ЕЛЕКТРИЧНІ МАШИНИ ТА АПАРАТИ

DOI: https://doi.org/10.15407/publishing2025.71.070

OPERATING MODES OF A BRUSHLESS MAGNETOELECTRIC MECHATRONIC MODULE WITH TWO-WIRE CONTROL

K.P. Akinin, **V.G. Kireyev, ***I.S. Petukhov, * A.A. Filomenko**
Institute of Electrodynamics of the National Academy of Sciences of Ukraine,
Beresteiskyi ave., 56, Kyiv, 03057, Ukraine
e-mail: kvg2016@ukr.net

The paper is devoted to the study of the characteristics and operation modes of the input rectifier in the structure of the mechatronic module based on a brushless AC motor with permanent magnets when two-wire control from a power source with pulse-width regulation of the sequence of rectangular voltage pulses. To reduce switching losses in the rectifier MOSFETs, it is proposed to introduce additional differentiating RC circuits into the gate circuits. The influence of the parameters of these RC circuits on the value of switching losses in transistors is studied. Preliminary values of these parameters for minimization of switching losses are obtained. Dependences of losses in transistors and rectifier efficiency on the value of load current are obtained. A comparison of rectifiers based on MOSFETs and Schottky diodes is carried out. Ref. 10, fig. 11.
Keywords: mechatronic module, MOSFET-based rectifier, brushless permanent magnet motor.

A distinctive feature of mechatronic modules is the integration into a single unit of an electric motor, power converter, control system and mechanical coordinate sensors in order to implement certain functions of electromechanical systems and devices, taking into account specified technical limitations [1-4].

There are many known variants of the construction and implementation of mechatronic modules, and the areas of their use are very extensive. Among all this diversity, there is a problem of development of a constructive and functional analogue of a DC collector motor based on a permanent magnet brushless motor (PMBM) for reversible control of the angular speed of rotation of the rotor by means of two input power conductors. Such mechatronic modules are intended to replace traditional DC collector motors, which have been the actuators of automated electromechanical systems for many decades, and they are controlled quite simply by a transistor reversible converter with pulse-width regulation of the output voltage.

The structures of mechatronic models based on the PMBM with two-wire power supply and control were proposed in [5, 6]. They are similar to AC electric drives built on the basis of two-link frequency converters with an input rectifier of the AC network voltage and an output three-phase voltage inverter [7]. However, in our case, the peculiarity is that a unipolar voltage from an external power source is supplied to the rectifier input, and after rectification, the voltage is supplied to the input of a three-phase voltage inverter, which, depending on the polarity of the voltage at the rectifier input, forms a three-phase sequence of voltage pulses, which is then supplied to the three-phase winding of the BMPM. And thus, reversible motor control is implemented.

The purpose of the paper is to study the operating modes of the input rectifier based on MOSFETs in the structure of the mechatronic module with a brushless AC motor with permanent magnets on the rotor, with two-wire control from a power source with pulse-width regulation of rectangular voltage pulses. The features of the operating modes in question are due to the processes of rectification of rectangular voltage pulse sequences, which can be of one polarity or another.

ORCID ID: *https://orcid.org/0000-0002-9407-1074 , **https://orcid.org/0000-0002-7830-2311 , ***https://orcid.org/0000-0003-1416-1174 , ****https://orcid.org/0000-0003-4289-8579

Main materials and results of the research. The general structure of the brushless magnetoelectric mechatronic module (BMMM) [4] is shown in Fig. 1, where SS is an external power source with an output pulse voltage, where the voltage pulses have a rectangular shape, and the average voltage value is regulated by changing the duty cycle of the pulse sequence; R is a bridge rectifier; S is a current sensor; VI is a three-phase bridge voltage inverter; CS is a control system; RPS is a rotor position sensor. All elements of the BMMM - rectifier, voltage inverter, control system, rotor position sensor and actuator brushless motor - are structurally combined in one body. And in this case, reversible regulation of the angular speed of the motor is carried out by two conductors connecting the power source with the module circuit. And as a result, we have a structural and functional analogue of a DC collector motor.

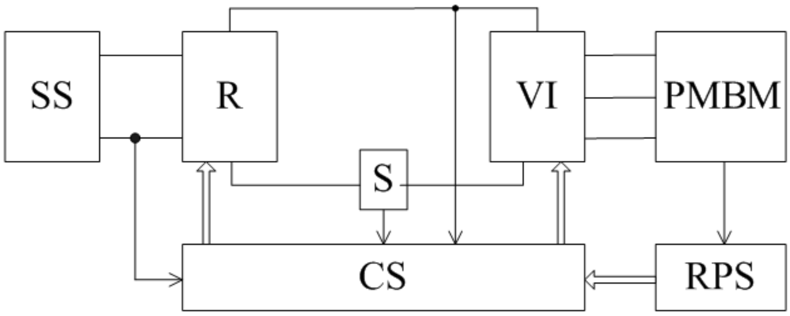


Fig. 1. The general structure of the brushless magnetoelectric mechatronic module

The voltage inverter circuit (Fig. 2) feeding a three-phase motor (Fig. 1) is known and traditional. In this case, the peculiarity of its control is that each of the six inverter transistors is in a conducting state for 120 electrical degrees of the phase voltage period and conducts a rectified sequence of rectangular voltage pulses with an adjustable duty cycle during this interval [8]. Depending on the polarity of the power source voltage pulse sequence, the alternation of the switching signals of the voltage inverter transistors changes, and thus the brushless motor is reversed.

