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Improving energy indicators of pulse converters

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ABSTRACT

All rectifier circuits are divided into single-phase and three-phase, according to the number of phases of the supply network, single-cycle and two-cycle. Voltage conversion, which can vary in both frequency and amplitude, is carried out by two series-connected converters-a rectifier (AC/DC converter) and an inverter (DC/AC converter). Using simulation techniques in the MATLAB-based Simulink environment, the blocks used were taken from the sim power system/Simscape library. Models of semiconductor converters with pulse-width modulation based on one power thyristor switch and a semiconductor converter with pulse-frequency modulation based on four power thyristor switches have been developed. Experiments prove the correctness of the models. The results of a study of the developed models of semiconductor converters with pulse-width and pulse-frequency modulation are presented. The static and dynamic characteristics of pulsed semiconductor converters are presented. Analysis of the static characteristics of pulse converter circuits showed that the rigidity of the output characteristics of converters with pulse-frequency modulation is higher than that of converters with pulse-width modulation. The results of assessing the efficiency of pulsed semiconductor converters based on the analysis of static output characteristics allow us to conclude that the efficiency of a semiconductor converter with pulse-frequency modulation is more than one percent higher than that of a semiconductor converter with pulse-width modulation.

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1. INTRODUCTION

A huge amount of electric motor control methods exist [1]-[3], but the mostly applied is the pulse-width modulation (PWM) [4]-[6]. This method allows to create required shape, frequency and amplitude of motor voltage, to achieve high smoothness and large range of controlling angular velocity with changing load in wide range [7]-[9]. Frequency regulation, starting and braking are among the most economical methods of controlling squirrel-cage asynchronous motors. Currently, frequency control is considered appropriate when powering motors from static frequency converters (FCs), covered in [10], [11]. To regulate an asynchronous

electric motor (IM) of medium and low power, an inverter with PWM is used more often than others according to work [12]. Such inverters provide electric drives with:
– Increased controllability.
– Speed due to the ability to obtain almost any required ratio of frequency and amplitude of the supply voltage.

Along with the advantages, PWM inverters have a number of disadvantages indicated in [12]:
– The voltage at the output of an inverter with PWM differs significantly from the sinusoidal voltage obtained when the IM is powered from a conventional alternating current network with a frequency of 50 Hz, and this circumstance requires taking into account the presence of higher harmonics in the voltage curve supplied from the inverter to the IM.
– The consequences of non-sinusoidal power supply include fluctuations in the electromagnetic force of blood pressure, an increase in eddy currents and mechanical resonances in the kilohertz range, which lead to increased noise and vibration.
– Torque fluctuations and acoustic noise can be reduced by increasing the valve switching frequency.

Modules with IGBT transistors have the following advantages:
– The turn-on time is hundreds of nanoseconds to a few microseconds.
– Multiple current overloads lasting up to 10 μs are allowed, which allows for their reliable protection at the control input according to [13].
– The IGBT is controlled by special driver chips with their own power and protection sources according to works [14], [15].
– Unfortunately, the PWM method has a number of disadvantages: efficiency drop, high cost of power switches (transistors), high electromagnetic noise [10]-[16].

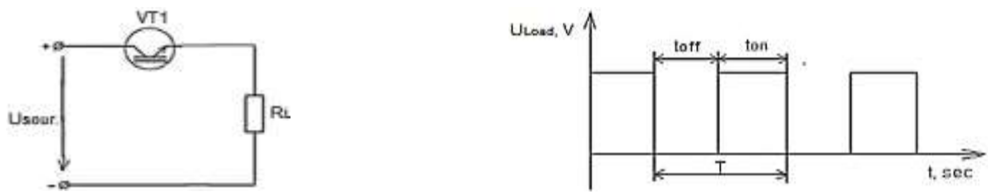
But there is one more method of pulse controlling, namely control through frequency-pulse modulation (FPM). This method is implemented by using DC pulse-frequency convertor (PFC), which potentially has advantages over the PWM method [3]: high efficiency, low cost of power switches (thyristors), low electromagnetic noise [17]-[19].

