Optimal Control Method of High-Voltage Frequency Converters with Damaged Cells

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Abstract. Application of high-voltage frequency converters is one of the most prospective trends in the development of current powerful electric drives, i.e. in high-speed trains. In terms of such converters, a multilevel cascaded H-bridge converter is becoming the most widespread one owing to its increased reliability, survival in terms of one or more damaged cells, and quick repairability due to its modular structure. The research proposes a control method, which provides maximum possible linear voltage in case of one or several damaged cells owing to the shift of zero point and turning of phase voltages. It is also demonstrated how turning angles of phase voltages should be set to preserve spatial position of the linear voltage vectors which provides the least complicated electromagnetic transients in terms of nominal rotation frequency; in case of low or middle frequencies, damage of the cells may have no effect on the motor operation. Fast algorithm to calculate turning points of phase voltages is proposed; the algorithm may be applied in the industrial microprocessor control systems. Algorithm of the operations, which provides implementation of the method, is described.

1. Introduction

High-voltage frequency converters are becoming more and more popular in different fields of technology where powerful electric drives are required. These are metallurgical enterprises, metal rolling mills, ship power systems, rail transport and much more. Along with the common benefits – smooth and efficient velocity control of the alternating-current machines – their implementation provides multiple reduction of both consumption of electrotechnical materials (first of all, that is copper) and THD (Total Harmonic Distortion), increase of EEDI (Energy Efficiency Design Index) and EEOI (Energy Efficiency Operational Index) giving the incontestable benefits while designing up-to-date electromechanical systems, which include transportation systems, i.e. high-speed trains [1]. It is in the
latter systems that high-voltage multilevel frequency converters can provide energy recovery to the common network, solving the problem of increasing energy efficiency [2]. However, a number of problems also arise, since high-voltage semiconductor power devices are still less reliable. Therefore, it is necessary to solve the problems of both improving the reliability of electronic components and finding methods to reduce damage in the event of failure of some of them.

The aim of the work is to find such a method for controlling high-voltage multilevel frequency converters that would provide the least voltage drop on the motor and the least ripple of the electromagnetic torque in case of damage to one or more cells in the inverter phases.

2. Analysis of the problem
High-voltage frequency converters (HVFC) with the following circuitries are the most widespread ones [3]:
1. Two-transformer FC with low-voltage inverter;
2. Multilevel FC with input sectional transformer.

Systems of the first types are being gradually ousted from the market as powerful high-voltage switches are entering the market; among the multilevel converters, several types are the most widespread ones [3]:
- diode-clamped converter;
- neutral point clamped converter;
- floating-capacitor converter;
- cascaded H-bridge converter.

Cascaded H-bridge converters are considered to be the most advanced ones from the viewpoint of reliability, survivability, and maintainability. Such circuit helps obtain any amount of voltage using standard low-voltage technologically independent modules (Figure 1) [4]. Moreover, the design modularity makes it possible to preserve operating capacity, if any or even several modules may get out of order.

![Figure 1](image-url)

**Figure 1.** The principle of building a cascaded H-bridge converter: a) one phase of the cascaded H-bridge converter; b) the formation of a three-phase high voltage system.

Layout and principles of the inverter control are determined by the power semiconductor components (IGBT, GTO, IGCT, SGCT) [5] and Pulse Width Modulation (PWM) methods [6–8]:
- sinusoidal PWM;
- modified algorithms of sinusoidal PWM;
- PWM with variable parameters;
- Space Vector PWM (SVPWM);
- algorithm of elimination of specific harmonics;
- wavelet-modulation etc.

In terms of multilevel cascaded H-bridge converter, response to the breakdowns of one or more modules is the most critical action [9, 10]. Common short circuit of the damaged module results in the
side-to-side linear voltage tilts, disbalance of currents, consequently, electric and electromechanical shock loads and a threat to the safety of the operation of the mechanism and personnel [11–13]. Thus, different correction algorithms are applied. For instance, in terms of Allen Bradley HV FC 6000, when defect is detected in one of the phases, the “like” cells in two other phases are closed [14]. In this case, voltage drops by \((N - 1)/N\) times. In some cases, the method of linear voltage balancing is applied by changing the interphase angles and the shift of zero point, as in terms of FC SIEMENS of Robicon PERFECT HARMONY series [15, 16]. However, solutions of the same problem in case of breakdown of several cells and reduced shock load at the moment of transition from standard to emergent operating mode as well as the evaluation of possible application of SVPWM in the emergency modes are still problematic.