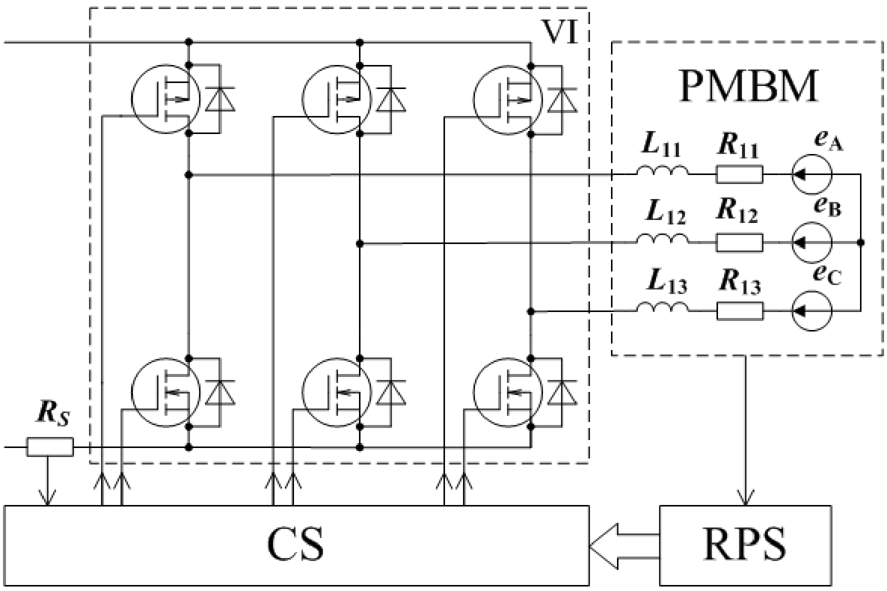
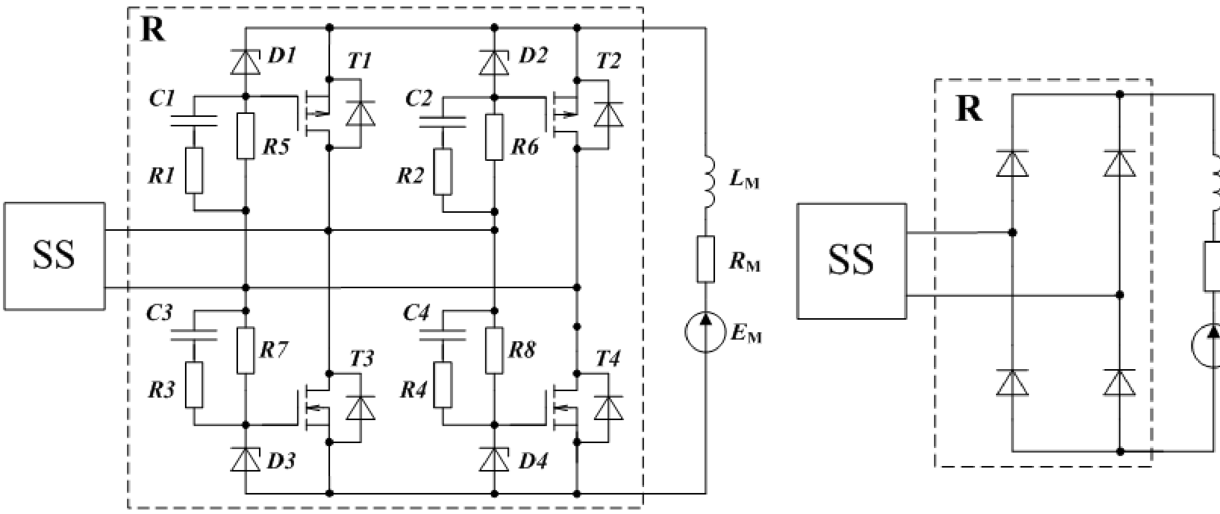


Fig. 2. The voltage inverter circuit feeding a three-phase motor

As for the bridge rectifier, in the structure (Fig. 1), it can be implemented on the basis of four MOSFETs (Fig. 3 *a*) or four Schottky diodes (Fig. 3 *b*). In the first case, depending on the polarity of the voltage supplied from the output of the external power source, a pair of transistors is switched on in the diagonal of the rectifier bridge according to the open pair of diodes. The possibility of implementing a rectifier on MOSFETs is considered in [9, 10] to reduce voltage drops on the power switches of the rectifier.