2. METHOD

In recent decades, it is impossible to imagine the modern branch of electrical engineering and household electrical engineering without the use of rectifiers. According to Sigala *et al.* [7] and Dovudov [9], to the type of power circuit, the rectifier is divided into single-phase and three-phase, according to the number of phases of the supply network, single-cycle and two-cycle. The voltage conversion from the input of the synchronous generator, which can change both in frequency and amplitude, is carried out by two series-connected converters - a rectifier (AC/DC converter) and an inverter (DC/AC converter).

2.1. Modeling the circuit of the pulse-width converter

The PWM is the main control unit of the pulse-width converter. A pulse-width converter converts a DC voltage [1] into a pulse-type voltage signal, the average value of which (i.e., its constant component separated by filters in the load) can be adjusted. The principle of the PWC-based output voltage control is based on the periodic switching on and off of gate switches–transistors or thyristors. Figure 1 shows the basic PWM circuit [14] Figure 1(a) and the load voltage curve Figure 1(b).



(a) (b)

Figure 1. Basic PWM circuit (a) pulse-width modulated semiconductor converter and (b) load voltage diagrams at r-load

The circuit consists of a VT1 transistor (IGBT), which operates in switch mode, power source (PS) and load (RL). Such a circuit provides only unipolar modulation. When the VT1 transistor is turned on (in switch mode) a positive voltage pulse is generated at the load. When the VT1 transistor is turned off, a voltage pause is formed at the load.

The most important parameter that characterizes the PWM operation is the pulsing ratio γ, which can be calculated using (1):

$$\gamma = \frac{t_{on}}{T} = \frac{t_{on}}{t_{on}+t_{off}} \quad (1)$$

where t_{on} – the duration of the positive or negative voltage pulse applied to the load; t_{off} – the duration of the pause; T – the period of PWM operation.

The $U_{Load} - \gamma$ curve is called the adjustment characteristic of the PWC [1], which can be calculated using (2):

$$U_{Load} = U_{sour} \cdot \gamma \quad (2)$$

where U_{Load} – voltage of load, $U_{sour.}$ – power supply voltage, γ – duty cycle.

The average value of the load voltage can be controlled by changing γ. The maximum load voltage is obtained when the pulsing ratio value γ =1. A single transistor PWC circuit Figure 1(a) is modeled in MATLAB environment, using blocks from the Simulink/SimPowerSystem library [15]-[21]. The method of modeling and the correct operation of the PWC model is proved by an experiment, which is described in detail in [14].

The PWC model, which is shown in Figure 2, contains: a voltage control unit (UC), which operates within the 0-10 V range; a PWM control system unit (CSU PWM) and a PWM power circuit unit, consisting of an IGBT transistor, an active load RL and a power (source) block, represented as a battery with a voltage rating of 100 V. The developed PWC model is unique in the way that it simultaneously displays the efficiency of the converter in addition to the load current and voltage. This allows to save time on calculating the power and efficiency characteristics of the PWM circuit. Figure 3 shows diagrams of currents and voltages under active load, as well as diagrams of current and voltage in the transistor VT1. These diagrams were obtained as a result of modeling for active load with duty cycles of 0.6.

