

STUDYING A VOLTAGE STABILIZATION ALGORITHM IN THE CELLS OF A MODULAR SIX-LEVEL INVERTER

O. Plakhtii

PhD, Electronic Engineer*

E-mail: a.plakhtiy1989@gmail.com

V. Nerubatskyi

PhD, Associate Professor**

E-mail: NVP9@i.ua

N. Karpenko

PhD, Associate Professor**

E-mail: kanape1909@gmail.com

O. Ananieva

Doctor of Technical Sciences, Associate Professor

Department of Automation and

Computer Telecontrol Train Traffic***

E-mail: romashka13052015@gmail.com

H. Khoruzhevskyi

Constructor Engineer*

E-mail: khoruzhevskyi@gmail.com

V. Kavun

Postgraduate Student**

E-mail: vitaliykavun2014@gmail.com

*LLC «VO OVEN»

Hvardiytsiv-Shyronivtsiv str., 3A,

Kharkiv, Ukraine, 61153

Department of Electric Power Engineering, Electrical Engineering and Electromechanics*

***Ukrainian State University of Railway Transport Feierbakha sq., 7, Kharkiv, Ukraine, 61050

Багаторівневі автономні перетворювачі напруги знаходять все більш широке застосування у промисловості, а саме: у вітровій та сонячній енергетиці, високовольтних підстанціях, у промислових та тягових електроприводах. Багаторівневі інвертори у порівнянні з дворівневими інверторами мають ряд значних переваг, а саме, більша вихідна потужність, більше значення ККД, менший вміст вищих гармонік у навантаженні та мережі живлення. Зменшення вмісту вищих гармонік вихідного струму багаторівневого інвертора безпосередньо знижує додаткові втрати в навантаженні та підвищує загальне значення ККД.

Проведене дослідження шестирівневого модульного інвертора показало, що алгоритм просторово-векторної модуляції викликає дисбаланс напруги на конденсаторах комірок. При цьому напруга на половині комірок прямує до нуля, а на іншій половині комірок збільшується вдвоє, що призводить до значного спотворення вихідної напруги. Представлено причини цієї нестабільності, а також вдосконалений просторово-векторний алгоритм модуляції багаторівневого перетворювача, що дозволяє стабілізувати напругу в комірках.

Запропоновано алгоритм стабілізації напруги на комірках модульного багаторівневого інвертора. Стабілізація напруги досягається гістерезисним регулюванням з почерговим переходом просторово-векторної широтно-імпульсної модуляції та інверсної векторної системи керування за умови відхилення напруги на комірці вище або нижче заданого допустимого рівня.

У програмі Matlab 2017b проведено імітаційне моделювання шестирівневого інвертора напруги, що підтверджує ефективність запропонованого алгоритму модуляції

Ключові слова: модульний багаторівневий інвертор, перетворювач, просторово-векторний алгоритм модуляції, широтно-імпульсна модуляція

Received date 30.09.2019

Accepted date 26.11.2019

Published date 23.12.2019

This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0>)

1. Introduction

In recent years, powerful semiconductor converters of the new type in industry have been widely used in industry – modular multilevel converters [1, 2].

The modular multi-level inverter (MMI) has the following advantages compared to other inverters:

- the possibility of using power circuit breakers of lower classes in high-voltage converters, including switches based on gallium nitride (GaN) and silicon carbide (SiC) [3];
- the capability of switches operation at lower switching frequencies compared to classical multilevel voltage converters;
- structural modularity and scalability;
- the improved reliability of the inverter as MMI can function even in case when individual modules fail;

– the enhanced efficiency due to an increase in the number of levels (modules) of MMI and a reduction in the frequency of key switching;

- significant reduction in higher harmonics that makes it possible to use filters with smaller mass dimensions;
- MMI makes it possible to combine asynchronous power grids without increasing a short-circuit power.

The first high-voltage DC line with modular multilevel inverters that connected the cities of Pittsburgh and San Francisco in California, USA, in 2010, was designed and implemented by Siemens [4]. The line has a capacity of 400 MV·A at voltage ± 200 kV. Paper [5] describes other implemented projects in Europe and China that involved MMI.

In general, modular multilevel inverters are a promising topology, which has already been widely used in

the high-voltage DC systems produced by SIEMENS and ABB [6]. It is also promising to apply MMI in high-voltage electric drives [7].

Fig. 1 shows the circuit of a three-phase six-level modular multi-level inverter. The three-phase frequency transducer (rectifier, direct current circuit, inverter) was constructed based on a modular topology. The alignment reactor L_A is included in each link of the circuit.

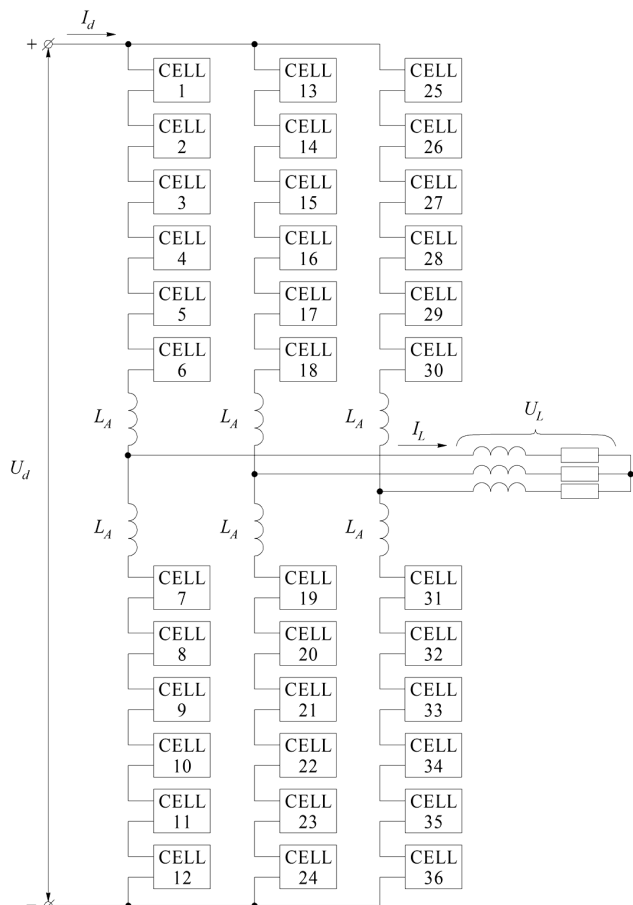


Fig. 1. Three-phase six-level modular inverter

The possibility to implement a large number of levels ensures high sinusoidal output voltage, which also ensures a reduction of power losses due to higher harmonics [8].