Objective of the research is to develop a universal method to correct linear voltages in terms of damaged cells of multilevel cascaded H-bridge converter with the minimization of shock loads during transition from standard to emergency operating modes and to estimate efficiency of the use of Space Vector Pulse Width Modulation in case of the emergency modes.

3. Materials of the research

Preliminary analysis has demonstrated that in terms of the multiphase electric machines, considerable oscillations of electromagnetic moment take place not only due to voltage changes but also because of the turning of linear voltage vectors at that moment.

The proposed correction method is based on the shift of zero point and turning of FC phase voltages to provide symmetry of the amplitudes and preserve spatial position of the linear voltages in terms of damaged cells (Figure 2).

![Figure 2. Linear and phase voltage vectors after damage of cells.](image)

Since all the cells generate certain similar voltage \(U\), it is possible to move on to the equations in relative units having substituted absolute values of phase voltages with the number of cells:

\[
\begin{align*}
N_A &= U_A / U, \\
N_B &= U_B / U, \\
N_C &= U_C / U
\end{align*}
\]

and having expressed linear voltages in their relation to \(U\). Then, in terms of standard operating mode at \(N_A = N_B = N_C = N\), we obtain \(L_0 = \sqrt{3}N\).

To determine interphase angles \(\alpha, \beta, \gamma\) in the emergency mode, it is required to meet the equality of the linear voltages to some unknown value \(L\):
\[
\begin{align*}
N_A^2 + N_B^2 - 2N_A N_B \cos(\alpha) &= L^2, \\
N_B^2 + N_C^2 - 2N_B N_C \cos(\beta) &= L^2, \\
N_C^2 + N_A^2 - 2N_C N_A \cos(\gamma) &= L^2, \\
\alpha + \beta + \gamma &= 2\pi,
\end{align*}
\]
where \(N_A, N_B, N_C\) are relative values of voltages of each phase, \(\alpha = \angle(U_A, U_B) = \angle AOB\), \(\beta = \angle(U_B, U_C) = \angle BOC\), \(\gamma = \angle(U_C, U_A) = \angle COA\).

In case of breakdown of one or several cells in two phases, two of the three angles become obviously equal; then, system (1) is reduced to a square equation being solved analytically. Thus, if \(N_A = N_B \neq N_C\), we obtain:

\[
\begin{align*}
a &= 4N_A^2, \\
b &= -2N_A N_C -3N_A^2 + N_C^2, \\
D &= b^2 - 4ac, \\
\beta &= \gamma = \arccos \left( \frac{b - \sqrt{D}}{2a} \right), \\
\alpha &= \pi - 2\beta, \\
L &= 2N_A \sin(\pi - \alpha).
\end{align*}
\]

If \(N_A \neq N_B \neq N_C\), then equation system (2) 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.

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.

Much faster solution is possible owing to a method based on Heron theorem. The idea is in the fact that the area of equilateral triangle \(S_{ABC}\), in terms of point \(O\) located within it, is equal to the total of the three internal triangles:

\[
S_{ABC} = S_{AOB} + S_{BOC} + S_{COA},
\]

where:

\[
\begin{align*}
S_{AOB}^2 &= \frac{2N_A^2 N_B^2 + 2N_A^2 L^2 + 2N_B^2 L^2 - N_A^4 - N_B^4 - L^4}{16}, \\
S_{BOC}^2 &= \frac{2N_B^2 N_C^2 + 2N_B^2 L^2 + 2N_C^2 L^2 - N_B^4 - N_C^4 - L^4}{16}, \\
S_{COA}^2 &= \frac{2N_C^2 N_A^2 + 2N_C^2 L^2 + 2N_A^2 L^2 - N_C^4 - N_A^4 - L^4}{16}, \\
S_{ABC} &= \sqrt{3L^2 / 4}.
\end{align*}
\]

