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APPROACHES TO THE DEVELOPMENT OF MECHATRONIC MODULES BASED ON BRUSHLESS PERMANENT MAGNET MOTORS WITH TWO-WIRE CONTROL

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This paper examines approaches to the development of mechatronic modules based on brushless permanent magnet (BPM) motors with two-wire control from an external power source by varying the duty cycle of a rectangular voltage pulse sequence and changing the polarity of these pulses to reverse the mechanism's direction of motion. Implementation options for the mechatronic module's structural elements – a voltage inverter, an input rectifier, switches driver circuits, and a power supply – are considered and proposed. Driver circuits are proposed for switching the p- and n-channel field-effect transistors of the rectifier and voltage inverter when the mechatronic module is powered by a rectangular voltage pulse sequence. Ref. 27, fig. 14.
Key words: mechatronic module, brushless permanent magnet (BPM) motor, pulse-width voltage regulation, voltage inverter, rectifier based on field-effect transistors.

Introduction. Currently, one of the main trends in the development of electromechanics is the implementation of actuator electric motors of a brushless design with a slotless or toothed stator and permanent magnets on a rotating rotor [1-6]. The brushless design ensures high reliability of the rotating mechanism, and the use of permanent magnets allows for the creation of an electric machine with minimal weight and dimensions. Currently, there are numerous applications for electric drives and systems based on such motors, characterized by a wide range of technical parameters and functional capabilities. Numerous implementation options for brushless permanent magnet electric machines and their control systems are also known. An attempt has even been made to classify such motors [7].

One of the requirements for modern electric drives is the integration of all component elements (motor, mechanical coordinate sensors, control system, and power converter) into a single structural unit. Such an electromechanical structure is then called a mechatronic module [8-14]. The purpose of creating such modules is to implement a specific, highly specialized function in a mechanism or electromechanical device.

To minimize the number of conductors connecting the mechatronic module and external control device, a method of transmitting control signals via power lines is used [15-17]. This connection can be implemented by using a transmitter and receiver at opposite ends of a two-wire line. In this case, the functions of two conductors are combined, transmitting power to the motor and speed control commands.

This paper examines approaches to the development of mechatronic modules based on brushless permanent magnet (BPM) motors for their use as actuators in electromechanical automatic control systems. A distinctive feature of such modules is the ability to provide two-wire control from an external power converter with pulse-width regulation of the duty cycle of the output rectangular voltage pulses. The approach to implementing such mechatronic BPM motors modules (MMs) enables the creation of a brushless structural and functional analogue of a DC brushed motor [18] for reversible control of the rotor angular speed via two input power conductors. The use of such a module allows for the replacement of an existing brushed motor with a brushless one without changing the overall control structure of the electromechanical system. Moreover, a simple semiconductor converter is sufficient to control the module.

The structures of electric drives based on BPM motors with two-wire power supply and control were proposed in [19-21]. They are similar to the structures of AC electric drives realized

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on the basis of two-link frequency converters with an input rectifier of the AC grid voltage and an output voltage inverter [22]. In this problem of constructing an electric drive, the circuit is powered from a DC source via two conductors, and the rectifier rectifies the sequences of input voltage pulses, the polarity of which can change.

The purpose of the paper is to research, develop and generalize approaches to creating mechatronic modules based on the BPM motors for electromechanical automatic control systems with a two-wire power supply and providing reversible motor speed control by pulse-width variation of the duty cycle of a sequence of rectangular supply voltage pulses, as well as by changing their polarity.

Main materials and research results. The basic approach to the development of mechatronic modules is the combination of all structural elements – a motor, mechanical coordinate sensors, a control system, and a power converter – in a single body. For the problem of constructing a mechatronic module formulated above with control from two conductors, its general structure is shown in Fig. 1, where PS is an external power source or a power semiconductor regulator with an output pulse voltage, wherein the voltage pulses have a rectangular shape, the average voltage value is regulated by changing the duty cycle of the pulse sequence, and the polarity of the pulse sequence can be changed to reverse the motor; 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; U_1, U_2 are signals for determining the polarity of the input voltage and setting the direction of rotation of the motor; U_3 is a voltage signal in the DC link; U_S is a voltage at the output of an external power source with pulse-width regulation.