Cells can be built based both on a half-bridge scheme (Fig. 2, a) and the full-bridge one (Fig. 2, b) [9, 10].

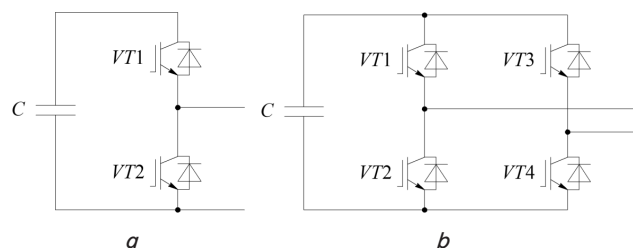


Fig. 2. Topology of MMI cells:
a – semi-bridge cell; b – full-bridge cell

Each scheme of the link has its advantages and disadvantages. The full-bridge scheme is more expensive but it makes it possible to better control and stabilize voltage on the cells.

The half-bridge scheme is cheaper but voltage stabilization in cells is more difficult [11, 12].

Along with a series of advantages, modular multilevel inverters have a disadvantage, which is the need to stabilize voltage in individual cells of the transducer, which predetermines the relevance of our work.

2. Literature review and problem statement

Control systems for modular multilevel inverters are a very important component, since they strongly affect quality indicators of electricity and power losses. Existing control systems based on the pulse-width and space-vector modulation in MMI have a series of drawbacks. Thus, existing modulation algorithms predetermine deterioration in electric energy quality indicators and the need to use a voltage stabilization algorithm on capacitor cells [13].

Paper [14] stated that in a modular five-level inverter, when using a space-vector PWM, the disbalance of voltages on capacitor cells amounts to 25...40 %. This causes deterioration in the quality of output voltage at which the coefficient of harmonic distortions worsens from 9 % (without imbalance) to 32 % (under a disbalance mode).

The results from studying voltage instability on the capacitor cells in multi-level modular inverters with a control system based on a sinusoidal pulse width modulation (SPWM) are reported in article [15]. It is shown that in the absence of a voltage stabilization algorithm there would be a disbalance in the control system, at which every 0.05 seconds voltage on the cells would deviate by $\approx 10\%$.

Work [16] demonstrated that SPWM makes it possible to implement the amplitude control of the first harmonic of output current, which is necessary in the scalar and vector control in an asynchronous electric drive [17, 18]. The disadvantages of SPWM were defined, specifically the high frequency of power keys switching, which leads to heating the semiconductor elements, to an increase in dynamic losses and, consequently, to a decrease in efficiency of the inverter with respect to space-vector PWM by 3...4 % [19]. In addition, studies [15, 17, 19] do not present the results of the MMI operation in the long-term mode and do not define the effect of a PWM algorithm on voltage stability on the MMI capacitors.

Papers [20, 21] reported studies in the operation of modular multilevel inverters with other topologies with a space-vector pulse width modulation (SVPWM), which confirmed the instability of the output voltage. However, the disadvantage of the cited publications, as well as papers [22, 23], is a lack of the description of a voltage stabilization algorithm on the capacitors of MMI cells.

The scientific literature describes different voltage stabilization algorithms on MMI cells, but they have different disadvantages. Thus, in a system given in [24] there is a need to use a phase auto-adjustment of frequency, synthesis of transmission functions of regulators. A stabilization algorithm outlined in [25] implies solving differential equations associated with a space-vector conversion of the $abc-dq$ coordinates in real time. Study [26] reports a stabilization algorithm, whose disadvantage is the impossibility to stabilize voltage at spatial-vector modulation. Such stabilization algorithms considerably complicate the control system for a modular multilevel inverter and make it more expensive. Paper [27] gives a stabilization algorithm that operates on the principle of sorting

and selecting cells with the least voltage. The disadvantage of this algorithm is a significant number of iterative computing and a large number of feedbacks equal to number of cells in the converter, which can reach more than 600 units.

Thus, there is a task to construct a method for stabilizing the voltage with a reduced number of mathematical calculations, with a reduced number of feedbacks and a capability to work with space-vector control systems.

3. The aim and objectives of the study

The aim of this work is to study patterns in the operation of a voltage stabilization algorithm on capacitor cells in modular multilevel converters, which would eliminate the shortcomings of algorithms reported in [26, 27].

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

- to analyze and define the causes of voltage instability on MMI cells under a classical SVPWM;
- to examine the proposed algorithm for voltage stabilization on the cells of a modular multilevel inverter;
- to confirm operational capabilities of the proposed algorithm by simulating the six-level MMI in the MATLAB 2017b software.

4. Modulation algorithms in modular multilevel inverters

Similarly to classic multilevel autonomous voltage inverters with locking diodes, MMI-converters can operate both under a mode of sinusoidal width-pulse modulation and under a space-vector modulation mode [28, 29].

The space-vector modulation mode provides for a series of advantages, such as high power, lower switching frequency of power switches, which results in the improved efficiency [30, 31].

Each phase of the six-level MMI converter consists of twelve cells. At the same time, it is possible to implement six different potentials of output voltage in each phase. In this case, each switching state of transistors, which triggers its output potential in a phase, is called a vector [32, 33].

The principle of forming a sinusoidal flat-shifted pulse-width modulation is shown in Fig. 3 [34, 35].

Switching states of power keys that underlie vectors in a classic space-vector modulation are shown in Fig. 4, where green color denotes the enabled status of the cell, that is, enabling the transistor VT_1 [36].

The switching states of key control under a space-vector width-pulse modulation (SVPWM) in three phases are shown in Fig. 5. The period of output voltage (one circle of a single space vector) consists of 36 temporary intervals, each of which is determined by the state of one of the three vectors, which determine the numbers of the enabled transistors [37, 38].

An analysis of output voltage formation intervals, which consists of 36 time intervals, has revealed that cell No. 1 includes 9 intervals, and cell No. 4 includes 15 intervals. Uneven loading of the MMI converter cells leads to that

voltage on certain cells grows more relative to the rated one, and on other cells voltage drops below the rated one and decreases over time to zero, which is confirmed by an imitation simulation.

