Józef TUTAJ

SELECTED APPLICATIONS OF THE MOSFETS IN AC-DC RECTIFIER SYSTEMS

Abstract

This paper describes the principles of operation and the physical model of an electronic commutator acting as a reverse-conducting transistor AC-DC rectifier with MOSFETs as fast-switching controlled electrical valves with a low ON-state voltage drop. An electronic commutator, when seen as a transistor AC-DC rectifier, can be used in many fields, e.g., for multifunctional automotive generator/starter and conventional DC motors and generators, generator sets, welding machines, etc. The paper also describes a new reverse-conducting transistor AC-DC rectifier, without the use of optoelectronic separation (which does not require a separate power supply), which may be easily realized in IC technology. Computer simulation allows for currents timing of all components of the electronic-commutator's physical model, both during normal operation as well as in some states of emergency. The paper presents the results of bench experimental studies where the MOSFETs were used as a fast-switching controlled electrical valves with a relatively low ON-state voltage drop. For experimental studies, an electronic commutator has been put together on the Mitsubishi FM600TU module. The reverse-conducting transistor AC-DC rectifier in a three-phase bridge connection has a lot of advantages compared to the conventional diode AC-DC rectifier, such as higher energy efficiency and greater reliability resulting from the lower temperature of electrical valves.

INTRODUCTION

Rectifiers are among the most commonly used converters that convert AC power to DC power. In practice, the ones most commonly used are the uncontrolled rectifiers (diode rectifiers), while in some applications. For example, control of power electronic devices, in particular, high-power applications where control of the average rectified voltage and the power factor on the power supply voltage side, controlled rectifiers are used, which had previously been implemented in thyristor technology and now - the bipolar transistor, MOSFET, HEXFET, IGBT, etc. [1, 3, 4, 5, 6, 8]. In this paper, the author examined an AC-DC rectifier in the three-phase bridge connection, comprising two heteropolar commutating groups of electrical valves. In this rectifier, the more appropriate fully controlled electric valve has replaced the power diode, which is the power field-effect transistor.

Among other things, in the conventional DC generators with electronic commutators (i.e., alternators with diode rectifiers), a rectification of the phase armature currents takes place in the diode rectifier in the three-phase bridge connection. However, in an automotive generator-starter with a magneto-electrically excitation, while acting as the generator with the electronic commutator, realized on the MOSFETs, when it is acting as the rectifier, the MOSFETs are not used for a rectification at all, because only its shunt feedback power diodes are used for rectification. This results in the formation of relatively large power losses for heat in the electronic commutator, heating it, and leading to the need for cooling. The developed rectifier uses a reverse conduction of MOSFETs as low on-state voltage–drop electrical valves your paper for review.

The silicon power diode, which is widely used as a component of the conventional rectifier, has a fundamental disadvantage, namely, a relatively high forward-voltage drop (Fig. 1).

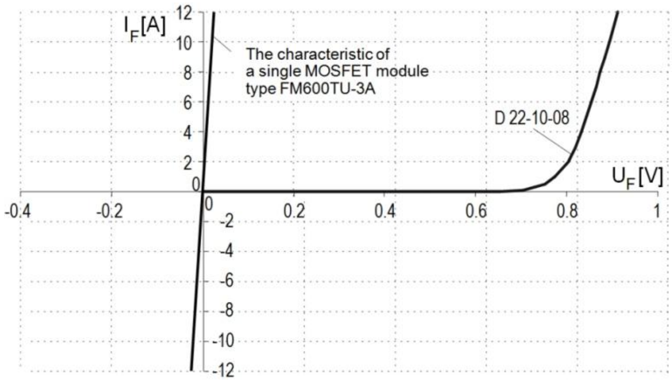


Fig. 1. Comparison of the static characteristics of a power diode type D22-10-08 and a single MOSFET module type TU-3A FM600.