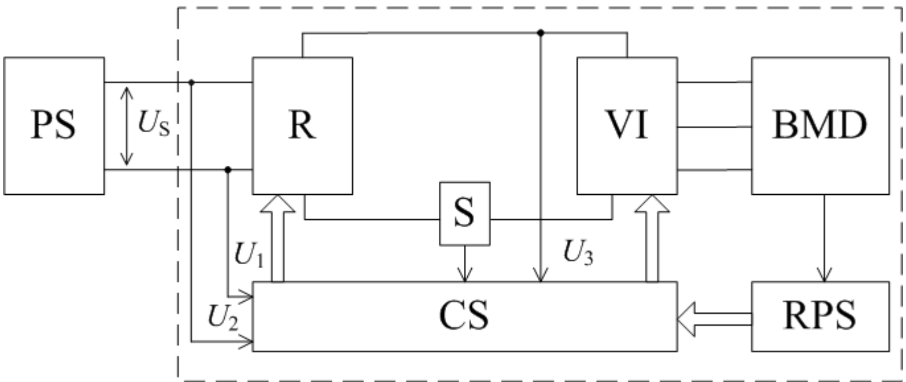

Fig. 1. General structure of mechatronic module

Based on the analysis of the requirements for the considered MMs and preliminary studies [19-21, 23, 24], we will define the features, principles and approaches to the development of this version of the devices:

– reversible change in the angular speed of the mechatronic module motor is achieved by regulating the duty cycle and changing the polarity of the sequences of rectangular voltage pulses that are supplied to the module via two conductors connecting the power source or external power regulator with the MM circuit, as a result of which we have a structural and functional analogue of a DC brushed motor, and the duty cycle of the pulse sequence can vary in the range from approximately 0.05 to 1;

– the considered MMs are intended for use in electromechanical automatic control systems, therefore the MM control system does not provide for an additional loop for regulating and stabilizing the angular speed, however, an angular speed sensor can be installed in the motor design for connecting its signal to an external regulator;

– the MMs under consideration are low-power devices, with power ratings ranging from several tens of watts to one or two kilowatts;

– the module's main parameters are the rated supply voltage, power, angular speed, and the motor shaft torque. This applies to a rated supply voltage of 27 V, motor power up to 1 kW, and angular speed up to 7000-9000 rpm;

– a three-phase motor with a slotless stator and surface-mounted permanent magnets on the rotor is typically used as the basis for constructing the module. This motor design is suitable for the production of even single samples, as it eliminates the need for significant investment in technological preparation for production and tooling. Furthermore, unlike toothed motor designs, this design ensures a nearly sinusoidal magnetic field distribution in the air gap and smooth rotation at low rotor angular speed. The ability to implement a motor with such properties in cylindrical or disk-shaped designs offers the important advantage of incorporating the motor's active elements into the specified volume of the electromechanical system being developed with virtually any proportions.

– the basic structure of the module's power circuit is a two-link converter with an input bridge rectifier and a three-phase bridge voltage inverter operating in a dependent mode in accordance with signals from the rotor position sensor;

– an important structural component of the mechatronic module is the driver system for the rectifier and inverter power transistors, for which the selection criteria are the supply voltage and motor power;

– since the mechatronic module is powered and controlled via only two external conductors from a rectangular pulse sequence, the same voltage must also be used to power the module's control system;

– the motor current limiting function is implemented either by an external power regulator of the electromechanical automatic control system or by the internal circuit of the mechatronic module. In the latter case, the current is limited by controlling the transistors of the voltage inverter based on signal from the current sensor in the DC link.

– since the voltage at the rectifier output and inverter input has a constant polarity, reversing the motor requires changing the switching order of the inverter transistors. To do this, a corresponding logical signal is generated based on the analysis of external signals U_1 and U_2 (Fig. 1);

– the mechanical coordinate sensor is integrated directly into the motor design. If the rotor position sensor is implemented using discrete Hall elements, energy-saving power supply algorithms can be used to reduce the power consumption of the MMM control system [21, 25, 26];

– the MMs under consideration are highly specialized devices designed to operate within a specified range of parameters.

Next, we will consider the implementation options for the structural elements of the mechatronic module.

Two implementation options are possible for the power section of the bridge rectifier and inverter with a supply voltage of up to 30 V: based solely on n-channel MOSFETs or pairs of p-channel and n-channel MOSFETs for the top and bottom groups of switches. It is difficult to determine the exact desirability of using the first or second power section option; however, the first implementation option, using n-channel transistors, should be used for motor currents starting from approximately one or more tens of amperes.

The choice of rectifier and inverter transistors determines their driver circuit. If the mechatronic module converters are powered by rectangular pulses with controlled duty cycle, the conductivity of the rectifier transistor pair (corresponding to open diodes) must be maintained over the entire time interval of constant supply voltage pulse polarity. The voltage inverter transistors must be open during conduction intervals lasting 120 electrical degrees, in accordance with the operating algorithm [21].

Fig. 2 shows a voltage inverter based on three pairs of p- and n-channel MOSFETs T1 and T4, T2 and T5, T3 and T6. To switch the p-channel transistors, top driver circuits are proposed based on complementary pairs of bipolar transistors T10 and T13, T11 and T14, T12 and T15, which are sequentially switched using transistors T7, T8, and T9. A distinctive feature of the circuit is that the collectors of the bipolar transistors of the complementary pairs are connected to a zener diode S1, which limits the amplitude of the voltage pulses on the gates of the p-channel MOSFETs to a safe level, enabling inverter operation over a relatively wide supply voltage range. The current of zener diode S1 is limited by resistor R7, and to accelerate the charging and discharging of the capacitances in the gates of p-channel transistors during sudden changes in the supply voltage pulses, it is proposed to use a differentiating RC circuit (R8, C1). This ensures that the top switch drivers can be powered directly by the rectangular supply voltage pulses.