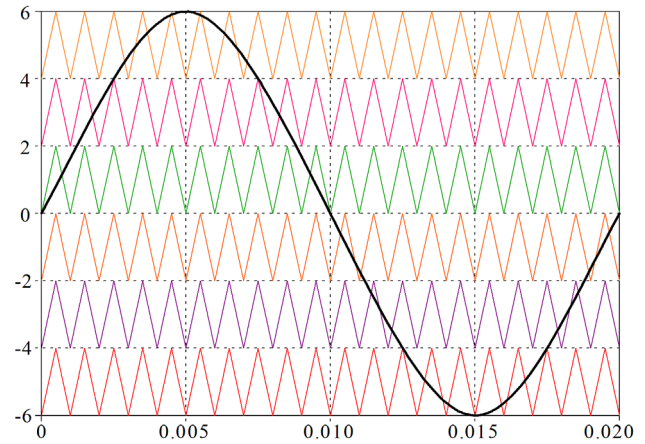


Fig. 3. Sinusoidal PWM for a six-level inverter

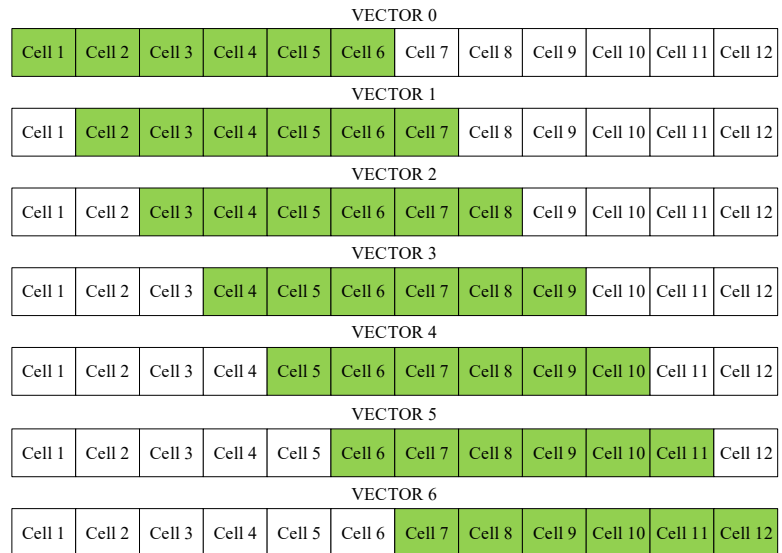


Fig. 4. Switching states of power keys of the six-level inverter cells

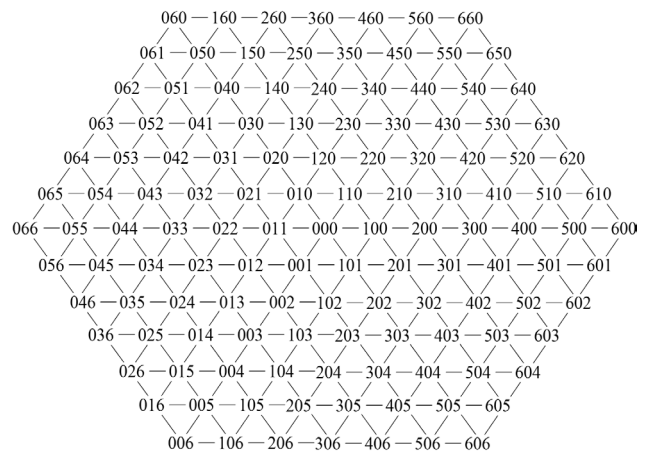


Fig. 5. Switching states of power keys in space-vector modulation

5. Simulating a modular multi-level inverter

We have designed a model of the modular multi-level inverter in the simulation environment MATLAB/SIMULINK. The MMI converter cells are constructed in line with a half-bridge topology. Simulation model parameters are given in Table 1.

Simulation was conducted under condition that at the start time all the capacitors of MMI converter cells are charged to the voltage of 2 kV.

The developed simulation model of a modular six-level inverter is shown in Fig. 6.

Table 1

Simulation model parameters

Parameter	Value
Voltage in a DC circuit, kV	8
MMI cell capacitor capacity, mF	1
Voltage on MMI cell capacitor, kV	2
Active load resistance, Ohm	20
Inductive load resistance, mH	0.1