There are no circuit problems when implementing a rectifier based on Schottky diodes. But in a rectifier based on MOSFETs, when rectifying unipolar sequences of rectangular voltage pulses, a problem of transistor switching occurs due to the presence of capacitances in their gates, which prolongs the switching process and causes additional switching losses. With a voltage pulse sequence amplitude of 27 V and a repetition rate of 10 kHz, the switching losses in an unloaded rectifier based on dual N and P channel IRF7343 MOSFET modules were 10.4 W, which is unacceptable for low-power transistors in an SO8 package intended for surface mounting. To overcome this problem, it was proposed to introduce additional differentiating RC circuits ($R1 = R2 = R3 = R4 = R$ and $C1 = C2 = C3 = C4 = C$), shown in the circuit in Fig. 3, for fast charging and discharging of the gate capacitances.

In the circuit (Fig. 3 *a*) D1…D4 zener diodes to limit the voltage on the T1…T4 transistor gates to an acceptable level of 18 V and R5…R8 resistors to limit the currents and power losses in the zener diodes are introduced. According to the condition of the specified supply voltage of 27 V and possible surges of this voltage, it is accepted $R5 = R6 = R7 = R8 = R_D = 10\ kOhm$.



a *b*

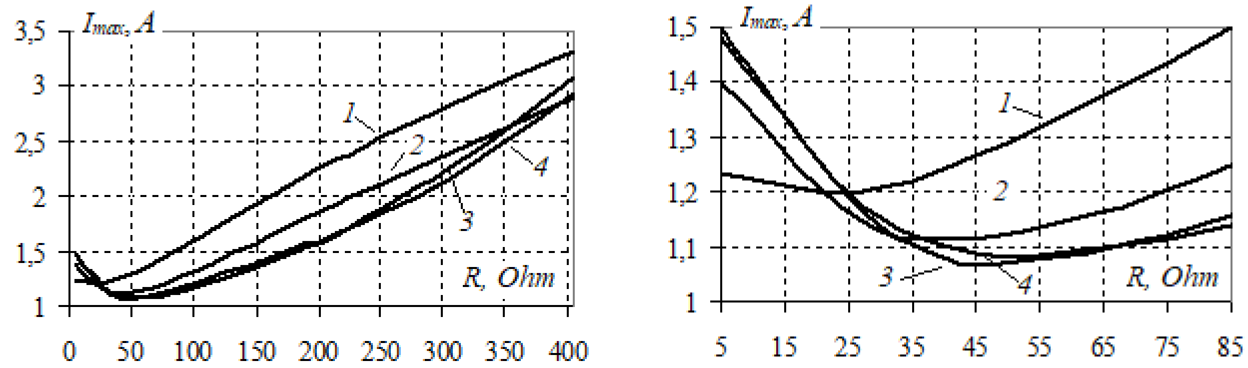
Fig. 3. Rectifier circuits based on MOSFETs (*a*) and Schottky diodes (*b*)

To study the features of the operating modes of the input rectifier, the voltage inverter with a three-phase motor is replaced by an equivalent RLE load circuit (Fig. 3).

We will study the operating modes of the mechatronic module for a low-power motor with a diameter of 25 mm under the following conditions: nominal supply voltage of the circuit is 27 V; voltage pulse repetition rate is 10 kHz; maximum motor rotation frequency is 12000 rpm; maximum current in the DC link is 3 A; $R_M = 4{,}62\ Ohm$; $L_M = 0{,}00129\ Hn$. The paper considers options for implementing a rectifier based on IRF7343 MOSFET modules, as well as 30BQ060 Schottky diodes.

The first task considered in the paper is to study the influence of the parameters of differentiating RC circuits on the value of switching losses in transistors in the unloaded rectifier mode. To evaluate this influence, we use the following indicators: $I_{\max}$ – the amplitude value of the current at the rectifier input; I_{ef} – the effective value of the current at the rectifier input; P_{L1} – the value of losses in the first MOSFET module of rectifier transistors; P_{L2} – the value of losses in the second MOSFET module of rectifier transistors; P_S – the total value of losses in two MOSFET modules of transistors.

Below are shown the dependences of the amplitude $I_{\max}$ (Fig. 4 *a* and *b*) and effective I_{ef} (Fig. 5) values of the rectifier input current, the power losses of two individual MOSFET modules P_{L1} and P_{L2} (Fig. 6), as well as their total power losses P_S (Fig. 7) on the resistance value R at four values of the capacitor capacitance – 750 *pF*, 1.8 nF, 3.0 *nF* and 3.6 *nF*, which are respectively designated on the graphs by the numbers 1, 2, 3 and 4. The calculations were performed at the duty cycle of the rectangular pulses of the power source voltage $\gamma = 0,5$. Fig. 6 shows the difference in the values of the switching losses in the first and second MOSFET modules. Obviously, the MOSFET module in which the P-type transistor is open has a higher power value.



a *b*

Fig. 4. The dependences of the amplitude $I_{\max}$ values of the rectifier input current on the resistance value R R at four values of the capacitor capacitance – 750 *pF*, 1.8 nF, 3.0 *nF* and 3.6 *nF*