In case of damage of one or several cells, \(S_{ABC}\) becomes less than the initial one, and solution is possible if \(L_{\text{min}} \leq L \leq L_{\text{max}}\), where:

\[
\begin{align*}
N_{\text{max}} &= \max(N_A, N_B, N_C), \\
L_{\text{min}} &= \min\left( N_{\text{max}} \left| N_A - N_B \right|, \left| N_B - N_C \right|, \left| N_C - N_A \right| \right), \\
L_{\text{max}} &= \min\left( \sqrt{3} N_{\text{max}}, N_A + N_B + N_C, N_A + N_C \right).
\end{align*}
\]
Consequently, while reducing (with some step) \( L \) from \( L_{\text{max}} \) to \( L_{\text{min}} \), it is possible to find a value meeting condition (4). Such calculation is over, if:

\[
S_{\text{ABC}} - S_{\text{AOB}} - S_{\text{BOC}} - S_{\text{COA}} = 0.
\]

Further, use a cosine theorem to determine angles:

\[
\alpha = \arccos \frac{N_A^2 + N_B^2 - L^2}{2N_A N_B}, \quad \beta = \arccos \frac{N_B^2 + N_C^2 - L^2}{2N_B N_C}, \quad \gamma = \arccos \frac{N_C^2 + N_A^2 - L^2}{2N_C N_A}.
\]

Below, Table 1 represents several solutions for 3-7-level inverters. The table shows the amount of undamaged cells \( N_A, N_B, N_C \), corresponding angles \( \alpha, \beta, \gamma \), value of linear voltage \( L \) and ratio \( L \) to \( L_n \), and ratio \( L_o / L_n \) during the balancing by preserving similar number of cells in each phase. Rows in bold correspond to the standard operating mode. The table data may be entered in the controller database which helps simplify considerably the software.

| \( N_a \) | \( N_B \) | \( N_C \) | \( \alpha \) | \( \beta \) | \( \gamma \) | \( L \) | \( L/L_n \) | \( L_o/L_n \) |
|---|---|---|---|---|---|---|---|---|
| 7 | 7 | 7 | 120.0 | 120.0 | 120.0 | 12.1 | 1.00 | 1.00 |
| 7 | 6 | 6 | 110.8 | 124.6 | 124.6 | 11.5 | 0.95 | 0.86 |
| 7 | 6 | 5 | 114.3 | 131.4 | 114.3 | 10.9 | 0.90 | 0.86 |
| 7 | 6 | 5 | 104.4 | 138.5 | 117.1 | 10.2 | 0.85 | 0.71 |
| 7 | 5 | 5 | 105.6 | 148.9 | 105.6 | 9.63 | 0.79 | 0.71 |
| 7 | 5 | 4 | 94.0 | 161.5 | 104.4 | 8.88 | 0.73 | 0.57 |
| 7 | 4 | 4 | 89.0 | 182.1 | 89.0 | 8.00 | 0.66 | 0.57 |
| 6 | 6 | 6 | 120.0 | 120.0 | 120.0 | 10.3 | 1.00 | 1.00 |
| 6 | 6 | 5 | 109.2 | 125.4 | 125.4 | 9.78 | 0.94 | 0.83 |
| 6 | 5 | 5 | 113.1 | 133.7 | 113.1 | 9.20 | 0.88 | 0.83 |
| 6 | 5 | 4 | 101.4 | 142.8 | 115.8 | 8.54 | 0.82 | 0.67 |
| 6 | 4 | 4 | 101.4 | 157.2 | 101.4 | 7.84 | 0.75 | 0.67 |
| 6 | 4 | 3 | 86.4 | 177.3 | 96.3 | 7.00 | 0.67 | 0.50 |
| 5 | 5 | 5 | 120.0 | 120.0 | 120.0 | 8.66 | 1.00 | 1.00 |
| 5 | 5 | 4 | 107.2 | 126.4 | 126.4 | 8.05 | 0.93 | 0.80 |
| 5 | 4 | 4 | 111.3 | 137.4 | 111.3 | 7.45 | 0.86 | 0.80 |
| 5 | 4 | 3 | 96.9 | 150.0 | 113.1 | 6.77 | 0.78 | 0.60 |
| 5 | 3 | 3 | 93.6 | 172.9 | 93.6 | 5.99 | 0.69 | 0.60 |
| 4 | 4 | 4 | 120.0 | 120.0 | 120.0 | 6.93 | 1.00 | 1.00 |
| 4 | 4 | 3 | 104.0 | 128.0 | 128.0 | 6.31 | 0.91 | 0.75 |
| 4 | 3 | 3 | 108.2 | 143.6 | 108.2 | 5.70 | 0.82 | 0.75 |
| 4 | 3 | 2 | 89.0 | 164.5 | 106.6 | 4.96 | 0.72 | 0.50 |
| 3 | 3 | 3 | 120.0 | 120.0 | 120.0 | 5.20 | 1.00 | 1.00 |
| 3 | 3 | 2 | 98.9 | 130.5 | 130.5 | 4.56 | 0.88 | 0.67 |
| 3 | 2 | 2 | 101.4 | 157.2 | 101.4 | 3.92 | 0.75 | 0.67 |
It is clear that in all cases correction of zero-point position and phase voltage directions helps obtain better result. For instance, Figure 3 shows vectors of phase and linear voltages for a case when one and two cells break down in phases B and C respectively in a 5-level inverter.