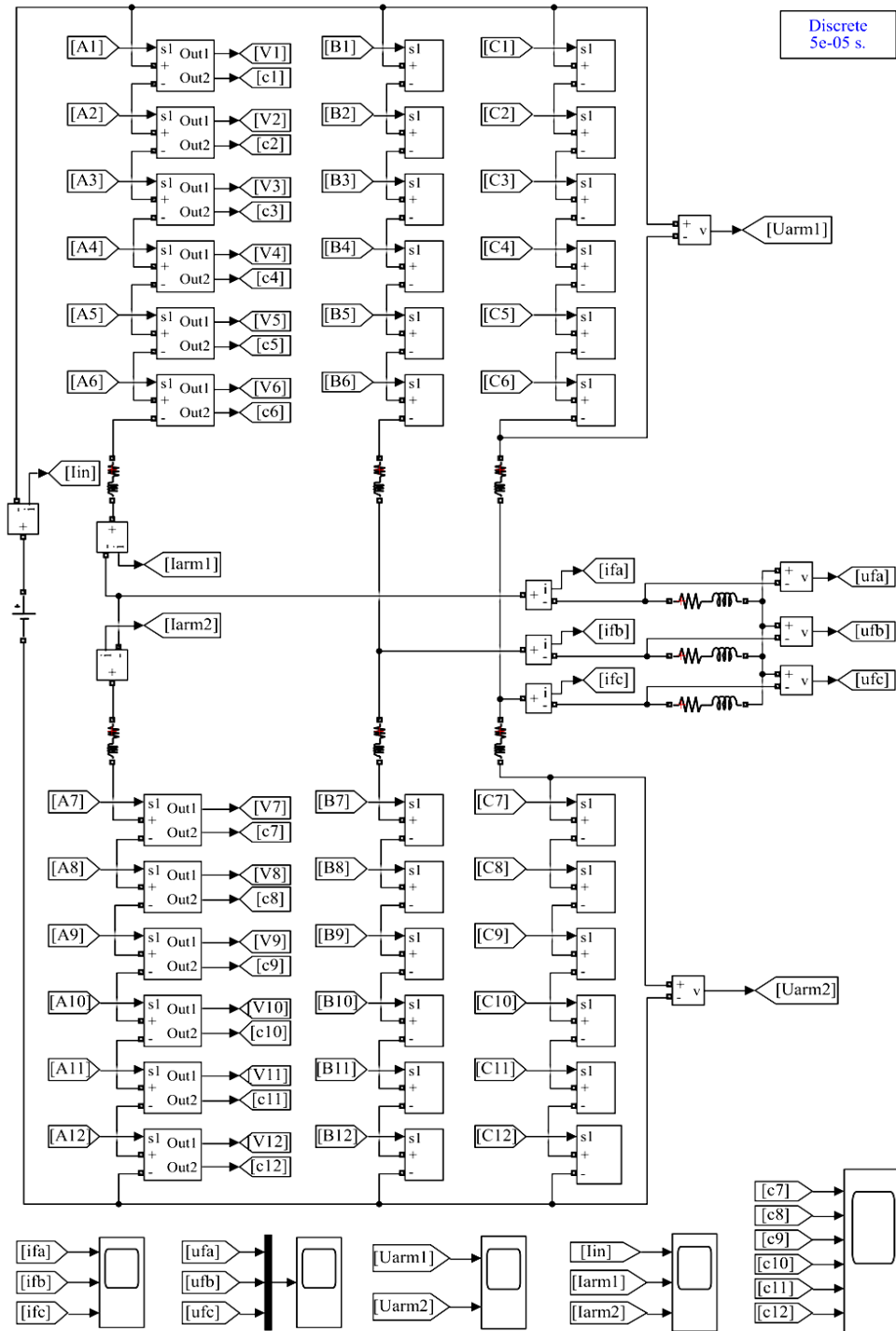


Fig. 6. Simulation model of a modular six-level inverter

Results from simulating the MMI operation, specifically voltage on cells 1, 2, 3, 4, 5, 6 under a mode of classic space-vector modulation are shown in Fig. 7.

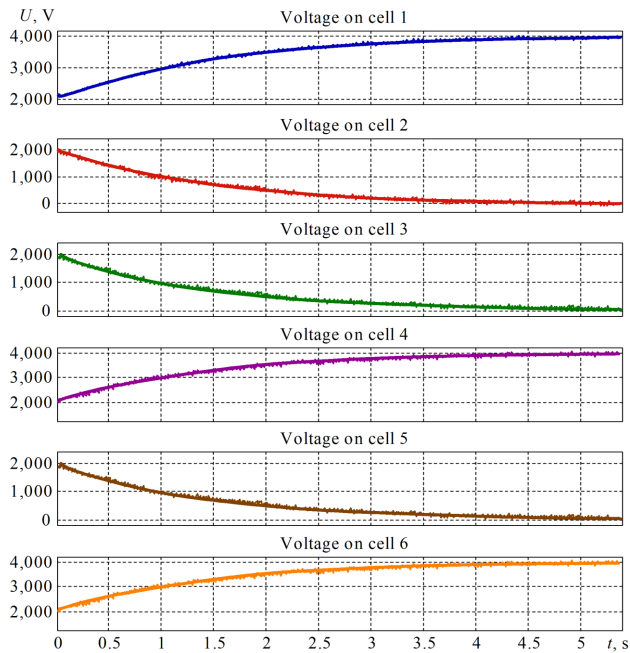


Fig. 7. Voltage on capacitors 1, 2, 3, 4, 5, 6 of MMI cells in the implementation of the algorithm of classic space-vector modulation

It was established during the simulation that at the specified parameters for the circuit voltage on cells 2, 3, 5 in the transducer operation was dropping over 5 seconds to zero, while voltage on cells 1, 4, 6 doubles (from 2 kV to 4 kV). Voltage on the cells of other phases perform similarly.

The voltage drop on the capacitors of half the cells of the MMI-converter leads to the reduction of steps in the formation of output voltage, which leads to deterioration of the sinusoidal operation of the output voltage, since half of the cells does not work in this case.

The shape of output voltage in the MMI phase, as well as its Fourier-analysis at the initial moment of transducer operation and after 5 seconds of its work, are shown in Fig. 8.

Fig. 8 shows that the shape of MMI output voltage over the time of a voltage drop on the capacitors of cells is significantly deteriorating. This is due to a decrease in the number of levels in the output voltage formation, and consequently leads to significant deterioration of the sinusoidal output voltage (Fig. 8, *b*). This leads to an increase in the content of higher harmonics and additional power losses associated with them [39]. A similar phenomenon occurs at a sinusoidal PWM [40].

Thus, it was established that the classic SVPWM pre-determines the voltage instability on the cells of a MMI converter and causes a significant deterioration in the quality of output voltage.

6. A space-vector modulation algorithm with voltage balancing function on MMI cells

The improved algorithm of SVPWM has been proposed, which ensures the balancing of voltage on the MMI cells. Due to the fact that MMI is based on the principle of a controlled capacitive voltage divider, then, to form the required potential of output voltage in the phase, of importance is the ratio of enabled cells in the upper and lower shoulders. That is, the following combination of enabled and disabled keys will form the same output voltage potential.

As shown by simulation of the classic PWM algorithm, voltage on cells 1, 4, 6 increases, while voltage on cells 2, 3, 5 decreases to zero. Thus, if all vectors replace the switching states in the pairs of registers 1–2, 3–4, 5–6, 7–8, 9–10, 11–12 then a given algorithm implements the reverse dynamics of voltage on the MMI cells. The space vectors system, which triggers the reverse dynamics of voltage on the MMI cells, is shown in Fig. 9.

The simulation results of a six-level inverter in the implementation of the timeline, which includes the inverse vectors, are shown in Fig. 10.