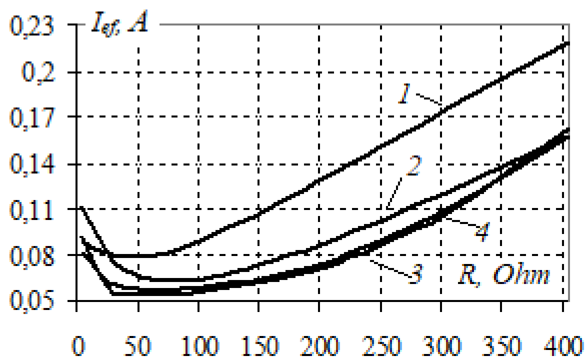
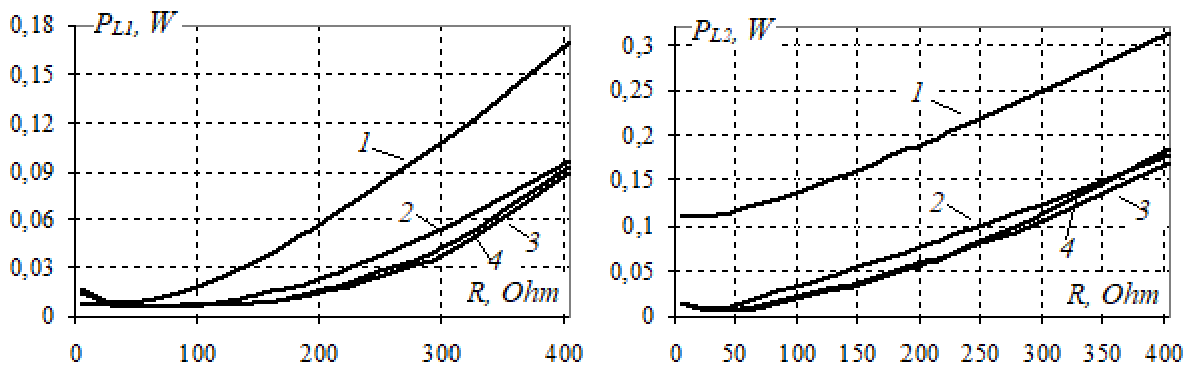


Fig. 5. The dependences of the effective I_{ef} (Fig. 5) value of the rectifier input current on the resistance value R



a *b*

Fig. 6. The dependences of the power losses of two individual MOSFET modules P_{L1} and P_{L2} on the resistance value R

The dependencies (Fig. 4–7) were obtained for the unloaded rectifier mode. For a more visual demonstration of the area of minimum values of current and switching losses, in Fig. 4 *b* and Fig. 7 *b* the characteristics are presented in a limited range of resistance change *R*.

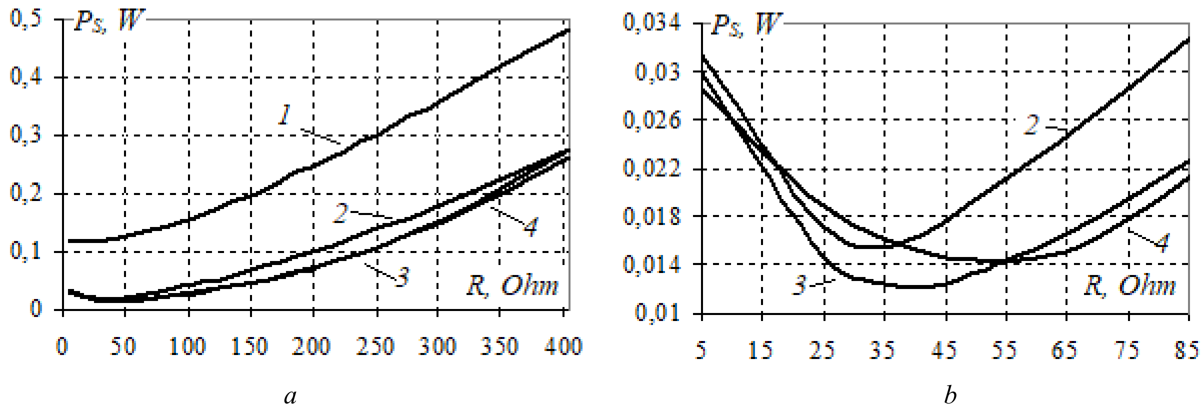


Fig. 7. The dependences of the total power losses P_S in the resistance value R

Preliminary calculations are performed for the operating mode of an unloaded rectifier, since it is in this operating mode that power losses are released in the transistors only due to the effect of switching the transistors in the rectification mode of a sequence of rectangular pulses without the influence of the load current.

Comparison of the dependencies in Fig. 4 *b* and Fig. 7 *b* shows that the minimum values of the current amplitude $I_{\max}$ and switching losses P_S are observed at different values of active resistance *R*. It is obvious that the selection of the parameters of the RC circuits should be carried out according to the condition of ensuring the minimum value of the switching losses of the transistor rectifier, which determine the thermal state of the transistors.

