doi.org/10.3390/sym11091175.

[2] B.K. Burdasov, S.A. Nesterov, Yu.B. Fedotov, Frequency converters for high-voltage AC drives, APRIORI Ser. Nat. Techn. Sci. 4 (2015) 2–15.

[3] W.P. Symington, A. Belle, H.D. Nguyen, J.R. Binns, Emerging technologies in marine electric propulsion, Proc. Inst. Mech. Eng., Part M, J. Eng. Marit. Environ. 230 (1) (2016) 187–198, https://doi.org/10.1177/1475090214558470.

[4] M. Malinowski, K. Gopakumar, J. Rodriguez, M.A. Pérez, A survey on cascaded multilevel inverters, IEEE Trans. Ind. Electron. 57 (7) (2010) 2197–2206, https://doi.org/10.1109/TIE.2009.2030767.

[5] V. Oleschuk, G. Grandi, F.A. Dragonas, Five-phase and six-phase converters with synchronized PWM: an overview, in: 2011 IEEE International Symposium on Industrial Electronics, 2011, pp. 283–288.

[6] A.P. Puchkov, O.I. Osipov, Correction of the control system of a multilevel converter with a defect in the power cell of its inverter, Electrotechn. Syst. Complexes 40 (3) (2018) 42–46, https://doi.org/10.18503/2311-8318-2018-3(40)-42-46.

[7] A. Gorodny, A. Dymerets, Y. Kut, Y. Denisov, D. Natalia, Generalized method of commutation processes calculation in high-frequency switched-mode power converters, in: A. Palagin, A. Anisimov, A. Morozov, S. Shkarlet (Eds.), Mathematical Modeling and Simulation of Systems, Springer International Publishing, Cham, 2020, pp. 71–80.

[8] V. Busher, O. Chornyi, V. Tytiuk, O. Glazeva, O. Rozlutskyi, V. Kuznetsov, Methods of pulse width modulation in cascaded high voltage frequency converters, in: 2022 IEEE 3rd KhPI Week on Advanced Technology (KhPIWeek), 2022, pp. 1–6.

[9] P.M. Lingom, J. Song-Manguelle, D.L. Mon-Nzongo, R.C.C. Flesch, T. Jin, Analysis and control of PV cascaded H-bridge multilevel inverter with failed cells and changing meteorological conditions, IEEE Trans. Power Electron. 36 (2) (2021) 1777–1789, https://doi.org/10.1109/TPEL.2020.3009107.

[10] B. Mirafzal, Survey of fault-tolerance techniques for three-phase voltage source inverters, IEEE Trans. Ind. Electron. 61 (10) (2014) 5192–5202, https://doi.org/10.1109/TIE.2014.2301712.

[11] Z. Gao, C. Cecati, S.X. Ding, A survey of fault diagnosis and fault-tolerant techniques - part I: fault diagnosis with model-based and signal-based approaches, IEEE Trans. Ind. Electron. 62 (6) (2015) 3757–3767, https://doi.org/10.1109/TIE.2015.2417501.

[12] S.P. Gautam, M. Jalhotra, L.K. Sahu, M.R. Kumar, K.K. Gupta, A survey on fault tolerant and diagnostic techniques of multilevel inverter, IEEE Access 11 (2023) 60866–60888, https://doi.org/10.1109/ACCESS.2023.3285722.

[13] P.M. Lingom, J. Song-Manguelle, J.M. Nyobe-Yome, M.L. Doumbia, A comprehensive review of compensation control techniques suitable for cascaded H-bridge multilevel inverter operation with unequal DC sources or faulty cells, Energies 17 (3) (2024) 722, https://doi.org/10.3390/en17030722.

[14] Y. Song, B. Wang, Survey on reliability of power electronic systems, IEEE Trans. Power Electron. 28 (1) (2013) 591–604, https://doi.org/10.1109/TPEL.2012.2192503.

[15] P. Lezana, G. Ortiz, Extended operation of cascade multicell converters under fault condition, IEEE Trans. Ind. Electron. 56 (7) (2009) 2697–2703, https://doi.org/10.1109/TIE.2009.2019771.

[16] P. Hammond, Enhancing the reliability of modular medium-voltage drives, IEEE Trans. Ind. Electron. 49 (5) (2002) 948–954, https://doi.org/10.1109/TIE.2002.803172.

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

[18] Frequency converters VEDADRIVE 315-25000 kVA, https://vedaindrives.com/products/medium-voltage-frequency-converters/.

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

[20] High voltage frequency converters Robicon PERFECT HARMONY 225 kW-120 MW, https://www.siemens.com/robicon-perfect-harmony.

[21] S. Krishnapriya, L. Unnikrishnan, Multilevel inverter fed induction motor drives, Int. J. Res. Eng. Technol. 04 (09) (2015) 60–64, https://doi.org/10.15623/ijret.2015.0409010.