1. TRANSISTOR RECTIFIER OPERATION

The silicon power diode, is widely used as a component of the conventional rectifier diode has a fundamental advantage, which is a relatively large voltage drop in the ON-state of current. Figure 1 shows that in the range of 2 - 10 A current conduction, an ON-state voltage drop on a single MOSFET used FM600 module type TU-3A ($R_{DS(ON)}$ = 1.5 mΩ), is in the range of 0.003 - 0.015 V, while under a power diode of type D22-10-08 the diode forward voltage is in the range 0.8 - 0.9 V. The advantage resulting from the replacement of power diodes with reverse conducting MOSFETs is obvious, especially for small values of currents, when the voltage drop across the electrical valves are reduced repeatedly. For example, for a rectified current of 10 A, i.e., more than 10-fold, which is connected with the same degree of change of decrease of power losses on heat dissipated by the electrical valves. Reducing the power losses of heat dissipated by the electrical valves is connected not only with improving the energy efficiency of the rectifier, but also a reduction in the size and cost of heat sinks, as well as improved reliability, resulting in the lower operating temperature of electrical valves. A MOSFET is an electric valve with bilateral (bipolar) direction of the electrical conductivity and at the full control has linear static characteristic I_D =

f(UDS), flowing the electric current in the first and third quarter of the output static characteristics.

In the literature on fundamental electronics, as well as catalogs of the individual MOSFETs or their modules manufactured [2, 4, 5, 6, 8], are included only single quarter of the output static characteristic. I quadrant (positive) - ID = f(UDS) of the MOSFET (See Fig. 2). However, in the presented case, the transistor rectifier, the author does not use the I quadrant (positive), but instead the III quadrant (negative) of the MOSFET static characteristics (Fig. 2) that is used for AC-DC rectifying, thus yielding the much lower voltage drop across the electrical valves in comparison to the voltage drop of silicon power diodes.

Figure 3 shows a simplified circuit diagram of an electronic commutator, acting as a transistor rectifier in the three-phase bridge connection. Electrical-valve control has been achieved in a simple way, by using the secondary diode rectifier, loaded on its output with the current source, which is realized on the JFET. The secondary diode rectifier is realized on LED optocouplers: D1+ ... D3+, D1- ...D3-, which act as the electric-valve controller, using the L0601 integrated circuit containing quad optocouplers. Phototransistors of optocouplers: Q1 + ... Q3+, Q1- ...Q3- have been used to control the rectifier's electrical valves to generate the MOSFETs' control pulses.

The simulation physical model of the new transistor rectifier in the three-phase bridge connection is shown in Figure 4.

This physical model, acting as the electronic commutator without the use of optoelectronic separation can be implemented as a high-power integrated circuit.

The fundamental problem with the electronic commutator's electric valve control lies in the detection and identification of the direction of the current flowing through each of diodes D1+, D3+, D5+, D2-, D4-, D6- (Fig. 4) and the generation of control signals for the MOSFETs' gates, which at a pre-determined time shunt a diode's activity during the electrical-current conduction.

2. AN INTEGRATED TRANSISTOR RECTIFIE IN THE SINGLE-PHASE BRIDGE CONNECTION WITH AN INTEGRATED STABILIZER

An integrated transistor rectifier with an integrated output-voltage stabilizer with continuous or pulse action may be used as a single integrated circuit, which can and should be replaced in many applications already widely used for this purpose with two separate integrated circuit: a conventional diode rectifier and an integrated stabilizer. However, the use of IGBTs as electrical valves in existing transistor rectifiers, results in significant power losses due to the relatively high voltage drop cross a single IGBT when acting in ON-state $U_{KE\ (ON)}$ = 3.3 V. Since the electrical valves of the electronic commutator operate in a three-phase bridge connection, the total voltage drop across the two electrical valves at the same time conducting electrical current exceeds 6.5 V.

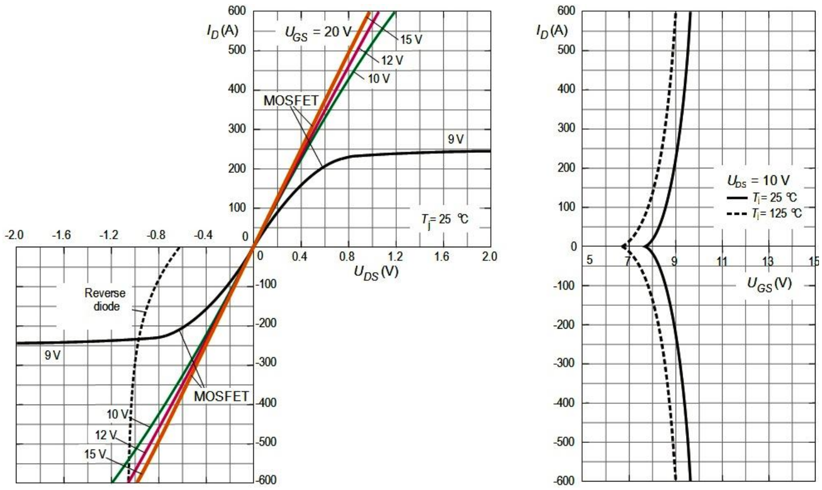
a)  b)