Blue color is for the vectors in standard operation mode; dashed line is for standard solution in that situation (three cells are preserved in all the phases). It is obvious that use of the calculation results from Table 1 (red lines with black highlights) makes it possible to reduce almost by half the drop of linear voltages.

![Figure 3. Vectors of linear and phase voltages in a 5-level inverter.](image)

Next stage involves application of those results while controlling the inverter. It is required to complete several operations in the system of control at the moment of emergency diagnosis.

First, change the phase shift by the difference between the position of vector of the corresponding phase in standard and emergency modes not interrupting the calculation of the turning angle of the field vector. Here we can address to the classic geometry to help us. Assuming that in terms of standard operation, vector of phase A is located vertically, we obtain new positions of vectors $\alpha_0, \beta_0, \gamma_0$:

$$\alpha_0 = \frac{\pi}{2} + \arcsin \left( \frac{N \sqrt{B}}{L} \sin(\alpha) \right), \quad \beta_0 = \alpha_0 + \alpha, \quad \gamma_0 = \beta_0 + \beta. \quad (9)$$

Secondly, multiply the generated sinusoidal signals in each phase by value $\frac{L}{L}$ which will help preserve linear voltage without any changes during the low and medium speed operation.

Sequence of those operations is represented by the model fragment in MATLAB / SIMULINK shown in Figure 4. Further, in terms of the system generating control signals of transistors in the phases with damaged cells, preserve and correlate the shifts of the number of the comparison triangular signals being similar to the number of the undamaged cells left; multiply the amplitudes of sinusoidal signals by the number of undamaged cells.

It is important to note that the proposed algorithm does not exclude the possibility of applying Space Vector Pulse Width Modulation. However, if linear voltage increases by 16% in terms of standard operation, the efficiency will decrease slightly in the emergency modes. The cause is in the fact that if the operation is standard, then the 3rd harmonic with relative amplitudes of 1/6, which is added to the phase voltages, forms symmetric curves with the saddle-like peak [17–19].

When cells are damaged, shifts of phases of the first harmonics “deform” the peaks. Thus, having calculated preliminarily one of the periods of phase voltages, it is necessary to define such a boundary admissible value of the main harmonic so that the amplitude of sum signal will not exceed $N_A, N_B, N_C$ [20–22]. It is important that in terms of the 3rd harmonic, optimal shift will be the one of the undamaged phase in the standard operation mode. Then, linear voltages may be increased by 2…10 % [23].
Figure 4. Model of electric drive “Frequency converter – asynchronous machine with ventilating load” with the correction system.

The results of the system operation are represented in Figure 5 (in the context of reduced frequency of the generated voltage) and Figure 6 (at nominal frequency) while using the following law: \( U/f = \text{const} \).

It is seen that in case of underfrequency, changes in an inverter do not affect the motor operation; in terms of nominal frequency, moment fluctuations experience the minimal possible amplitude owing to both minimized voltage changes and preservation of the spatial position of the linear voltage vectors.