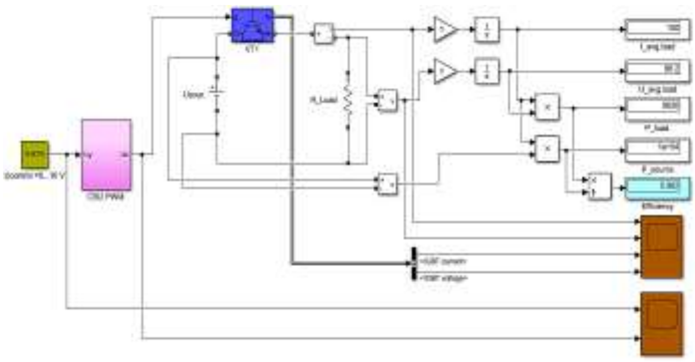


Figure 2. The model of the PWM converter

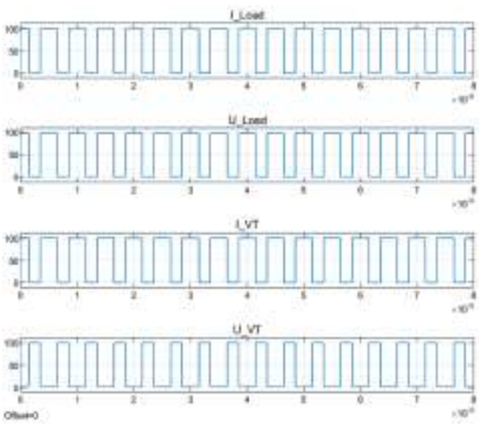
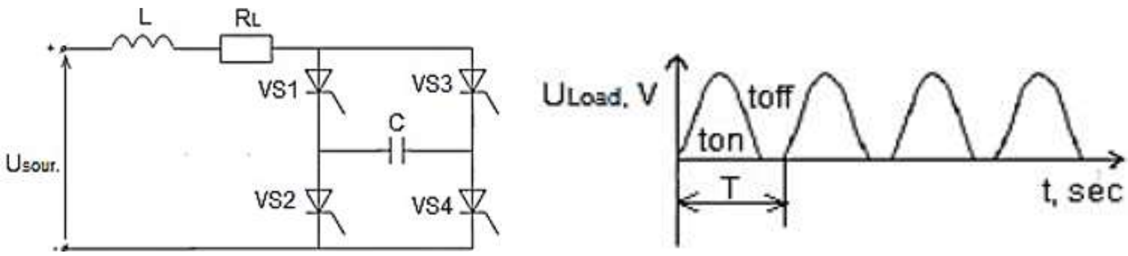


Figure 3. Dynamic performance of PWC operation with the pulsing ratio γ=0,6: 1) load current (IL); 2) load voltage (UL); 3) current (IVT) of the transistor VT1; 4) voltage (UVT) of the transistor VT

2.2. Modelling the circuit of the frequency-pulse converter

PFC output voltage Figure 4. The diagram shown in Figure 4(a) is an example of a power PFC. In fact, this is a diagram of a single-phase inverter, the load RL is connected to the DC (pulsating) side. The PFC output voltage is controlled by changing the output PWC frequency with constant pulse time (width) of output voltage ton, in other words the pause time is changed Figure 4(b).



(a) (b)

Figure 4. PFC output voltage (a) power circuit frequency-pulse converter and (b) load voltage diagrams at R-load

The diagram consists of: VS1-VS4 – power thyristors, connected in bridge diagram; C – switching capacitor; L – switching coil; RL – active load. The circuit operates as follows. Control pulses alternately open switch of thyristor pairs VS1-VS4 and VS2-VS3. The switching capacitor C recharges following the operation principles of RLC circuits with one of thyristor pairs (VS1-VS4 or VS2-VS3).

Main operation mode of the circuit Figure 4(a) is the mode of intermittent current on the load. In this case there might be natural switching of thyristors, that is those of working pair are switched off, when capacitor C is charged and current drops to zero. It should be noted, that this switching method is reliable.

Similarly, the dependence of UL on frequency duty cycle f is referred to as regulation curve/characteristics of pulse frequency converter (PFC) which is calculated as follows:

$$U_{Load} = U_{max} \cdot f_{rel.} \qquad (3)$$

where U_{max} – maximum output voltage of PFC, $f_{rel.}$ – relative frequency. The maximum voltage corresponds to maximal output-pulse frequency $f_{rel.} = \frac{f}{f_{max.}}$. By changing f, the average load voltage can be regulated.