***Fig. 2.** Full range of output static characteristics of MOSFET with a built-in fast, shunt-feedback diode (a) and its transient characteristics (b).*

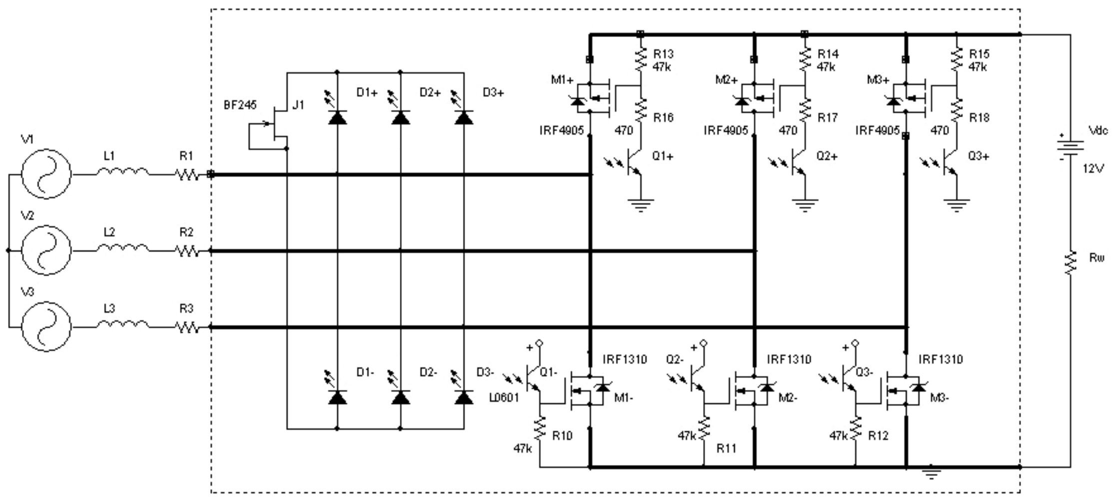


***Fig. 3.** Electrical circuit of a simple transistor rectifier in the three-phase bridge connection.*

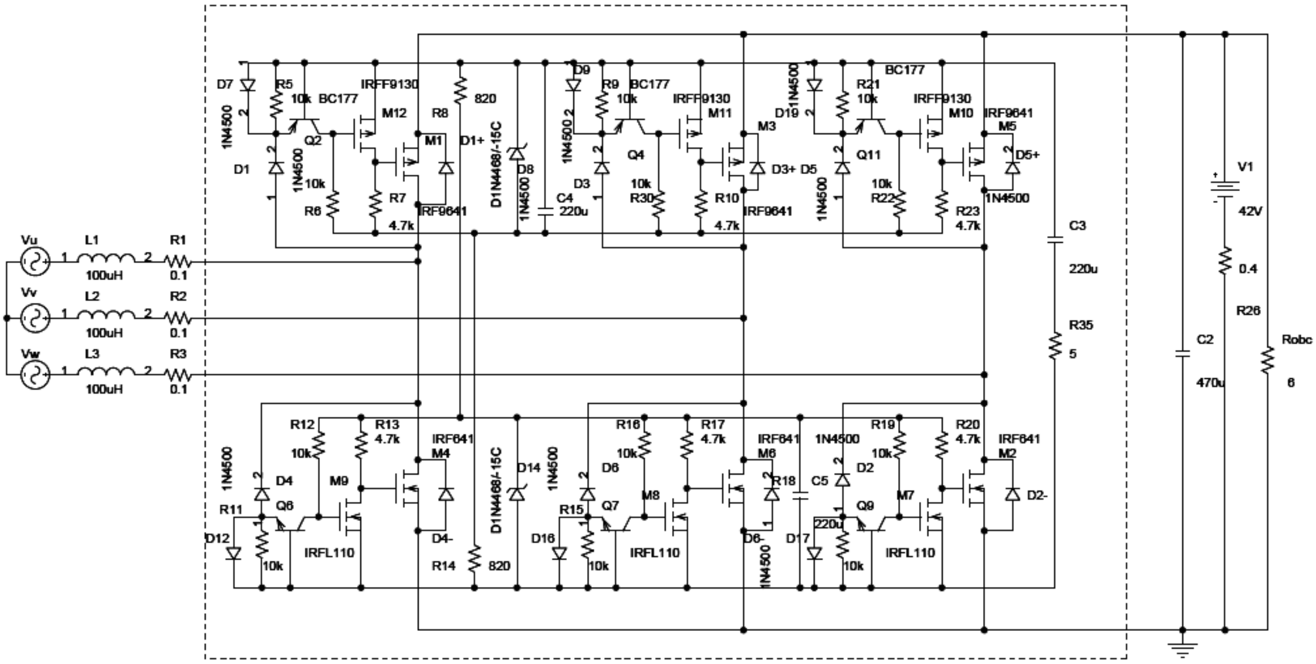


Fig. 4. *Electrical circuit of a transistor rectifier acting as an electronic commutator.*

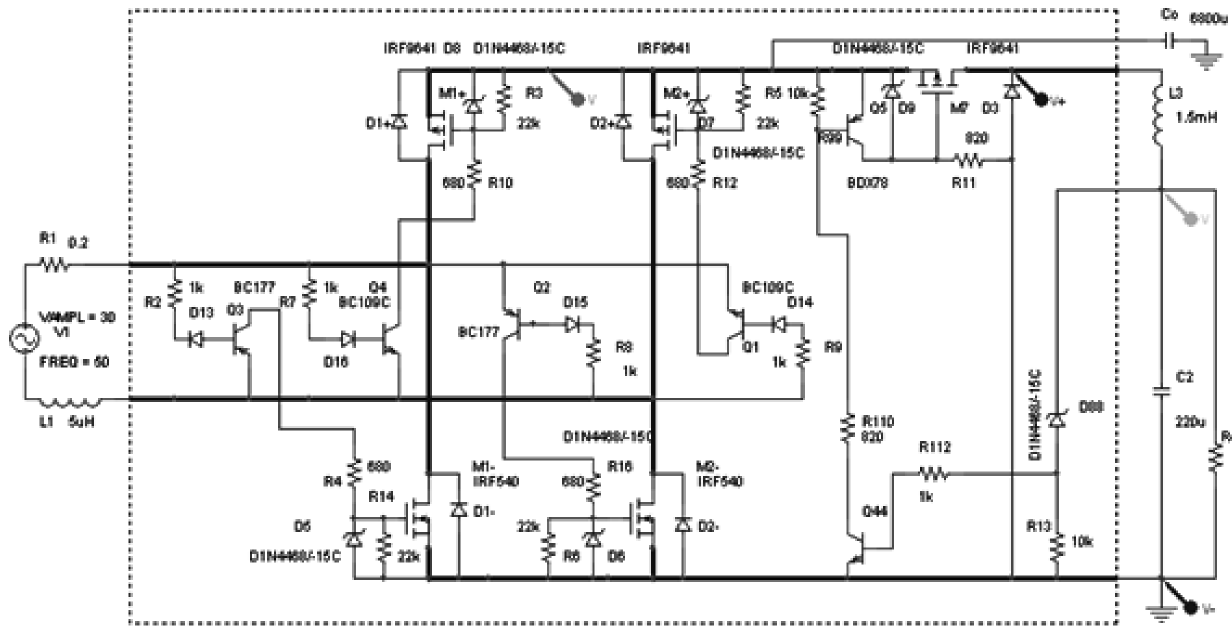


Fig. 5. *Electrical circuit of an integrated transistor rectifier in the single-phase bridge connection with an integrated stabilizer.*

3. COMPUTER SIMULATION ANALYTICAL STUDIES OF TRANSISTOR RECTIFIER IN THE BRIDGE CONNECTION

An important advantage of the transistor rectifier under consideration is the use of MOSFETs in order to reduce voltage drops across the electrical valves. Below are presented the results of computer simulation in PSPICE of the transistor rectifier in the single-phase bridge connection (See. Fig. 6).

The physical model of the modified transistor rectifier in the three-phase bridge connection, without the use of optoelectronic separation, and which does not require a separate power supply is easy to implement in integrated technology, as shown in Figure 4.

In order to perform a rapid computer simulation of the transistor rectifier the author adopted a simplified simulated physical model of the three-phase AC power source.