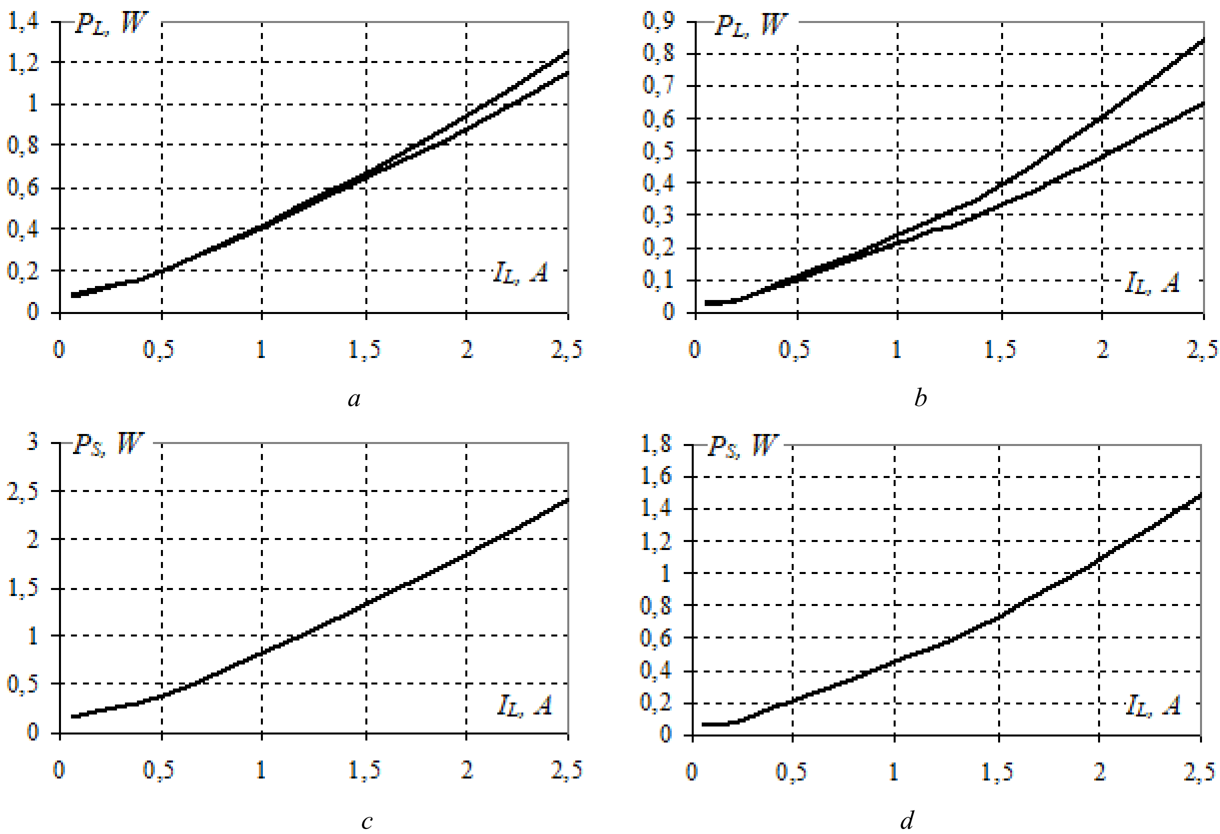


Fig. 8. The dependences of the switching power losses of two individual MOSFET modules P_{L1} and P_{L2}, as well as of their total power losses P_S on the average current I_L in the load circuit for two duty cycle values $\gamma = 0,5$ (*a, c*) and $\gamma = 0,8$ (*b, d*)

At this stage, the paper does not solve the problem of optimizing the transistor rectifier to achieve minimum losses P_{L1} , P_{L2} and P_S in transistors. This problem will be considered in the next paper. Nevertheless, the preliminary analysis of the dependencies allowed us to select such parameters of the RC circuits that provide satisfactory values of the indicators. For further studies of the rectifier operating modes under load, *R =40 Ohm* and *C=3 nF* were selected according to the condition of ensuring minimum switching loss power.

Further, Fig. 8 shows the dependences of the switching power losses of two individual MOSFET modules P_{L1} and P_{L2} on the average current I_L in the load circuit for two duty cycle values $\gamma = 0,5\,(a)$ and $\gamma = 0,8\ (b)$ as well as the dependences of their total power losses for the same two duty cycle values, marked with the letters *c* and *d*, respectively.

To evaluate the efficiency of the rectifier operating mode under load, we also use the efficiency factor

$$\eta = \frac{P_U}{P_S + P_U},$$

where P_U is the useful power on the load, which in one period T of the power source pulses is determined as

$$P_U = \frac{1}{T}\int_0^T u_L i_L \, dt ,$$

where u_L, i_L are the voltage and current in the equivalent RLE circuit of the rectifier load.

In addition, studies were conducted on the operating mode of the rectifier implemented on 30BQ060 Schottky diodes. Fig. 9 shows comparative characteristics of the total power loss P_S (*a, b*), as well as the efficiency η (*c, d*) from the average current I_L at two duty cycle values of γ 0.5 (*a, c*) and 0.8 (*b, d*) of the transistor (solid line) and diode (dotted line) rectifiers.