Fully-controlled Bridge PFC model Figure 4(a) is developed by means of MATLAB software using Simulink/Simscape libraries Figure 5. The adequacy of the PFC model operation is proved by means of the experimental study, which is described in detail in [20]. PFC model consists of:

- Control (regulation) block Uc – control voltage, which is within the interval from 2 V to 24 V. The frequency f reacts to Ur regulation accordingly.
- The pulse generator (PG) block includes elements of Simscape library, which is shown in Figure 7.

Simscape is the software tool which enables to rapidly create models of physical systems within the Simulink environment. The basic library of Simscape includes such sublibraries as: foundation library, driveline, electrical, fluids, and multibody. Simscape allows to model systems such as electric motors, bridge rectifiers, hydraulic actuators, and refrigeration systems, by assembling fundamental components into a schematic.

Connecting lines in Simscape, a physical connection model is obtained by means of which the signal is transmitted. Connecting blocks in Simulink model, lines have arrows [22]-[25]. This means that signals are transmitted in one direction only, i.e. the energy flow is unidirectional. Unlike Simulink, in Simscape model, the lines that connect the physical elements do not have arrows and the energy flow is bi-directional.

The main elements that are used in Simscape model for measurement are shown in Figure 6. They include current sensor and voltage sensor blocks, which are ideal sensors. The current and voltage sensor converts the current and voltage measured in any electrical branch into a physical signal which is proportional to the current and voltage.

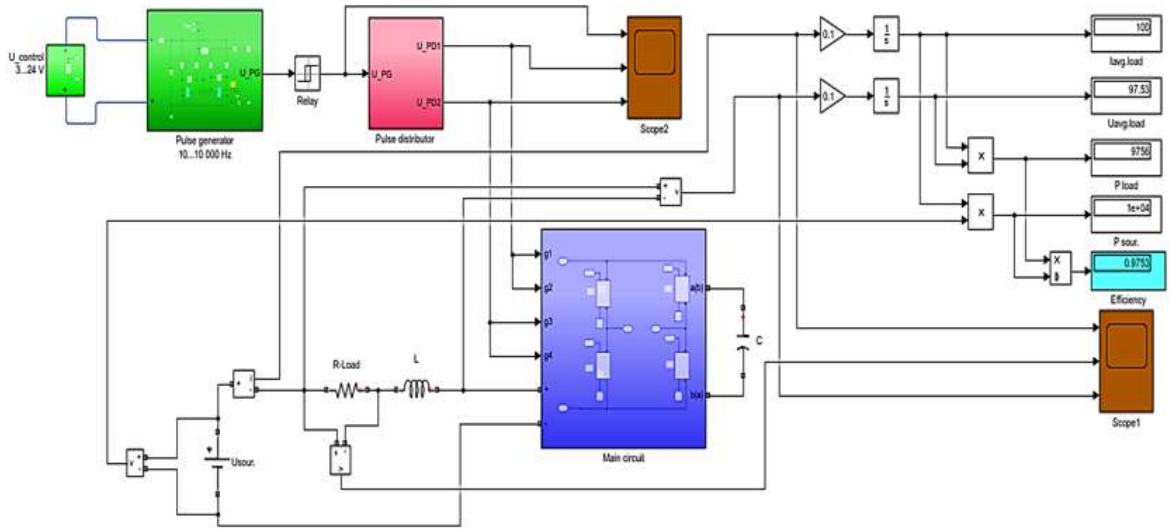


Figure 5. PFC model

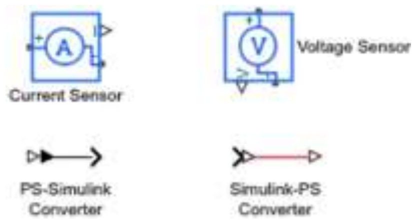


Figure 6. The main elements in Simscape

In order to convert a physical signal to a Simulink output or a Simulink input to a physical signal, the PS-Simulink converter and the Simulink-PS converter are used. These blocks convert a physical signal to a Simulink output signal and vice versa. The parameters of the elements that were used in the PG model are shown in Table 1. Transistors V1, V2 are n-p-n bipolar ones.