In Figures 7, 8 the selected, characteristic waveforms during normal operation are shown, both in the main transistor rectifier's circuits, as well as the MOSFETs gate-pulses control circuits.

At the same time, the nominal values (ratings) of supply AC voltages were chosen as those corresponding to the generator's average load in real conditions.

As an example, Figures 7 show the waveforms of the neutral voltage as regards to ground, power-supply, voltages and the control voltage across the gate of the MOSFET. When the transistor is given the function of current conduction, the shunt diode current is much smaller.

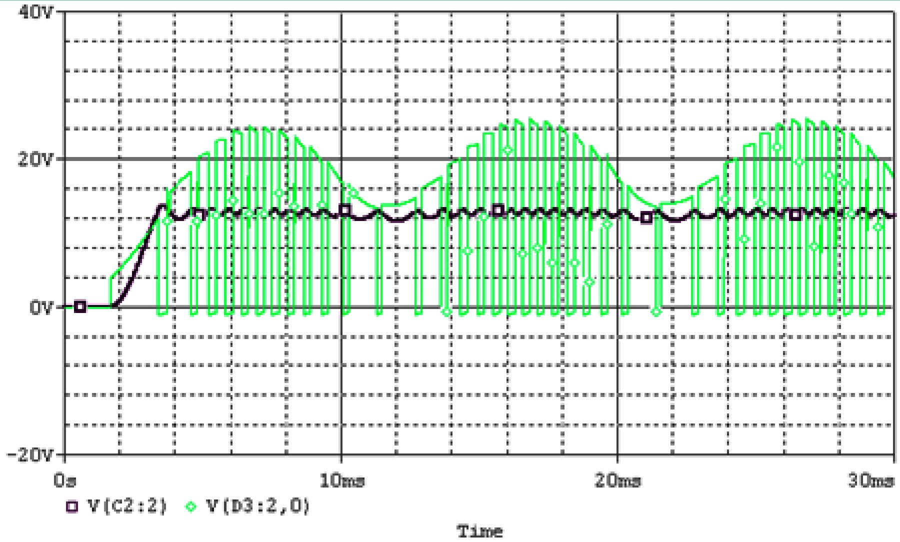


Fig. 6. *Selected waveforms of the integrated transistor rectifier in the single-phase bridge connection with an integrated stabilizer (See Fig. 5).*

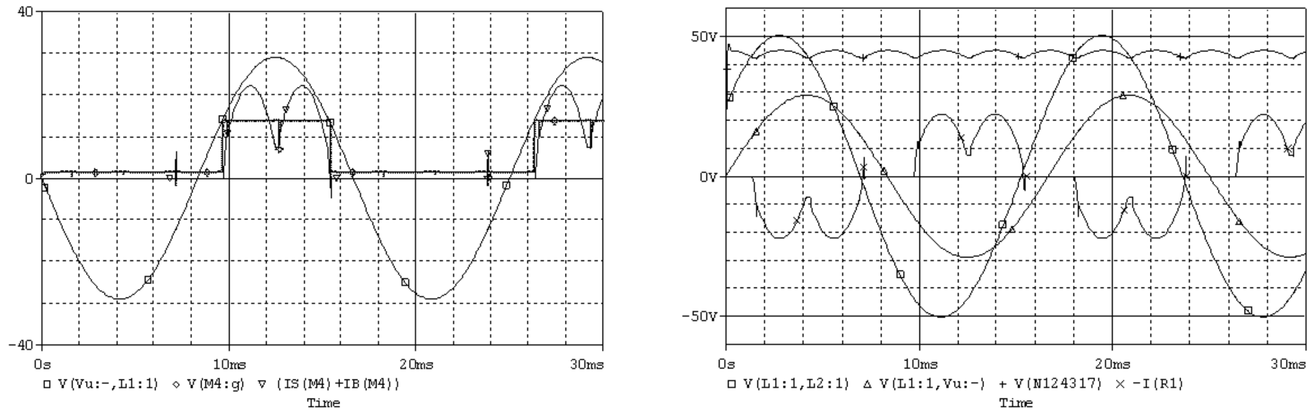


Fig. 7. *Selected waveforms of the voltages and currents in the modified transistor rectifier in the three-phase bridge connection at the frequency of 60 Hz.*