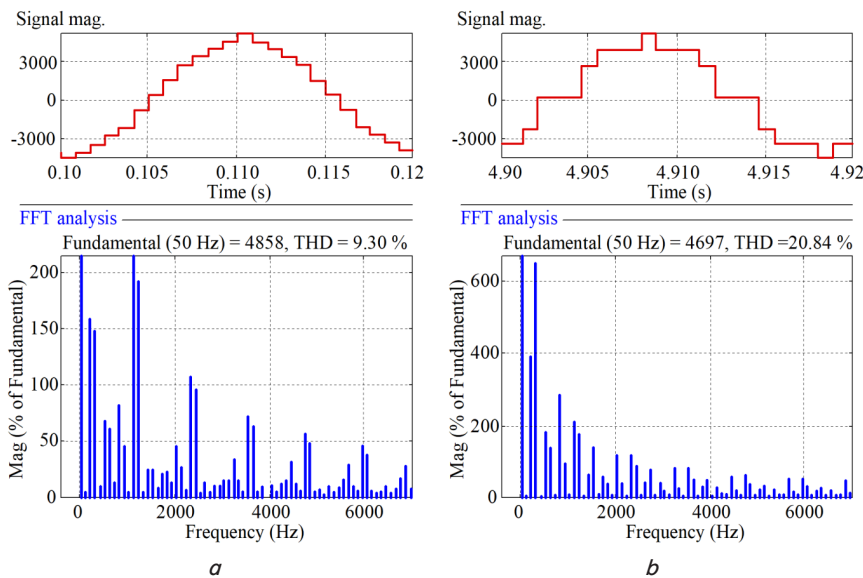


Fig. 8. The shape of output voltage in MMI converter and its Fourier-analysis when using a classic space vector PWM: *a* – at the initial time of MMI operation; *b* – 5 s into the scheme’s operation

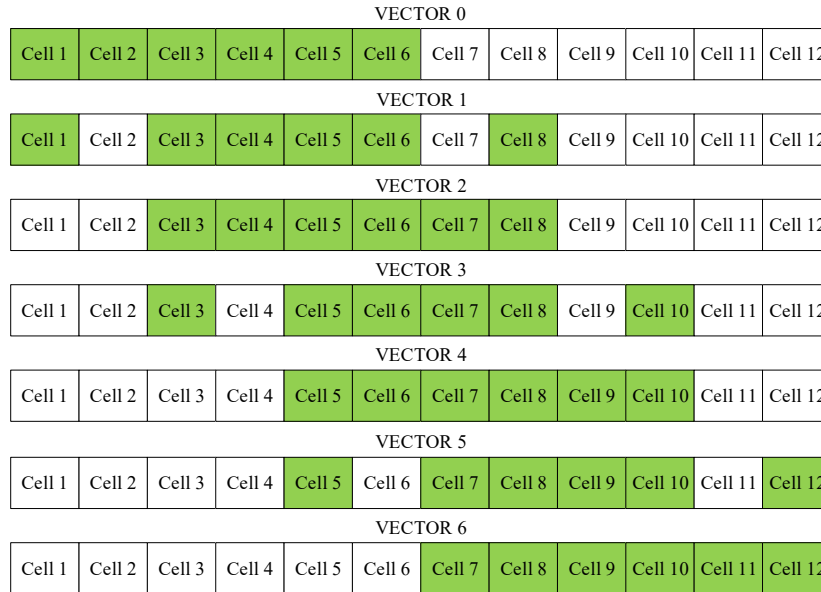


Fig. 9. Switching states of MMI cells, defining the inverse vectors 0, 1, 2, 3, 4, which cause the inversion of growth/descent of voltage on cells

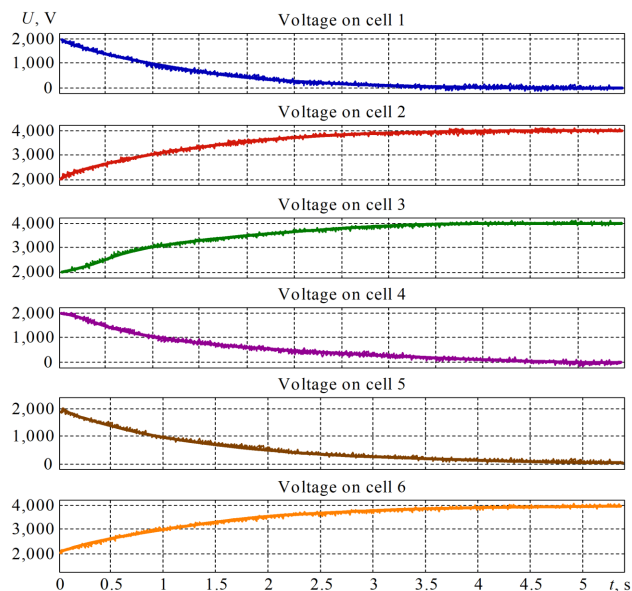


Fig. 10. Voltage on capacitors 1, 2, 3, 4, 5, 6 of MMI cells in the implementation of a space-vector modulation algorithm

As is evident from the simulation results, the replacement in the vectors of values for pairs of cells 1–2, 3–4, 5–6, 7–8, 9–10, 11–12 resulted in the inverse dynamics of the voltage change on the MMI cells.

Alternate switching of modulation algorithms leads, accordingly, to the growth and decrease in voltage on the MMI cells. As a result, it turns out that the voltage on the cells of MMI capacitor is stabilized (Fig. 11).

Thus, it is possible to set the control over hysteresis on the voltage of MMI cells at reaching the threshold level of voltage deviation in a cell relative to the predefined value.

The principle of voltage stabilization on the MMI cells by switching the switching tables was confirmed by the simulation results. In this case, the permissible threshold of deviation on a cell is set at $2,000 \pm 150$ V.

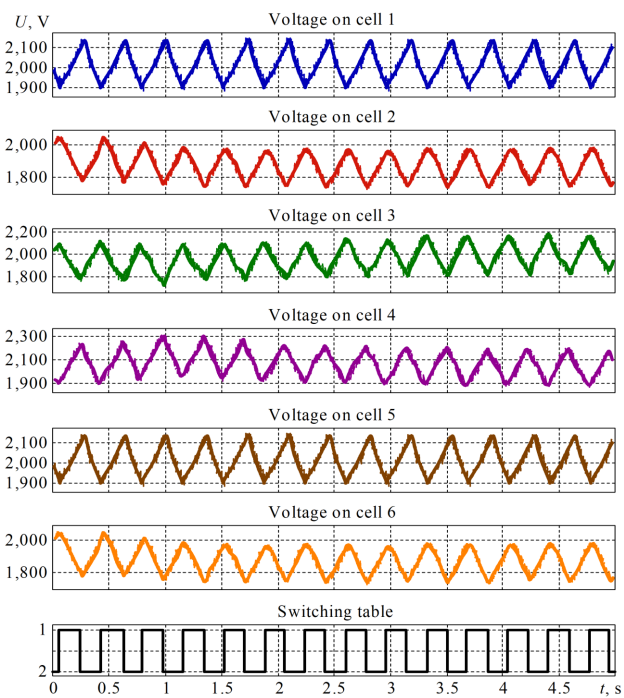


Fig. 11. MMI cell voltage after balancing by alternately switching while setting the permissible deviation ± 150 V

Fig. 11 shows that voltage on the MMI elements does not deviate from the predefined value. In the course of subsequent modeling it was found that even after 60 s of MMI operation voltage on the cells does not deviate above the permissible value. Thus, when assigning a rather low permissible voltage deviation on MMI cells, it becomes possible to ensure almost the absence of significant voltage deviations (Fig. 12).