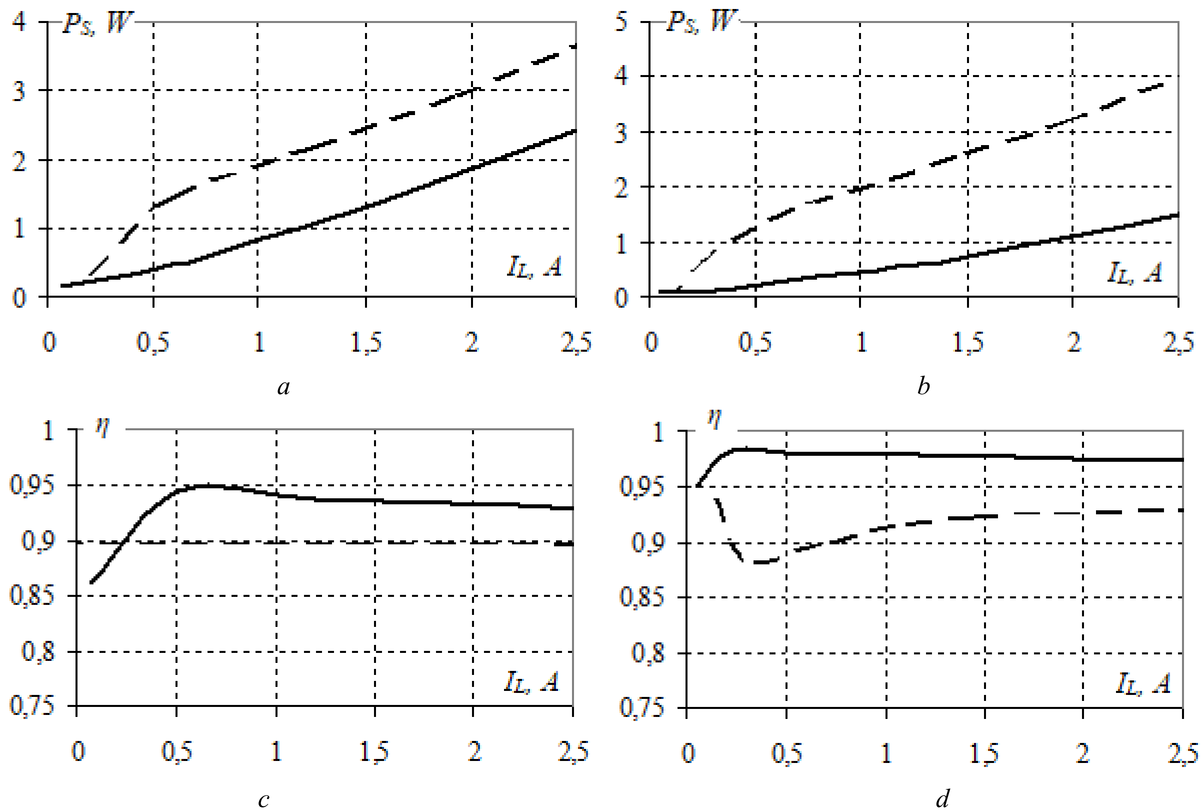
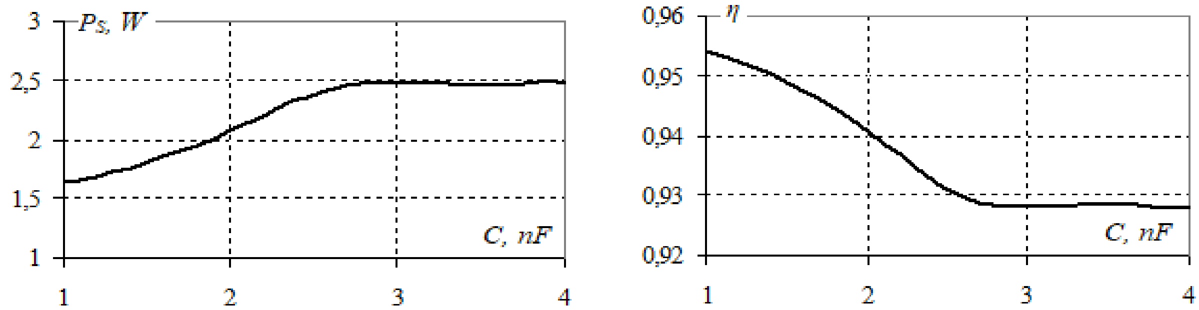


Fig. 9. Comparative characteristics of the total power loss P_S (*a, b*), as well as the efficiency η (*c, d*) from the average current I_L at two duty cycle values of γ 0.5 (*a, c*) and 0.8 (*b, d*) of the transistor (solid line) and diode (dotted line) rectifiers

The dependencies (Fig. 9) show the obvious advantage of a transistor-based rectifier over a diode rectifier. Although it can be recognized that the advantage of the latter is its simplicity and reliability, which may be preferable for low-power systems.

The paper did not perform a complete optimization of the switching mode of the transistor rectifier in all its operating modes, and the parameters of the RC circuit were preliminarily selected based on the study of the characteristics of the unloaded operating mode. Therefore, the characteristics (Fig. 10) of the total switching losses (a) and efficiency (b) were additionally calculated when changing the capacitance of the capacitor *C* from 1 to 4 nanofarads with an active resistance *R*=40 Ohm, an EMF value $E_L = 0$ and a duty cycle γ 0,5.