[22] V. Busher, O. Chornyi, O. Glazeva, V.G. Kuznetsov, V. Tytiuk, M. Tryputen, Optimal control method of high-voltage frequency converters with damaged cells, IOP Conf. Ser., Mater. Sci. Eng. 985 (1) (2020) 012021, https://doi.org/10.1088/1757-899X/985/1/012021.

[23] V. Busher, A. Shestaka, O. Chornyi, O. Glazeva, L. Melnikova, V. Tytiuk, Method of space vector pulse width modulation in high voltage cascaded frequency converter with damaged H-cells, in: 2021 IEEE International Conference on Modern Electrical and Energy Systems (MEES), 2021, pp. 1–5.

[24] V. Busher, O. Chornyi, V. Tytiuk, O. Glazeva, V. Kuznetsov, Features of space vector pulse width modulation in 5-phases cascaded high voltage converters, in: 2024 IEEE 5th KhPI Week on Advanced Technology (KhPIWeek), 2024, pp. 1–5.

[25] X. Wu, C. Xiong, S. Yang, H. Yang, X. Feng, A simplified space vector pulsewidth modulation scheme for three-phase cascaded H-bridge inverters, IEEE Trans. Power Electron. 35 (4) (2020) 4192–4204, https://doi.org/10.1109/TPEL.2019.2934821.

[26] J. Gholinezhad, R. Noroozian, Application of cascaded H-bridge multilevel inverter in DTC-SVM based induction motor drive, in: 2012 3rd Power Electronics and Drive Systems Technology (PEDSTC), 2012, pp. 127–132.

[27] Y. Kuznetsova, V. Kuznetsov, M. Tryputen, A. Kuznetsova, M. Tryputen, M. Babyak, Development and verification of dynamic electromagnetic model of asynchronous motor operating in terms of poor-quality electric power, in: 2019 IEEE International Conference on Modern Electrical and Energy Systems (MEES), 2019, pp. 350–353.

[28] M. Tryputen, V. Kuznetsov, A. Kuznetsova, M. Tryputen, Y. Kuznetsova, T. Serdiuk, Improving the reliability of simulating the operation of an induction motor in solving the technical and economic problem, in: Z. Hu, S. Petoukhov, I. Dychka, M. He

(Eds.), Advances in Computer Science for Engineering and Education III, Springer International Publishing, Cham, 2021, pp. 143–152.

[29] H. Heydari-doostabad, M. Monfared, An integrated interleaved dual-mode time-sharing inverter for single-phase grid-tied applications, IEEE Trans. Ind. Electron. 66 (1) (2019) 286–296, https://doi.org/10.1109/TIE.2018.2829686.

[30] A.S. Hussein, A.M.Y.M. Ghias, Cascaded multioutput multilevel converter: modulation and operating limits, IEEE Trans. Ind. Electron. 69 (1) (2022) 399–408, https://doi.org/10.1109/TIE.2021.3050374.

[31] A. Abdelkarim, B. Youcef, L. Zellouma, D. Toumi, A. Ibrahim, R. Aboelsaud, Improved space vector modulation algorithm of 5-level three-phase z-source based cascaded inverter, Int. J. Power Electron. Drive Syst. 13 (4) (2022) 2286–2295, https://doi.org/10.11591/ijpeds.v13.i4.pp2286-2295.

[32] Q. Sun, Z. Wang, S.M. Sharkh, W. Hao, A flexible and decoupled space vector modulation scheme with carrier-based implementation for multilevel converters, IEEE Trans. Power Electron. 38 (7) (2023) 8135–8149, https://doi.org/10.1109/TPEL.2023.3262783.

[33] J. Yu, Q. Zhao, H. Li, X. Yue, S. Wen, High-performance fractional order PIMR-type repetitive control for a grid-tied inverter, Energies 15 (11) (2022) 3854, https://doi.org/10.3390/en15113854.

[34] O. Kuzenkov, T.M. Serdiuk, A. Kuznetsova, M. Tryputen, V. Kuznetsov, Y. Kuznetsova, M. Tryputen, Mathematical Model of Dynamics of Homomorphic Objects, CEUR Workshop Proceedings, vol. 2516, 2019, pp. 190–205.

[35] O. Mykhailenko, Modeling and simulating dynamics of lithium-ion batteries using block-oriented models with piecewise linear static nonlinearity, E3S Web Conf. 280 (2021) 05004, https://doi.org/10.1051/e3sconf/202128005004.

[36] F. Barrero, M.G. Satué, F. Colodro, M.R. Arahal, Tuning of modern speed drives using IFOC: a case study for a five-phase induction machine, Results Eng. 24 (2024) 103145, https://doi.org/10.1016/j.rineng.2024.103145.

[37] V. Busher, V. Zakharchenko, A. Shestaka, V. Kuznetsov, V. Kuznetsov, S. Nader, Optimization of the control of electromagnetic brakes in the stand for tuning internal combustion engines using id regulators of fractional order, Energies 15 (24) (2022), https://www.mdpi.com/1996-1073/15/24/9378.