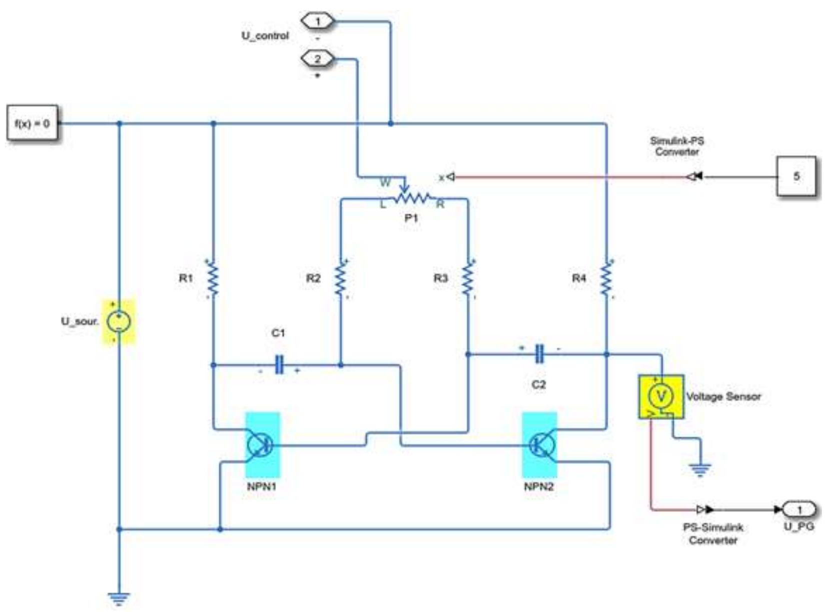


Figure 7. Square wave generator model

Table 1. Parameters of the PFM model elements

Ucontrol.	Usource	R1, R4	R2, R3	C1, C2	P1
V		kOmh		nF	кОм
3···24	6	0,1	10	140	5

Pulse distributor (PD) block over control channels. The developed model of the PD block over control channels is shown in Figure 8. The input signal is square wave pulses of pre-determined frequency from PG block. Using the SR latch and NAND logic gates, the PD forms output square wave pulses with a 180 degree shift and a frequency that is half the frequency of the PG.

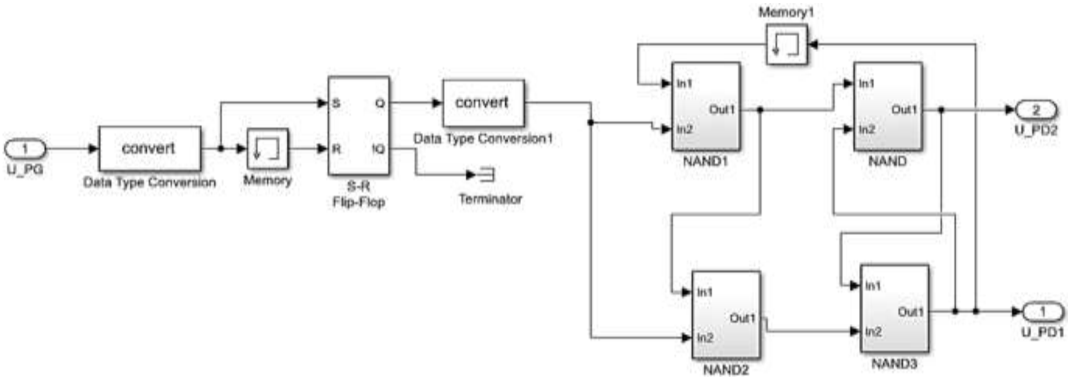


Figure 8. The model of PD block over control channels

The voltage UPD1 is supplied to the control electrodes of the thyristors VS1 and VS4. Consequently, through the inductance L, the load RL and the capacitor C, current flows. In this case, the capacitor C is charged. When voltage UPD2 is supplied to unlock thyristors VS3 and VS2, capacitor C turns off thyristors VS1 and VS4 and the current will flow through inductance L and load RL. Capacitor C starts charging again. Thus, the turning on thyristors occurs when pulses are supplied from the DG block. The thyristors are turned off due to the discharge of the capacitor C. Figure 9 shows the diagrams of the formed square wave pulses.