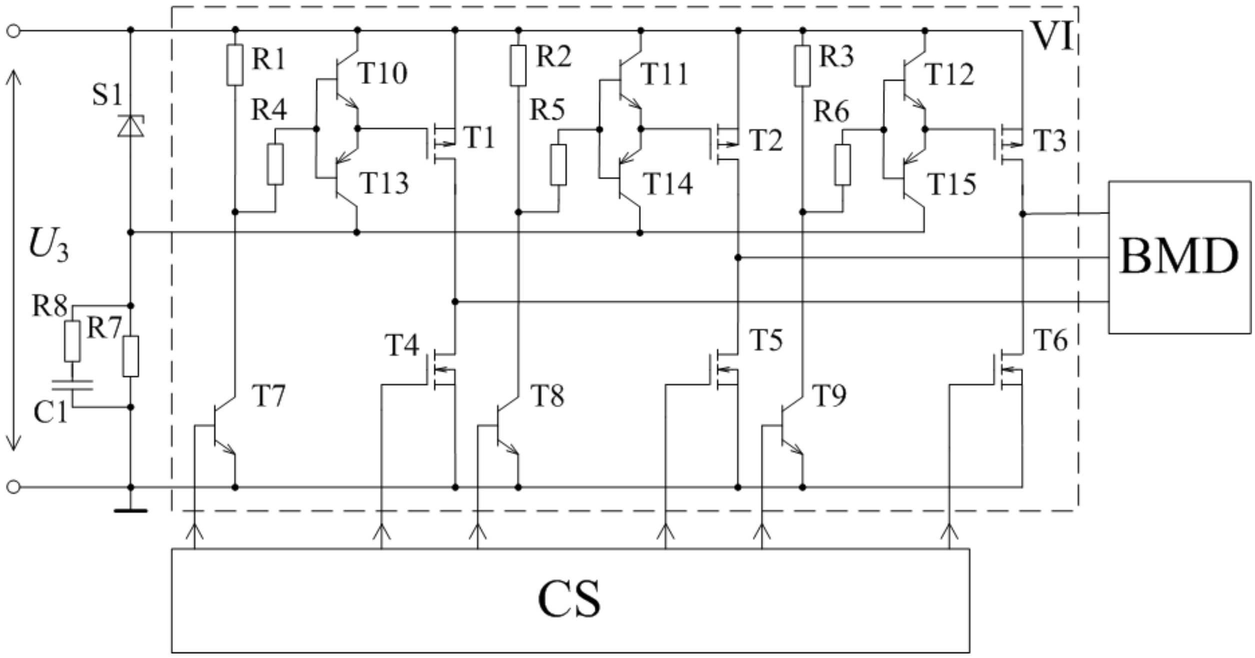

Fig. 2. Voltage inverter based on three pairs of p- and n-channel MOSFETs

Fig. 3 shows an example of calculating the signal diagrams of the input supply voltage U_S and the voltage U_{GT1} on the gate of the p-channel transistor T1 with a pulse sequence duty cycle of 0.5. Power switches T1-T6 of the voltage inverter (Fig. 2) are made on dual n- and p-channel IRF7343 MOSFET modules. The circuit also uses bipolar transistors BC847C (T7–T12) and BC857C (T13–T15), as well as passive elements with the following parameters: R1 = R2 = R3 = 30 kOhm, R4 = R5 = R6 = 20 kOhm, R7 = 10 kOhm, R8 = 47 Ohm, C1 = 3.3 nF. The nominal stabilization voltage of the zener diode S1 is 18 V. The obtained diagrams (Fig. 3) confirm the high switching speed of the gates of p-channel transistors under pulsed supply voltage.

Fig. 4 shows a voltage inverter based on six n-channel MOSFETs T1-T6, which are suitable for relatively higher-current circuits (over 10 A). The circuits shows the drivers for the top (TD1, TD2, TD3) and bottom (BD1, BD2, BD3) switches. The drivers must ensure the open state of the corresponding transistors at intervals of 120 electrical degrees across the entire range of the motor's angular speed. In this case, drivers with isolated power supplies should be used for the top group of switches, while another common power supply can be used for the bottom group of switches. The driver power supplies are not shown in the figure.