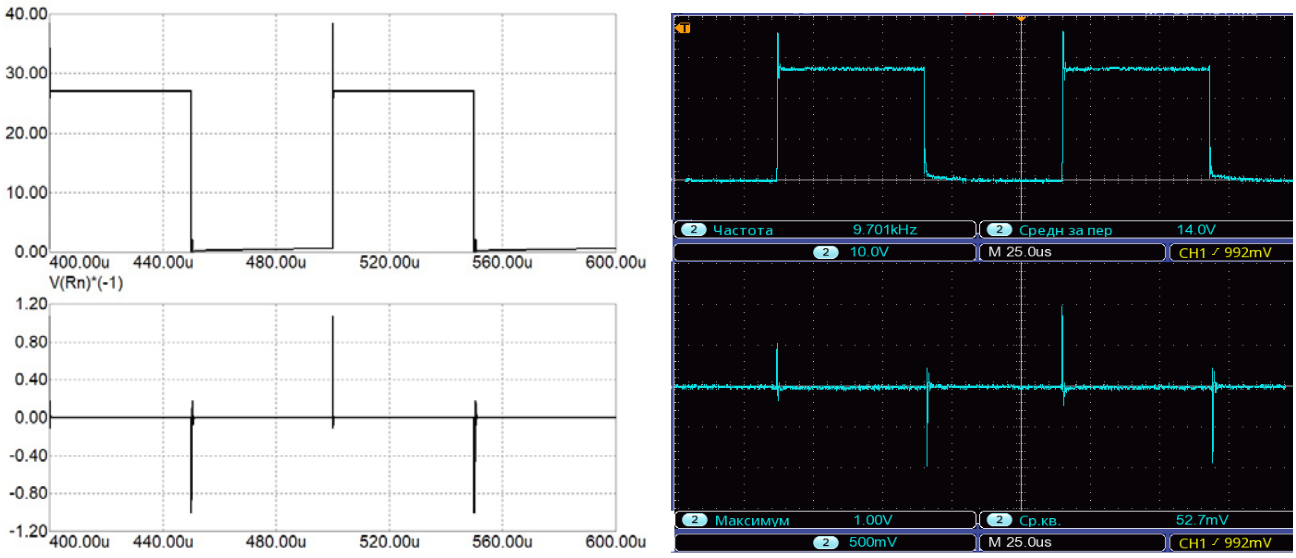


a *b*

Fig. 10. The characteristics of the total switching losses (a) and efficiency (b) when changing the capacitance of the capacitor *C* from 1 to 4 nanofarads with an active resistance *R*=40 Ohm

An examination of the dependencies (Fig. 10) shows that the lowest loss values are observed with other parameters of the RC-circuits compared to the parameters selected for the unloaded mode of operation of the rectifier. And, therefore, additional research is needed here.

Below are shown the calculated (Fig. 11 *a*) and experimental (Fig. 11 *b*) time diagrams of the rectified voltage and the input current of the rectifier, which demonstrate the correspondence of the studied processes in the rectifier. Experimental obtaining of the studied dependencies was not performed, since measuring losses in low-power transistors is difficult in practice, since the power values of these losses can be insignificant and equal to tens of milliwatts. Measuring the values of the input current amplitude is also problematic due to the short time duration of the narrow input current pulse and the limited frequency properties of available measuring devices.



a *b*

Fig. 11. The calculated (*a*) and experimental (*b*) time diagrams of the rectified voltage and the input current of the rectifier

Conclusions. Comparison of the dependencies of maximum current values and switching losses shows that they do not correlate with each other, and therefore optimization of the rectifier operating mode to achieve the minimum value of losses must be carried out precisely according to the value of the latter indicator.

The studies have shown that with the parameters of RC circuits selected for the unloaded operation mode of the rectifier, the optimal values of efficiency coefficient are not ensured in the operation mode of the rectifier under load and, therefore, additional studies and complex optimization are required according to the criterion of the minimum value of switching losses in the rectifier transistors, taking into account the influence of the values of the load current and the duty cycle of the input voltage pulse sequence. This problem will be presented in the next paper. Although it can be noted that even with the selected parameters of RC circuits, quite satisfactory energy characteristics are already ensured.

The use of simple and reliable RC circuits for switching rectifier transistors allows avoiding the use of expensive and complex drivers that are unacceptable for low-power devices.

Фінансується за держбюджетною темою «Розробити наукові засади та принципи побудови керованих n-степеневих магнітоелектричних систем з екстремальними характеристиками» (шифр «МЕХАТРОН»), що виконується за Постановою Бюро ВФТПЕ 11.07.2023 р. (Протокол №8). Державний реєстраційний номер роботи 0124U000396. КПКВК 6541030.