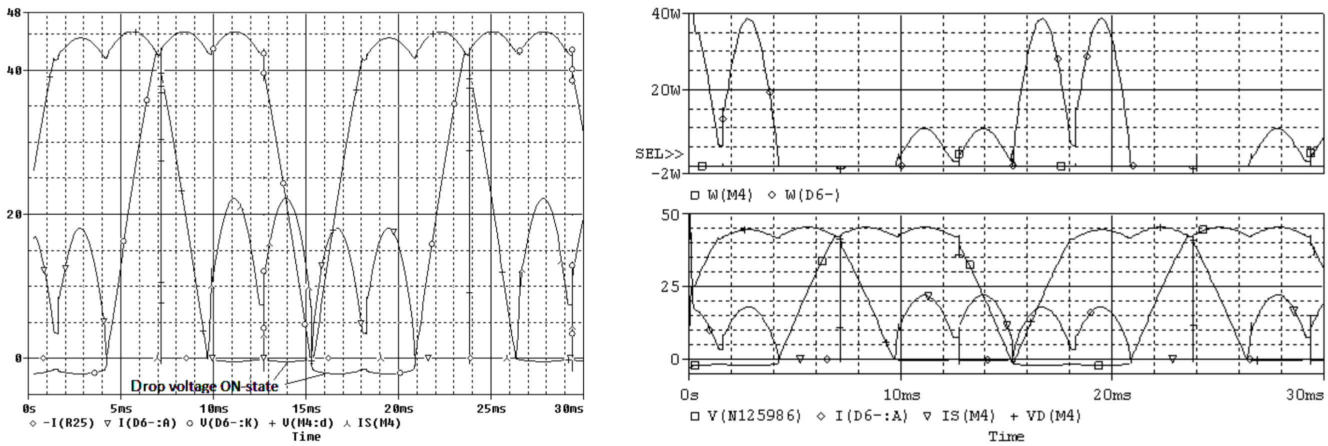


Fig. 8. *Selected waveforms of the transistor rectifier's voltages, currents and power losses to heat (comparison of electrical valves' conduction).*

Figure 8 shows the waveforms of the currents flowing through the transistor rectifier's electrical valves, and the voltages across electrical valves, both in the ON-state as well as OFF-state (blocking).

For a comparison of the currents and voltage drops as well as to estimate the power losses on the diode rectifier's electrical valves and transistor rectifier' electrical valves, the author made the following experiment: he conducted a computer simulation of the modified transistor rectifier, with one of the MOSFETs disabled (M4 in Fig. 4). The function of the current conduction in the transistor rectifier is taken over by the D6– diode.

The waveform shown in Figures 8 the difference in the voltage drops between the D6 diode and MOSFET current conduction in the adjacent branch of the three-phase bridge connection (part of the waveform under the of the zero-axis). Moreover, there occurs much less voltage drop of the MOSFET during current conduction, compared to the voltage drop across the diode rectifier's electrical valves, causing a significant reduction in heat losses, and the difference in the voltage drops across the electrical valves results in an increase in the output voltage, as shown in Figure 8.

Significant reduction in voltage drops across the MOSFET, compared to voltage drops across the diode, is confirmed in the experimental studies given below.

4. EXPERIMENTAL STUDIES

An electronic commutator of the generator-starter with the electromagnetic excitation, based on the dual electrical machine, is made on the six MOSFETs integrated module in a single enclosure using a new generation of such modules FM600 type TU-3A Mitsubishi Electric Semiconductor (Fig. 9) [9].

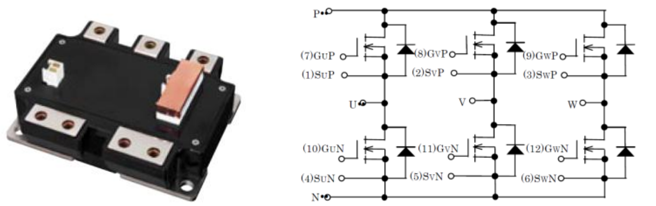


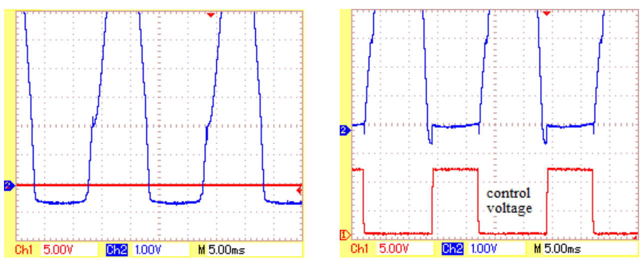
Fig. 9. *A view and an electric circuit of FM600TU-3A module interconnections [9].*

The main advantages of this module compared to similar - this kind are:

– very low ON-state resistance R_{ON} = 1.5 mΩ (typical) R_{ON} = 2.2 mΩ (max.);
– fast feedback diodes, parallel to the MOSFET electrical valves;
– built-in thermistor temperature sensor for a temperature control module;
– convenient terminals for connection to the electrical power supply;
– favorable load parameters: U_{DS} = 150 V, I_D = 300 A (maximum current pulse 600 A), each of the six built-in MOSFETs.