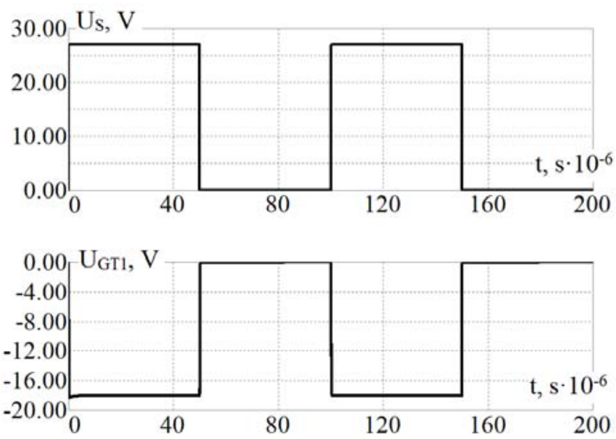

Fig. 3. Signal diagrams of input supply voltage U_S and voltage U_{GT1}

Next, we will consider the implementation features of input rectifiers for such mechatronic modules. Rectifier circuits based on Schottky diodes and p- and n-channel MOSFETs [24] are shown in Figs. 5 and 6, respectively. There are no circuit design problems when implementing a rectifier based on Schottky diodes. And for the case of rectifying unipolar sequences of rectangular voltage pulses when switching p- and n-channel MOSFETs of the rectifier, it is proposed to use differentiating RC circuits [24], through which accelerated charging and discharging of gate capacitances is carried out, then additional switching losses in the rectifier transistors are reduced. The amplitude of the pulses on the gates of the transistors is limited using appropriate zener diodes. The choice between a diode rectifier and a field-effect transistor rectifier should be made based on a comparative analysis of the power losses caused by the voltage drop across the switching elements. The possibility of implementing a MOSFET rectifier to reduce the voltage drop across the power switches is discussed, for example, in [27].