1. Peresada S. M., Pushkar M. V. Fundamentals of mechatronics: a basic guide. Kiev: KPI named after Igor Sikorsky, 2020. 136 p.
2. Introduction to mechatronics: textbook. A.I. Grabchenko, V.B. Klepikov, V.L. Dobroskok et al. Kharkiv: NTU KhPI, 2014. 264 p.
3. Current electromechatronic complexes and systems: textbook. T.P. Pavlenko, V.M. Shavkun, O.S. Kozlova, N.P. Lukashova; Kharkiv: Kharkiv National University named after O. M. Beketov. 2019. 116 p.
4. Semenyuk V.F., Mikhailov E. P. Mechatronics: basic textbook. Odessa: OP, 2021. 130 p.
5. Akinin K.P., Barannikov O.V. Method for controlling a brushless motor: Patent Ukraine 98265. MPK N02R 6/00; 04.21.2011.
6. Akinin K.P., Barannikov O.V. Device with brushless motor: Patent Ukraine 104079. MPK N02R 6/00; 08.30.2012.
7. Bose B.K. Modern Power Electronics and AC Drives. New York: Prentice Hall, 2002, 710 p.
8. Akinin K.P., Kireev V.G., Petukhov I.S., Filomenko A.A., Electromechanical characteristics of a brushless motor with permanent magnets when pulse-width operation. *Pratsi Instytutu Elektrodynamiky NAN Ukrainy*. 2024. V. 69. Pp. 95–104.
9. Tomofumi Hirose Rectifier Circuit Using FET Bridge Circuit, and method of Controlling the Same: Patent JP 2012085369 A; 26.04.2012.
10. Dhayabarasivam, S. S., & Jayanthi, K. Energy Harvesting Circuit Utilizing MOSFET Based Bridge Rectifier. 2018 IEEE International Conference on System, Computation, Automation and Networking (ICSCA). DOI: https://doi.org/10.1109/icscan.2018.8541201

УДК 621.313.8

РЕЖИМИ РОБОТИ БЕЗКОНТАКТНОГО МАГНІТОЕЛЕКТРИЧНОГО МЕХАТРОННОГО МОДУЛЯ ПРИ ДВОПРОВІДНОМУ УПРАВЛІННІ

К.П. Акинін*, докт. техн. наук, **В.Г. Кіреєв****, канд. техн. наук**, ***Пєтухов І.С.,** докт. техн. наук,
А.А. Філоменко**,** канд. техн. наук
Інститут електродинаміки НАН України,
пр. Берестейський, 56, Київ, 03057, Україна
e-mail: kvg2016@ukr.net

Статтю присвячено дослідженню характеристик та режимів роботи вхідного випрямляча у структурі мехатронного модуля на основі безконтактного двигуна змінного струму з постійними магнітами при двопровідному управлінні від джерела живлення з широтно-імпульсним регулюванням послідовності імпульсів напруги прямокутної форми. Для зменшення комутаційних втрат у MOSFETs випрямляча запропоновано ввести в кола затворів додаткові RC-ланцюжки, що диференціюють. Проведено дослідження впливу параметрів цих RC-ланцюжків на величину комутаційних втрат у транзисторах. Отримано попередні значення цих параметрів для мінімізації комутаційних втрат. Отримано залежності втрат у транзисторах і коефіцієнта корисної дії випрямляча від величини струму навантаження. Проведено порівняння випрямлячів на основі MOSFETs та діодів Шотки. Бібл. 10, рис. 11.

Ключові слова: мехатронний модуль, випрямляч на основі MOSFETs, безконтактний двигун з постійними магнітами.

1. Пересада С.М., Пушкар М.В. Основи мехатроніки: навчальний посібник. Київ: КПІ ім. Ігоря Сікорського, 2020. 136 с.
2. Введение в мехатронику: уч. пособие. А.И. Грабченко, В.Б. Клепиков, В.Л. Доброскок и др. Х.: НТУ «ХПИ», 2014. 264 с.
3. Сучасні електромехатронні комплекси і системи : навч. посібник. Т.П. Павленко, В.М. Шавкун, О.С. Козлова, Н.П. Лукашова; Харків. нац. ун-т міськ. госп-ва ім. О. М. Бекетова. Харків: ХНУМГ ім. О. М. Бекетова, 2019. 116 с.
4. Семенюк В.Ф., Михайлов Є. П. Мехатроніка: навчальний посібник. Одеса: ОП, 2021. 130 с.
5. Акинін К.П., Баранніков О.В. Спосіб керування безконтактним двигуном: пат. на винахід 98265 Україна. МПК H02P 6/00; заявл. 21.04.2011, опубл.
6. Акинін К.П., Баранніков О.В. Пристрій керування безконтактним двигуном: пат. на винахід 104079 Україна. МПК H02P 6/00; заявл. 30.08.2012, опубл. 25.12.2013, Бюл. № 24. 6 с.
7. Bose B.K. Modern Power Electronics and AC Drives. New York: Prentice Hall, 2002, 710 p.
8. Акинін К.П., Кіреєв В.Г., Пєтухов И.С, Філоменко А.А. Електромеханічні характеристики безконтактного двигуна з постійними магнітами при широтно-імпульсному живленні. *Праці Інституту електродинаміки НАН України.* 2024. Вип. 69. С. 95–104.
9. Tomofumi Hirose Rectifier Circuit Using FET Bridge Circuit, and method of Controlling the Same: Patent JP 2012085369 A; 26.04.2012.
10. Dhayabarasivam, S. S., & Jayanthi, K. Energy Harvesting Circuit Utilizing MOSFET Based Bridge Rectifier. 2018 IEEE International Conference on System, Computation, Automation and Networking (ICSCA). DOI: https://doi.org/10.1109/icscan.2018.8541201

Надійшла: 31.07.2025
Прийнята: 26.08.2025

Submitted: 31.07.2025
Accepted: 26.08.2025