Each of MOSFETs of the module is an almost ideal electrical valve - drain current in OFF-state cannot exceed the value of 1 mA, and the saturation voltage U_{DS} at a current conduction of 300 A, and at 25°C is of 0.66 V.

Below in Figure 10 shows the results of bench experimental studies in the form of voltage waveforms on electrical valves and transistor and diode rectifiers in a single-and/or three-phase bridge connections.



(a) (b)

Fig. 10. *Voltage waveforms on electrical valves: (a) a diode rectifier, (b) transistor rectifier in the single-phase bridge connection, at the load current 10A.*

Below the zero-axis in the oscillogrammes (see Fig. 10) is registered the voltage on the electrical valve with the positive value (during ON-state), while above this zero-axis – the reverse voltage, which due to the relatively large maximum value of this voltage has been recorded only partially.

Comparing the voltage waveforms on the diode and transistor rectifiers' electrical valves, one can easily notice a significant decrease in the voltage drop across the conductive MOSFET (see Fig. 10b) - the voltage-drop value during applying gate control signal is very small, almost imperceptible, while for the diode rectifier (see Fig. 10a) it is significant, around 0.8 V.

The presence of a significant voltage drop across the diode rectifier's electrical valves causes them to overheat and causes deterioration of energy efficiency as well as the need for effective ventilation of the diode electronic commutator, which generates more power dissipation caused using an additional fan. The waveforms depicted in Figure 10 show that during controlling of the electronic commutator's electrical valves, it can be obtained a substantial improvement of the energetic parameters. A voltage drop across the single MOSFET electrical valve is about 60 mV (peak value) at a load current of 20 A, which is more than 10-fold reduction compared to the same in the diode rectifier.

These reduce, in the analogous degree, the power losses and increase an efficiency of the electronic commutator, and thus the energetic efficiency. In this case, the rectification of the armature phase currents is almost perfect.

Figure 11 shows the electronic-commutator-driver's mounting plate, based on integrated circuit IR2136, which is installed on a connector box of the MOSFET module, located in the terminal box of the electric machine.

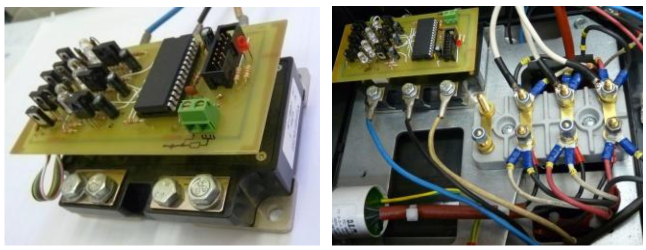


Fig. 11. *View of the electronic-commutator-driver's plate based the integrated IR2136, and its installation in the terminal box of the electric machine.*

The driver plate is designed with the assumption that the controller's output terminals are at the same time the connector (plugs) of the MOSFET module. This allows avoiding additional wired connections between the mounting plate and the MOSFET module's driver, due to these resistance, inductance, and capacitance parasitic values are reduced; and more compact design of the modified electronic commutator of the electrical machine is obtained.

CONCLUSIONS

The paper presents the principle of the uncontrolled transistor rectifier single- and/or multi-phase. The results of computer simulation waveforms of power and voltages are also given as well as of the currents of the uncontrolled transistor rectifier in single- and/or multi-phase, single- and/or double-way connections using PSPICE. The possibility of using a modified transistor rectifier in low-voltage power supply systems is indicated. In comparison with the conventional diode rectifiers (realized on the silicon power diodes), the transistor rectifier, exhibit a number of advantages, namely: they have a much lower forward-voltage drop, and therefore less power losses on heat, and better energetic efficiency and reliability. These transistor rectifiers can be made in the form of a Modular Circuit (MC) or an Application Specified Integrated Circuit (ASIC). Computer simulation allowed for the imitation of any selected waveforms of voltages and currents in the electronic commutator acting as a modified transistor rectifier.