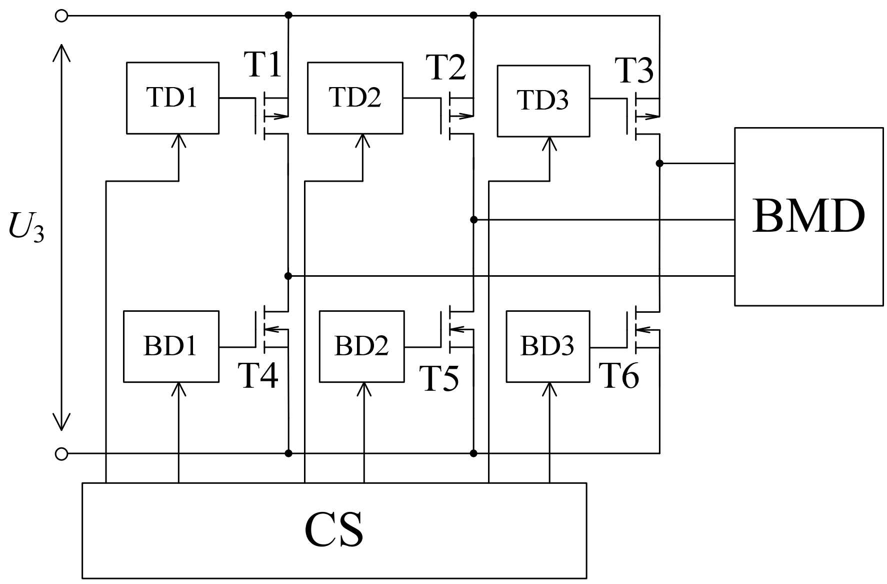

Fig. 4. Voltage inverter based on six n-channel MOSFETs

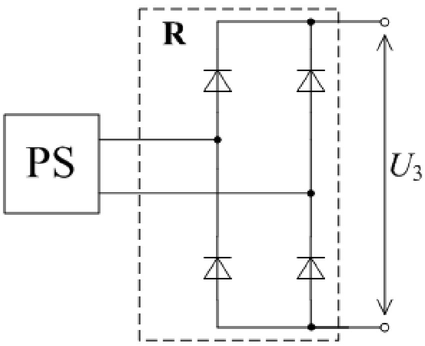

Fig. 5. Rectifier based on Schottky diodes

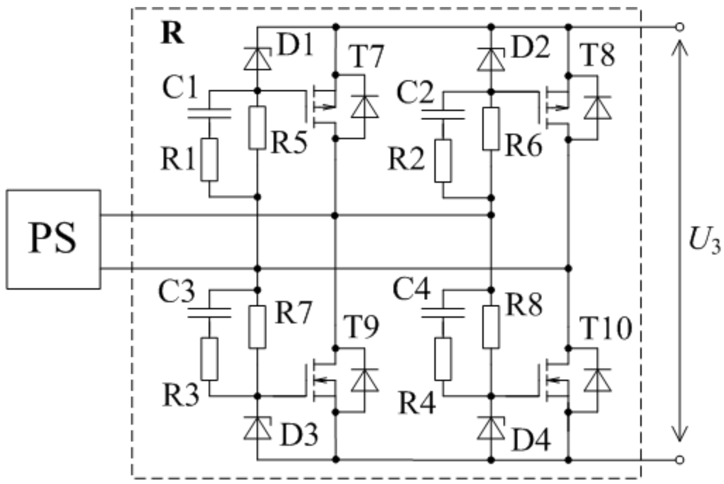

Fig. 6. Rectifier based on p- and n-channel MOSFETs

Fig. 7 shows an example of calculating the timing diagrams of the input supply voltage U_S, signals U_{GT7}, U_{GT8}, U_{GT9}, U_{GT10} on the transistor gates and the rectifier output voltage U_3 with a pulse sequence duty cycle of 0.5. Power switches T7-T10 of the rectifier (Fig. 6) are also implemented on the basis of IRF7343 MOSFET modules, the parameters of the passive elements are R1=R2=R3=R4=47 Ohm, R5=R6=R7=R8=10 kOhm, C1=C2=C3=C4=3.3 nF, the nominal voltage of the zener diodes D1-D4 is 18 V. The diagrams (Fig. 7) demonstrate the high speed of switching signals in the transistor gates when the rectifier is powered by a sequence of rectangular pulses.

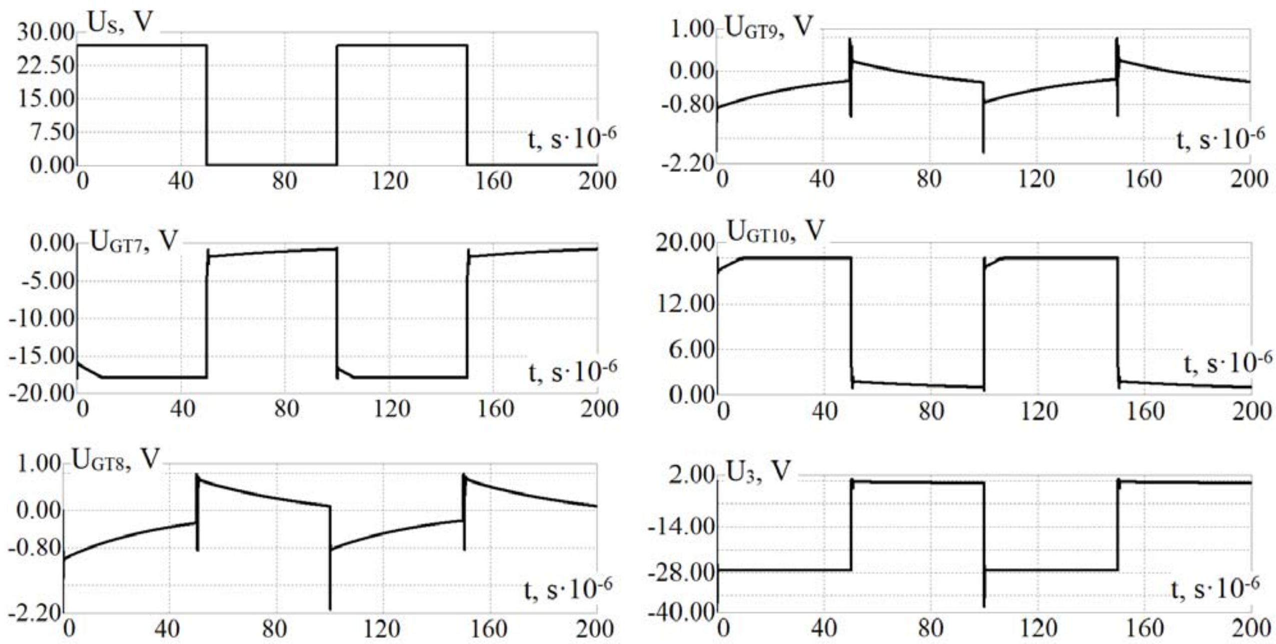

Fig. 7. Timing diagrams of input supply voltage U_S, signals U_{GT7}, U_{GT8}, U_{GT9}, U_{GT10} on transistor gates and rectifier output voltage U_3

Fig. 8 shows a rectifier based on four n-channel MOSFETs T7-T10, the use of which is also more effective in higher-current applications (above approximately 10A). The same remarks apply to the circuit of the drivers of the top (TD4, TD5) and bottom (BD4, BD5) rectifier switches (Fig. 8) as to the drivers of the voltage inverter switches (Fig. 4). Only the pair of top and bottom drivers along the diagonal of the rectifier bridge should be connected in accordance with the open pair of diodes.

As for the power supply in low-power MMs based on p- and n-channel MOSFETs, the switching circuits of the top group are powered by the rectangular supply voltage pulses themselves (Fig. 2). To power the voltage inverter control system, a circuit (Fig. 9) can be used with a peak detector based on a Schottky diode D and capacitor C, followed by a voltage converter (VC) to stabilize the supply voltage, with the common terminal of such a power supply being connected to the common terminal of the control system. The peak detector allows the voltage on the capacitor to be obtained at a level of at least 26 V over the entire specified range of change in the duty cycle of the voltage pulse sequence from 0.05 to 1.0.