The simulation results demonstrated that the use of the proposed voltage stabilization algorithm on MMI cells by balancing makes it possible to achieve, at the predefined simulation parameters, a voltage deviation of ± 50 V, which

predetermines a pulsation coefficient of 5%. Further lowering of pulsations could be achieved by increasing the capacity of the cells.

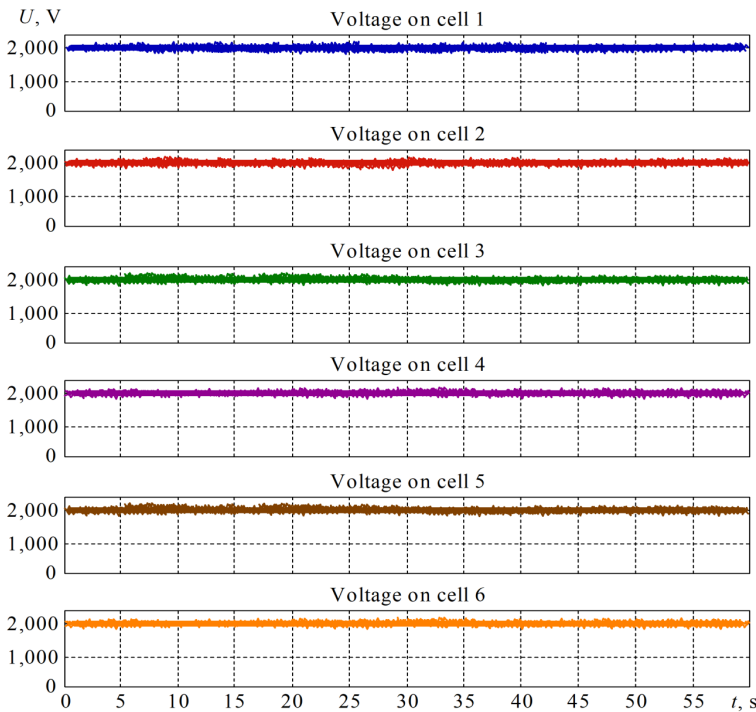


Fig. 12. MMI cell voltage after applying the new balancing algorithm

The shape of output voltage in a modular six-level inverter after 50 seconds of its operation in the implementation of the proposed control algorithm with an alternate switching of switching tables is shown in Fig. 13.

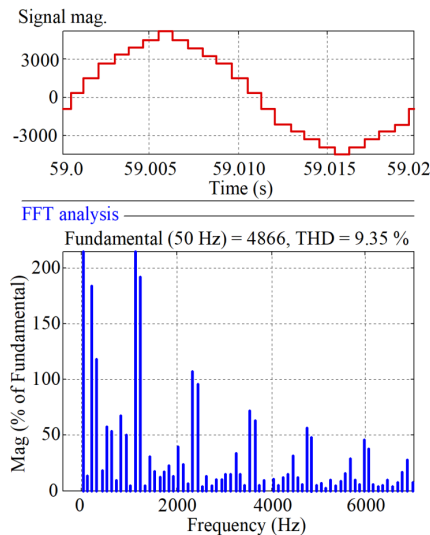


Fig. 13. The shape and harmonic analysis of output voltage of a six-level inverter in the implementation of the proposed control approach

As one can see from Fig. 11–13, the proposed algorithm ensures the stability of voltage on the cells of a MMI converter and does not cause any deterioration in the output voltage shape over time.

7. Discussing the results of studying the proposed control system

This paper reports results of our examination of the improved space-vector modulation algorithm for a modular multilevel converter (Fig. 1), which makes it possible to stabilize voltage on cells (Fig. 4–9).

The obtained results, specifically, the stabilization of voltage on the MMI cells, are achieved by means of an alternating transition from the SVPWM system involving classic vectors to the system with inverse vectors (Fig. 11). The effect of stabilization is explained the fact that the proposed mode employs the inverse vectors system, which makes it possible to change the voltage dynamics on the MMI capacitors (Fig. 9).

Special feature of this study is that in order to confirm the effect of voltage stabilization by applying the proposed modulation algorithm we performed simulation of electromagnetic processes in a three-phase modular inverter in the MATLAB/Simulink environment (Fig. 6–8, 10–13).

The limitation of this work is that the designed simulation model works adequately only under the rated modes, while emergency regimes, under which the voltage values exceed the rated values, would be inadequately reflected by the model.

The disadvantages of the study are the lack of descriptions of an automatic adjustment system for a modular multi-level inverter.

The developed algorithm for stabilizing the voltage on MMI cells is recommended for practical use in engineering projects. In this case, a practical advantage of the proposed stabilization algorithm over known algorithms [24–27] is the possibility to simplify the control system, that is, it would need a smaller number of mathematical calculations (microprocessor could be simplified and be less expensive) and a smaller number of feedbacks (fewer analog-to-digital converters). Thus, this would lead to a much lower cost of the transducer. The quality of the output voltage does not deteriorate in this case (Fig. 8, a, Fig. 13).

Scientific novelty of our research relates to that the new method (new approach) of voltage stabilization on capacitor cells in modular multi-level converters has been proposed, based on the creation of a space-vector modulation with the inverse vectors system. The advantage of the proposed method is fewer mathematical calculations and fewer feedbacks.

The further advancement of our research necessitates conducting an experimental study, which implies the development of prototype samples with microprocessor control systems.

8. Conclusions

1. It has been shown that the implementation of a classic space-vector PWM is accompanied by an unbalanced loading of MMI cells, which results in voltage disbalance on the capacitors of cells and, consequently, deterioration of output voltage quality.