Figure 5. Transients at 39 Hz: a) phase and linear voltages; b) signals of SVPWM; c) stator currents, speed, and torque; d) phase voltages.
Figure 6. Transients at 60 Hz: a) phase and linear voltages; b) signals of SVPWM; c) stator currents, speed, and torque; d) phase voltages.

4. Conclusions
The paper proposes a method to control multilevel cascaded H-bridge converter in case of damage of one or several cells in different phases. The method provides minimization of shock loads in terms of transitions from the standard to emergency operating modes owing to such shift of zero point and turning of phase voltages, at which amplitude of linear voltages decreases by the minimal possible value and spatial position of the linear voltage vectors remains the same. Fast algorithm to calculate turning points of the phase voltages is proposed; the algorithm may be applied in the industrial microprocessor control systems. Algorithm of the operations, which provides implementation of the method, is described. It is demonstrated that in terms of nominal frequency, application of the method provides shock load minimization; in case of low and medium frequencies, damage of cells may not affect the motor operation (under conditions of fast reaction and disconnection of the damaged cells). Conditions of the application of Space Vector Pulse Width Modulation in the emergency modes have been identified which help increase considerably the operating efficiency of the frequency converters.

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References
[1] Glazeva O V 2018 The use of high-voltage frequency converters as a method of increasing the energy efficiency index at the marine industry Materials of the scientific-methodical conference “Ship engineering, electronics and automation” pp 70–78
[2] Urbaniak M, Kardas-Cinal E and Jacyna M 2019 Optimization of Energetic Train Cooperation Symmetry 11 9 1175 https://doi.org/10.3390/sym11091175
[3] 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
[4] Malinowski M, Gopakumar K, Rodriguez J and Pérez M A 2010 A Survey on Cascaded Multilevel Inverters *IEEE Transactions on Industrial Electronics* **57** 7 pp 2197–2206

[5] 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

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

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

[8] Kolpakov A 2009 Multilevel Converter Control Algorithms *Silovaya Elektron.* **2** pp 57–65

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

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

[11] Busher V V 2020 Research of high-voltage frequency converters in ship electric power systems 9th Conference on Ships’ Electrical Engineering, Electronics and Automation NU «OMA» Publ pp 231–237

[12] 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

[13] Rudyk T, Szczepański E, Jacyna M 2019 Safety factor in the sustainable fleet management model. *Archives of Transport* **49** 1 pp 103–114

[14] 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

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

[16] 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

[17] Kuznetsov V, Tryputen N and Kuznetsova Y 2019 Evaluating the effect of electric power quality upon the efficiency of electric power consumption *IEEE 2nd Ukraine Conference on Electrical and Computer Engineering* pp 556–561

[18] Dymerets A V, Yershov R D, Gorodny A N, Denisov Y O, Boiko S, Kuznetsov V 2020 Dynamic Characteristics of Zero-Current-Switching Quasi-Resonant Buck Converter under Variation of Resonant Circuit and Load Parameters *IEEE 40th International Conference on Electronics and Nanotechnology* pp 848–853

[19] Denisov Y, Gordienko V, Gorodny A, Stepenko S, Yershov R, Prokhorova A, Kostyrieva O 2016 Power losses in MOSFET switch of quasi-resonant pulse converter with series resonant circuit 2nd International Conference on Intelligent Energy and Power Systems pp 1–6

[20] Kuzenkov O, Kuznetsov V, Tryputen N 2019 Analysis of phase trajectories of the third-order dynamic objects *IEEE 2nd Ukraine Conference on Electrical and Computer Engineering* pp 1235–1243

[21] 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

[22] Kuznetsova Y, Kuznetsov V, Tryputen M, Kuznetsova A, Tryputen M and Babyak M 2019 Development and Verification of Dynamic Electromagnetic Model of Asynchronous Motor Operating in Terms of Poor-Quality Electric Power *Proceedings of the International Conference on Modern Electrical and Energy Systems* pp 350–353

[23] Perekrest A, Chornyi O, Mur O, Nikolenko A, Kuznetsov V, Kuznetsova Y 2018 Preparation and preliminary analysis of data on energy consumption by municipal buildings *Eastern-European Journal of Enterprise Technologies* **6** 8 96 pp 32–42