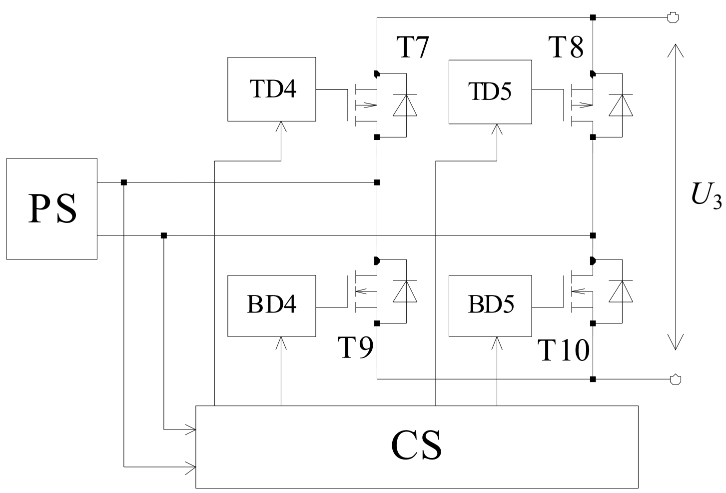

Fig. 8. Rectifier based on four n-channel MOSFETs

For relatively high-power MMs circuits based on n-channel MOSFETs that require an isolated power supply, it is advisable to use the circuit (Fig. 10) that utilizes a low-power Schottky diode rectifier, a filter capacitor C, and voltage converters (VC1, VC2) to provide galvanically isolated power supplies for the control system and n-channel transistor drivers. This configuration makes it possible to isolate the control system power supply from electromagnetic interference and switching transients generated in the voltage inverter and rectifier.

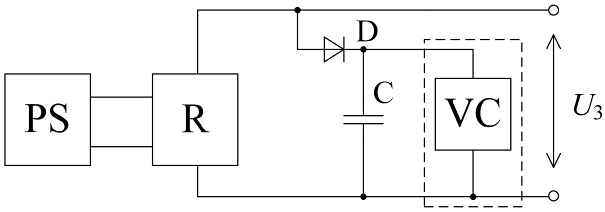

Fig. 9. Control system power supply based on peak detector

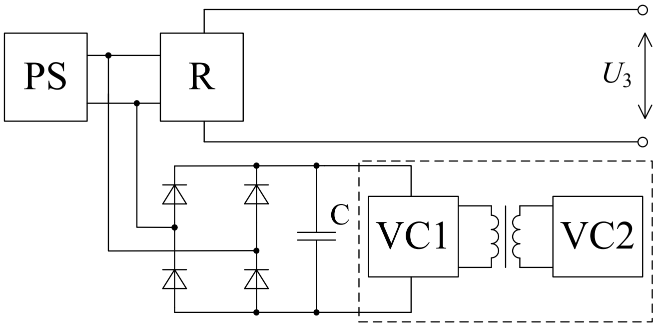

Fig. 10. Control system power supply based on diode rectifier

Fig. 11 shows the calculated plots of the average voltage U_C dependences and the relative magnitude of the pulsation ΔU_C peak-to-peak on capacitor C (Fig. 9) depending on the duty cycle γ of the rectangular pulse sequence for three values of capacitor capacitance: 10, 6,8, and 4,7 µF. The corresponding dependencies are designated by the numbers 1, 2, and 3. Thus, the peak detector allows one to obtain a voltage on capacitor C at a level of at least 26 V over the entire specified range of the duty cycle of the voltage pulses, from 0.05 to 1.0.

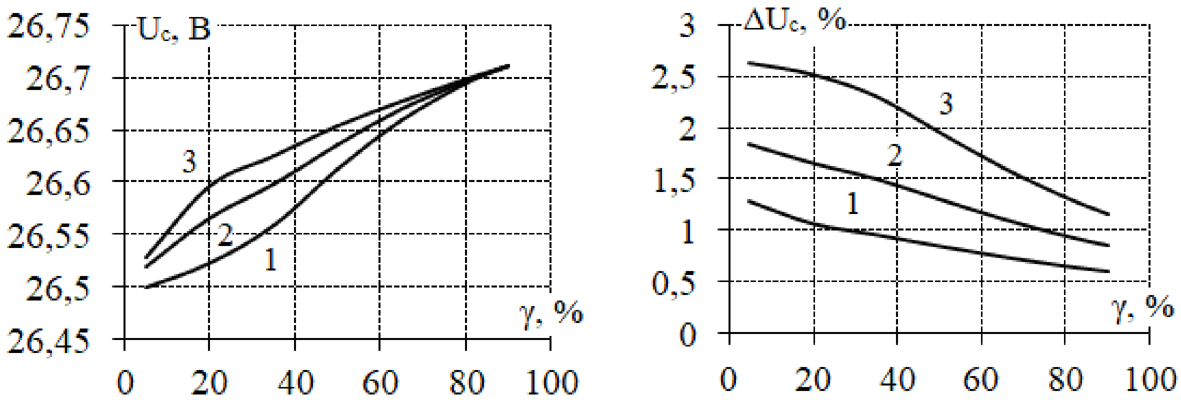

Fig. 11. Plots of average voltage U_C dependences and relative magnitude of pulsation ΔU_C peak-to-peak on capacitor C (Fig. 9) depending on duty cycle γ