2. We have proposed using inverse vectors, which implement the replacement of switching states in pairs of cells 1–2, 3–4, 5–6, 7–8, 9–10, 11–12. Application of inverse vectors causes the reverse dynamics of voltage change on the MMI cells. To stabilize voltage on the cells of MMI, an operation mode has been proposed, under which, over time, there is an alternate transition of operation from a SVPWM system with classic vectors to the

system with inverse vectors. The transition occurs under a condition of voltage deviation on a MMI cell above or below the specified permissible level.

3. To confirm operability of the proposed algorithm, a simulation model of a modular six-level inverter was developed in the MATLAB 2017b software. The constructed model has confirmed efficiency of the proposed voltage stabilization algorithm on MMI cells.

References

- Zhemerov, G. G., Krylov, D. S. (2018). Concept of construction of power circuits of a multilevel modular converter and its transistor modules. *Electrical Engineering & Electromechanics*, 6, 26–32. doi: <https://doi.org/10.20998/2074-272x.2018.6.03>
- Kumari, B., Sankar, M. (2014). Modeling and individual voltage balancing control of modular multilevel cascade converter. *International Journal of Emerging Engineering Research and Technology*, 2 (1), 42–48.
- Gevorkyan, E. S., Rucki, M., Kagramanyan, A. A., Nerubatskiy, V. P. (2019). Composite material for instrumental applications based on micro powder Al₂O₃ with additives nano-powder SiC. *International Journal of Refractory Metals and Hard Materials*, 82, 336–339. doi: <https://doi.org/10.1016/j.ijrmhm.2019.05.010>
- Bohra, A., Sajeesh, D., Patel, C., Saldanha, M. (2016). Modulation techniques in single phase PWM rectifier. *IJCA Proceedings on International Conference on Advances in Science and Technology*, 5–7.
- Deng, Y., Teo, K. H., Duan, C., Habetler, T. G., Harley, R. G. (2014). A Fast and Generalized Space Vector Modulation Scheme for Multilevel Inverters. *IEEE Transactions on Power Electronics*, 29 (10), 5204–5217. doi: <https://doi.org/10.1109/tpel.2013.2293734>
- Sonia, K., Seshadri, G. (2015). Analysis and modelling of a multilevel inverter in distribution system with FACTS capability. *International Journal of Innovative Research in Science, Engineering and Technology*, 4 (5), 3015–3021.
- Javier Arcega Solsona, F., Pardina Carrera, A. (2014). Study of harmonics thermal effect in conductors produced by skin effect. *IEEE Latin America Transactions*, 12 (8), 1488–1495. doi: <https://doi.org/10.1109/tla.2014.7014518>
- Scherback, Y. V., Plakhtiy, O. A., Nerubatskiy, V. P. (2017). Control characteristics of active four-quadrant converter in rectifier and recovery mode. *Tekhnichna Elektrodynamika*, 6, 26–31. doi: <https://doi.org/10.15407/techned2017.06.026>
- Shobini, M. M., Kamala, J., Rathna, R. (2017). Analysis and simulation of flying capacitor multilevel inverter using PDPWM strategy. 2017 International Conference on Innovative Mechanisms for Industry Applications (ICIMIA). doi: <https://doi.org/10.1109/icimia.2017.7975578>
- Kurwale, M. V., Sharma, P. G., Bacher, G. (2014). Performance analysis of modular multilevel converter (MMC) with continuous and discontinuous pulse width modulation (PWM). *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering*, 3 (2), 7463–7474. Available at: <https://pdfs.semanticscholar.org/d351/b7b2b80426065468fd-39c8d746f70fee1296.pdf>
- Oleksandr, P., Volodymyr, N. (2018). Analyses of Energy Efficiency of Interleaving in Active Voltage-Source Rectifier. 2018 IEEE 3rd International Conference on Intelligent Energy and Power Systems (IEPS). doi: <https://doi.org/10.1109/ieps.2018.8559514>
- Swamy, M., Guddanti, C. (2014). An improved single-phase active front end rectifier system for use with three-phase variable frequency drives. 2014 IEEE Applied Power Electronics Conference and Exposition - APEC 2014. doi: <https://doi.org/10.1109/apec.2014.6803514>
- Martinez-Rodrigo, F., Ramirez, D., Rey-Boue, A., de Pablo, S., Herrero-de Lucas, L. (2017). Modular Multilevel Converters: Control and Applications. *Energies*, 10 (11), 1709. doi: <https://doi.org/10.3390/en10111709>
- Deng, F., Chen, Z. (2015). Voltage-Balancing Method for Modular Multilevel Converters Switched at Grid Frequency. *IEEE Transactions on Industrial Electronics*, 62 (5), 2835–2847. doi: <https://doi.org/10.1109/tie.2014.2362881>
- Du, S., Dekka, A., Wu, B., Zargari, N. (2018). *Modular Multilevel Converters: Analysis, Control, and Applications*. Wiley-IEEE Press, 368. doi: <https://doi.org/10.1002/9781119367291>
- Shruti, K. K., Valsalan, T., Poorani, S. (2017). Single phase active front end rectifier system employed in three phase variable frequency drive. *International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering*, 121–129. Available at: <https://ijireeice.com/wp-content/uploads/2017/05/IJIREEICE-nCORETech-16.pdf>
- Sondur, V. V., Sondur, V. B., Rao, D. H., Latte, M. V., Ayachit, N. H. (2007). Issues in the Design of Equiripple FIR Higher Order Digital Differentiators using Weighted Least Squares Technique. 2007 IEEE International Conference on Signal Processing and Communications. doi: <https://doi.org/10.1109/icspc.2007.4728287>
- Ahmadzadeh, T., Sabahi, M., Babaei, E. (2017). Modified PWM control method for neutral point clamped multilevel inverters. 2017 14th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON). doi: <https://doi.org/10.1109/ecticon.2017.8096351>
- Gervasio, F., Mastromauro, R. A., Liserre, M. (2015). Power losses analysis of two-levels and three-levels PWM inverters handling reactive power. 2015 IEEE International Conference on Industrial Technology (ICIT). doi: <https://doi.org/10.1109/icit.2015.7125248>