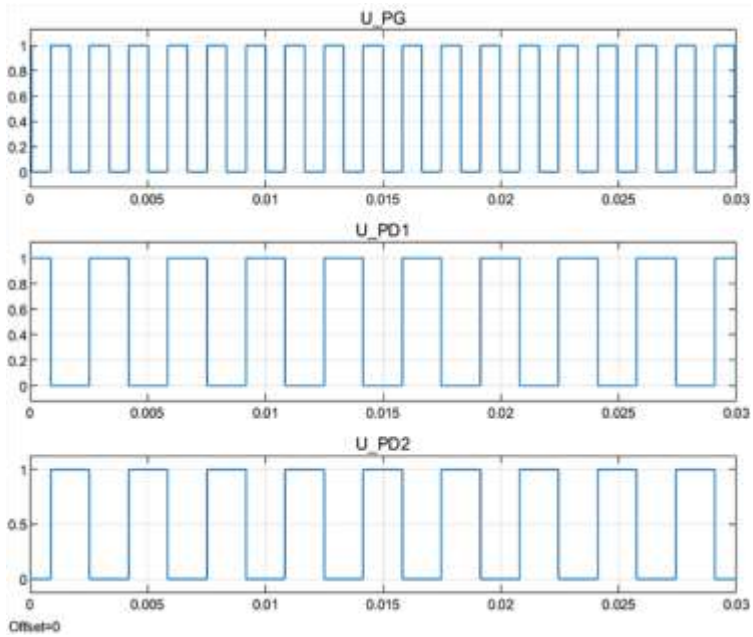


Figure 9. Diagrams of the formed square waves pulses

PFC power circuit block, which is shown in Figure 10, consists of thyristors VS1-VS4; load RL; commutation inductor L, connected in series with the load; commutating capacitor C connected to the middle of the bridge circuit; and 100 V power supply.

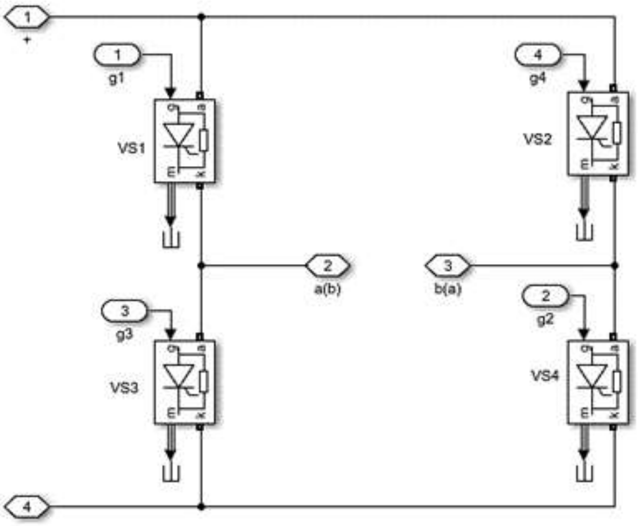


Figure 10. PFC power circuit block

3. RESULTS AND DISCUSSION

The developed PFC model as well as the PWC model, simultaneously calculates and shows the load current, load voltage and converter efficiency. Figure 11 shows the dynamic characteristics of the PFC operation at a frequency f = 145 Hz (γ = 0.6), obtained as a result of simulation. As can be seen from Figure 11, at low frequencies there is a pause between the pulses and at the frequency which corresponds to nominal operating condition of the converter, the pulses are superimposed on each other. It results in nonlinear static control characteristic of the PFC [20].