As an example of calculation [23], Fig. 12 shows the mechanical characteristics of the motor - the dependence of the motor shaft rotational speed n on its average torque M_{av}. The plots are constructed for four values of the duty cycle γ of the rectangular pulses of the supply voltage – 1; 0.75; 0.5 and 0.25, which are marked in the figure with numbers from 1 to 4, respectively. Fig. 13 shows the graphs of the mechanical characteristics $n\left(M_{av}\right)$ of the motor with a duty cycle of 1 and three specified values of the maximum current – 20, 40 and 80 Amperes. Solid and dashed lines show the transistor turn-off time duration T_{off}, respectively, $4\cdot10^{-5}$ and $2\cdot10^{-5}$ seconds. The calculation was performed for a motor with the following parameters: rated power – 180 W; maximum no-load speed - 4000 rpm; rated speed – 3000 rpm; rated torque – 0.57 N·m; number of pole pairs – 1; rated supply voltage – 27 V; active resistance of the winding 0,05 Ohm; inductance of the winding $2{,}27\cdot10^{-5}$ Hn; back-EMF constant 0,06446 V·s; frequency of the pulse-width controller – 10 kHz.

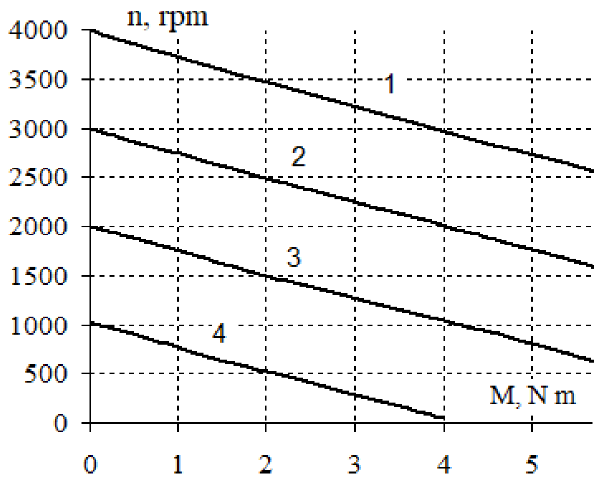

Fig. 12. Motor mechanical characteristics at four values of duty cycle of supply voltage pulses

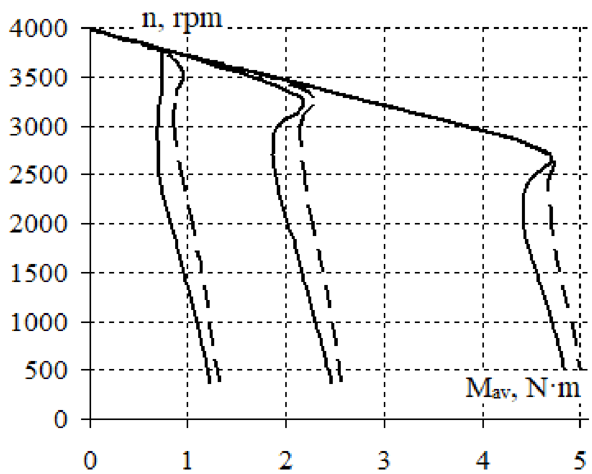

Fig. 13. Motor mechanical characteristics under current limitation

To illustrate the electromagnetic processes, Fig. 14 shows the waveforms of the three-phase stator EMFs, the current in the stator winding of phase A and the instantaneous motor torque.