This simulation also confirmed the benefits of using a transistor rectifier instead of a conventional diode rectifier, such as higher energetic efficiency (reduction of power losses caused by the heat in the electronic commutator) and the associated reliability.

REFERENCES

1. Fijalkowski B., Single Chip Macrocomutator - An Indispensable Module of New Concept AC and/or DC Dynamotors for Automotive Very Advanced Propulsion Systems, EVS9, November 13-16, Toronto, Ontario, Canada, 1989.
2. Malikopoulos A., Filipi Z., Simulation of an Integrated Starter /Alternator (ISA) System for the HMMWV, Proc. 2006 SAE World Congress, April 3- 6 Detroit, Michigan, 2006.
3. Ochije K., Pollock Ch., A Controlled PWM AC/DC Converter for a High-Speed Brushless Generator for Minimum kVA Rating, IEEE Transactions on Industry Applications, Vol. 40, No. 3 May/June 2004.
4. Pelz G., Mechatronic Systems: Modelling and Simulation with HDLs, John Wiley & Sons, 2003.
5. Rashid M., Power Electronics Handbook, 3rd Edition, Elsevier, 2011.
6. Rodriguez J., Silva E., Modelling, Analysis and Simulation of Matrix Converters, Proceedings of the International Conference & Workshop on Emerging Trends in Technology, New York, 2011.
7. Tutaj J., Fijalkowski B., High-Performance AC-DC Power Electronic Converter Generator for Hybrid-Solar Vehicles, Journal of Energy and Power Engineering, Vol. 9, No. 7, July 2015.
8. Vázquez N., Three-Phase Rectifier With Active Current Injection and High Efficiency, IEEE Transactions on Industrial Electronics, Vol. 56, No. 1, January 2009.
9. www.mitshubishichips.com

WYBRANE ZASOSOWANIA TRANZYSTORÓW MOSFET W UKŁADACH PROSTOWNIKOWYCH

STRESZCZENIE

Artykuł opisuje zasadę działania oraz modele fizyczne komutatorów elektronicznych, działających jako tranzystorowe prostowniki z wykorzystaniem tranzystorów MOSFET z wstecznym przewodnictwem prądu jako klucze elektroniczne o małym spadku napięcia. Komutator elektroniczny, dzialający jako tranzystorowy prostownik, może być stosowany w wielu dziedzinach, na przykład, jako prostownik prądnicy samochodowej i konwencjonalnego prądnico-rozrusznika, spawarek mobilnych itp. Artykuł opisuje również nową konfigurację prostownika tranzystorowego bez użycia optoelektronicznych elementow separacyjnych, dzięki czemu możliwa jest łatwa realizacja prostownika w technologii układów scalonych. Symulacja komputerowa pozwala na uzyskanie przebiegów czasowych prądów i napięć na wszystkich elementach modelu fizycznego komutatora elektronicznego, zarówno podczas normalnej pracy, jak również w wybranych stanach awaryjnych. W pracy przedstawiono również wyniki badań laboratoryjnych, gdzie eksperymentalne tranzystory MOSFET były używane jako szybko przełączalne sterowalne zawory elektryczne (klucze elektroniczne) o stosunkowo niskim spadku napięcia w stanie przewodzenia. W badaniach eksperymentalnych, jako komutator elektroniczny został wykorzystany moduł tranzystorów MOSFET typu FM600TU firmy Mitsubishi. Tranzystorowy prostownika trójfazowy w układzie mostkowym ma wiele zalet w porównaniu z konwencjonalnym diodowym prostownikiem, takich jak wyższa sprawność energetyczna oraz większa niezawodność, wynikająca z niższej temperatury zaworów elektrycznych. W artkule zamieszczono również prostownik tranzystorowy jednofazowy, zintegrowany ze stabilizatorem impulsowym, który może być zrealizowany również jako jeden układ scalony.

Autor:

Józef Tutaj - Mechatronics Institution, Institute for Automotive Vehicles and Combustion Engines, Department of Mechanical Engineering, Krakow University of Technology, Al. Jana Pawła II 37, PL 31-864 Krakow, E-mail: **pmtutaj@cyf-kr.edu.pl**, Tel. +48 12 628-33-23.