20. Deng, Y., Wang, Y., Teo, K. H., Harley, R. G. (2016). A Simplified Space Vector Modulation Scheme for Multilevel Converters. *IEEE Transactions on Power Electronics*, 31 (3), 1873–1886. doi: <https://doi.org/10.1109/tpel.2015.2429595>
21. Chen, F., Qiao, W. (2016). A general space vector PWM scheme for multilevel inverters. 2016 IEEE Energy Conversion Congress and Exposition (ECCE). doi: <https://doi.org/10.1109/ecce.2016.7854687>
22. Colak, K., Asa, E., Czarkowski, D. (2016). A novel phase control of single switch active rectifier for inductive power transfer applications. 2016 IEEE Applied Power Electronics Conference and Exposition (APEC). doi: <https://doi.org/10.1109/apec.2016.7468107>
23. Wei, L., Jankovic, Z., Patel, Y. P., Hu, J. (2016). Single phase precharge control method for active front end rectifier. 2016 IEEE Energy Conversion Congress and Exposition (ECCE). doi: <https://doi.org/10.1109/ecce.2016.7855436>
24. Meshram, P. M., Borghate, V. B. (2012). A novel voltage balancing method applied to direct control strategy of MMC-HVDC system. *IEEE-International Conference On Advances In Engineering, Science And Management (ICAESM -2012)*, 448–452.
25. Bashir, S. B., Memon, Z. A. (2018). An Improved Voltage Balancing Method for Grid Connected PV System Based on MMC Under Different Irradiance Conditions. 2018 IEEE 61st International Midwest Symposium on Circuits and Systems (MWSCAS). doi: <https://doi.org/10.1109/mwscas.2018.8623947>
26. Solas, E., Abad, G., Barrena, J. A., Aurtenetxea, S., Carcar, A., & Zajac, L. (2013). Modular Multilevel Converter With Different Submodule Concepts – Part I: Capacitor Voltage Balancing Method. *IEEE Transactions on Industrial Electronics*, 60 (10), 4525–4535. doi: <https://doi.org/10.1109/tie.2012.2210378>
27. Lin Wang, Ping Wang, Zixin Li, Yaohua Li. (2013). A novel capacitor voltage balancing control strategy for modular multilevel converters (MMC). 2013 International Conference on Electrical Machines and Systems (ICEMS). doi: <https://doi.org/10.1109/icems.2013.6713283>
28. Dai, P., Guo, G., Gong, Z. (2016). A Selection Precharge Method for Modular Multilevel Converter. *International Journal of Control and Automation*, 9 (4), 161–170. doi: <https://doi.org/10.14257/ijca.2016.9.4.16>
29. Bashir, S. B., Beig, A. R. (2016). A novel SVPWM-based switching algorithm for MMC for high power applications. 2016 IEEE 59th International Midwest Symposium on Circuits and Systems (MWSCAS). doi: <https://doi.org/10.1109/mwscas.2016.7870123>
30. Plakhtii, O., Nerubatskyi, V., Ryshchenko, I., Zinchenko, O., Tykhonravov, S., Hordiienko, D. (2019). Determining additional power losses in the electricity supply systems due to current's higher harmonics. *Eastern-European Journal of Enterprise Technologies*, 1 (8 (97)), 6–13. doi: <https://doi.org/10.15587/1729-4061.2019.155672>
31. Zheng, Z., Can, C. (2014). The research of control algorithm and topology for high voltage frequency converter based on modular multilevel converter. The 26th Chinese Control and Decision Conference (2014 CCDC). doi: <https://doi.org/10.1109/ccdc.2014.6852960>
32. Plakhtii, O., Nerubatskyi, V., Karpenko, N., Hordiienko, D., Butova, O., Khoruzhevskiy, H. (2019). Research into energy characteristics of single-phase active four-quadrant rectifiers with the improved hysteresis modulation. *Eastern-European Journal of Enterprise Technologies*, 5 (8 (101)), 36–44. doi: <https://doi.org/10.15587/1729-4061.2019.179205>
33. Plakhtii, O., Tsybulnyk, V., Nerubatskyi, V., Mittsel, N. (2019). The Analysis Of Modulation Algorithms and Electromagnetic Processes in a Five-Level Voltage Source Inverter with Clamping Diodes. 2019 IEEE International Conference on Modern Electrical and Energy Systems (MEES). doi: <https://doi.org/10.1109/mees.2019.8896567>
34. Podder, S., Biswas, M. M., Khan, M. Z. R. (2016). A modified PWM technique to improve total harmonic distortion of Multilevel Inverter. 2016 9th International Conference on Electrical and Computer Engineering (ICECE). doi: <https://doi.org/10.1109/icece.2016.7853970>
35. Zhao, L., Wang, Q., Li, G., Chen, Q., Hu, C. (2014). Analyze and compare the efficiency of two-level and three-level inverter in SVPWM. 2014 9th IEEE Conference on Industrial Electronics and Applications. doi: <https://doi.org/10.1109/iciea.2014.6931488>
36. Dias, R. A., Lira, G. R. S., Costa, E. G., Ferreira, R. S., Andrade, A. F. (2018). Skin effect comparative analysis in electric cables using computational simulations. 2018 Simposio Brasileiro de Sistemas Eletricos (SBSE). doi: <https://doi.org/10.1109/sbse.2018.8395687>
37. Zhou J., Suand J., Wang X. (2014). Pre-charging control of modular multilevel converter. *High Voltage Apparatus*, 50 (4), 103–107.
38. Plakhtii, O., Nerubatskyi, V., Sushko, D., Ryshchenko, I., Tsybulnyk, V., Hordiienko, D. (2019). Improving energy characteristics of ac electric rolling stock by using the three-level active four-quadrant rectifiers. *Eastern-European Journal of Enterprise Technologies*, 4 (8 (100)), 6–14. doi: <https://doi.org/10.15587/1729-4061.2019.174112>
39. Plakhtii, O. A., Nerubatskyi, V. P., Hordiienko, D. A., Tsybulnyk, V. R. (2019). Analysis of the energy efficiency of a two-level voltage source inverter in the overmodulation mode. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, 4 (172), 68–72. doi: <https://doi.org/10.29202/nvngu/2019-4/9>
40. Plakhtii, O. A., Nerubatskyi, V. P., Kavun, V. Ye., Hordiienko, D. A. (2019). Active single-phase four-quadrant rectifier with improved hysteresis modulation algorithm. *Scientific bulletin of National mining university*, 5 (173), 93–98. doi: <https://doi.org/10.29202/nvngu/2019-5/16>