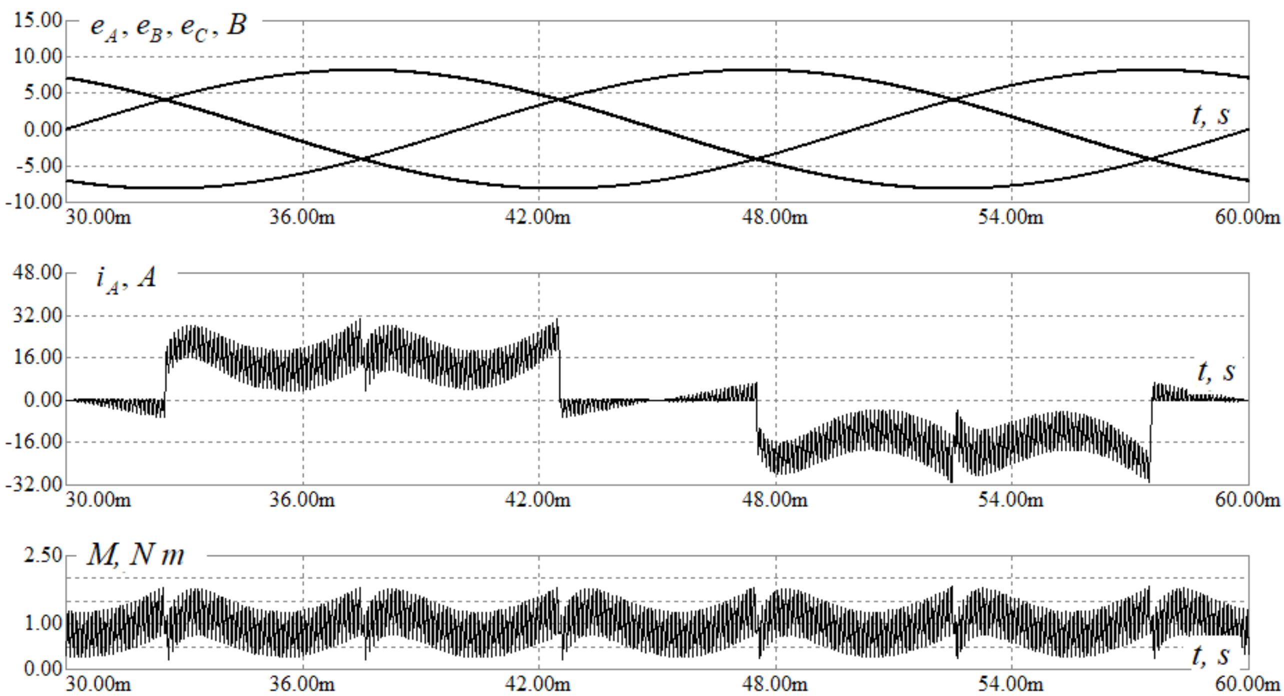

Fig. 14. Waveforms of three-phase stator EMFs, stator current and instantaneous motor torque

The current waveform in the phase stator winding (Fig. 14) when the inverter is powered by a rectangular voltage pulse sequence is similar to the current waveform when the inverter is powered by a smoothed DC voltage, but with pulse-width control of the transistors. The mechanical characteristics are also no different from those of conventional voltage regulation (Fig. 12).

Conclusions. The proposed mechatronic module is a brushless permanent magnet system with the minimum possible number of conductors for external control, which makes it similar to a

DC brushed motor when powered by a pulsed voltage with a controlled duty cycle and changing the polarity of a rectangular pulse sequence to reverse the direction of rotation.

Rectifier and voltage inverter circuits based on pairs of p- and n-channel MOSFETs are suitable for use in mechatronic modules with relatively low power, typically with currents up to 10 A. The advantage of these circuits is that they eliminate the need for additional power supplies for the top drivers. The top p-channel field-effect transistors are controlled directly by the energy of the input supply voltage pulses.

Stable operation of the control system power supplies of the mechatronic modules with the formation of the required output voltages is ensured over the entire operating duty cycle range of the external power supply pulses (from 0.05 to 1). This ensures the operability of the mechatronic module within a given range of change in the average value of the supply voltage.

These mechatronic modules can be used in electromechanical systems for automatic control of moving objects, which previously traditionally used DC brushed motor.

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ПІДХОДИ ДО ПОБУДОВИ МЕХАТРОННИХ МОДУЛІВ НА ОСНОВІ БЕЗКОНТАКТНИХ МАГНІТОЕЛЕКТРИЧНИХ ДВИГУНІВ З ДВОПРОВІДНИМ УПРАВЛІННЯМ

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У статті розглянуто підходи до побудови мехатронних модулів на основі безконтактних двигунів із постійними магнітами з двопровідним керуванням від зовнішнього силового джерела живлення шляхом зміни шпаруватості послідовності прямокутних імпульсів напруги та зміни полярності цих імпульсів для здійснення реверсу механізму. Розглянуто та запропоновано варіанти реалізації елементів структури мехатронного модуля – інвертора напруги, вхідного випрямляча, схем драйверів ключів, джерела живлення. Запропоновано схеми драйверів для перемикання p- та n-канальних польових транзисторів випрямляча та інвертора напруги в умовах живлення мехатронного модуля від послідовності прямокутних імпульсів напруги. Бібл. 27, рис. 14.
Ключові слова: мехатронний модуль, безконтактний двигун із постійними магнітами, широтно-імпульсне регулювання напруги, інвертор напруги, випрямляч на основі польових транзисторів.

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