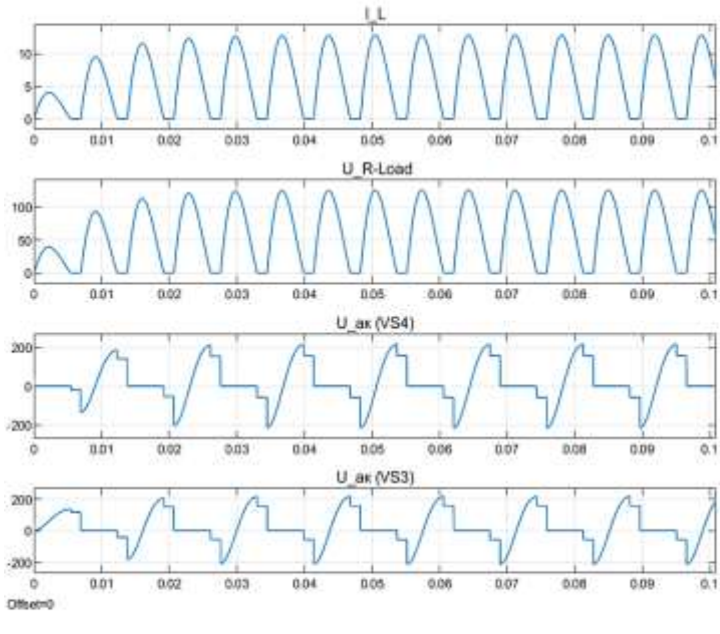


Figure 11. Dynamic characteristics of the PFC operation at a frequency of f = 145 Hz (γ = 0.6): the first graph- load current (IL); the second graph- load voltage (UR); the third graph- voltage (Uak) of the thyristor VS4; the fourth graph - voltage (Uac) of the thyristor VS3

3.1. Comparison of PWC and PFC characteristics

For the purpose of the PWC and PFC energy indicators comparison the studies were carried out on the developed models. The results are shown in Figures 12 and 13.

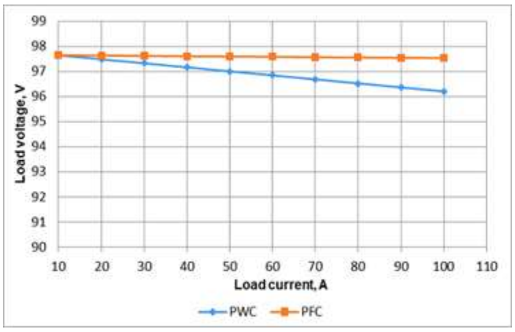


Figure 12. Output characteristics of pulse converters at rated operating conditions

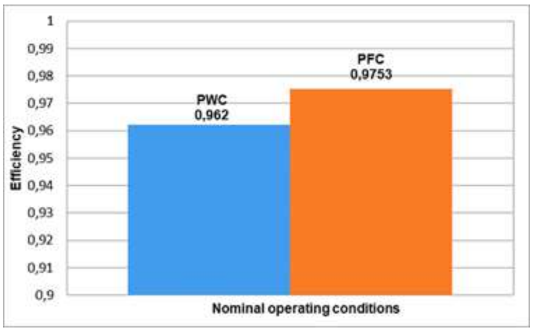


Figure 13. Efficiency of pulse converters at nominal operating conditions

Figure 12 shows the output characteristics of the PWC and PFC at nominal operation. As can be seen, the output characteristic of the PFC has more robustness than the output characteristic of the PWM. This is due to the fact that the transistor has a higher internal resistance than the thyristor. Figure 13 shows the characteristics of the pulse converters efficiency at nominal operating conditions. It is obvious that the efficiency of the PFC exceeds the one of the PWC by 1.33%. This is due to the fact that the output characteristic of the PFC has more robustness than the output characteristic of the PWM.

4. CONCLUSION

Models of converters with pulse width and pulse frequency modulation were studied using the MATLAB/Simulink software environment using blocks from the SimPowerSystem/Simscape libraries. The results obtained based on the developed research models are presented in the form of converters with dynamic and static characteristics. The analysis of the obtained characteristics showed that the use of the PFM control method increases the efficiency of the energy characteristics and thereby increases the efficiency of pulse converters in comparison with the PWM control method. The obtained models can be used for the purpose of study the control of DC electric drives.

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