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Analysis and comparison of energy indices of dc-dc pulse converters

***Abstract**. The computer simulation was used in order to analyze and compare circuit configurations of pulse-width converters and pulse-frequency converters. The principle of operation and main differences were described. The circuits of pulse-width converter and pulse-frequency converter were modelled in the Matlab software using blocks from the following library: Simulink / SimPowerSystem / Simscape. The block, which performs calculation of static and dynamic power losses of insulated gate bipolar transistor (IGBT), was created. The performance curves of the IGBT were approximated in order to calculate losses. The obtained curves quite accurately describe those of the IGBT in use (CM800HC-66H by MITSUBISHI). It was shown that dynamic losses can be reduced and conversion efficiency can be increased when using the pulse-frequency converters in comparison with pulse-width converters. It was noted that for values of duty cycle in the range from 0.1 to 0.5 the efficiency of pulse-frequency converter is significantly higher than that of pulse-width converter.*

***Streszczenie.** Symulacja komputerowa została wykorzystana do analizy i porównania konfiguracji obwodów przetworników o szerokości impulsu i częstotliwości impulsu. Opisano zasadę działania i główne różnice. Obwody przetwornika szerokości impulsu i przetwornika częstotliwości impulsu zamodelowano w programie Matlab z wykorzystaniem bloków z biblioteki: Simulink / SimPowerSystem / Simscape. Stworzono blok, który wykonuje obliczenia statycznych i dynamicznych strat mocy tranzystora bipolarnego z izolowaną bramką (IGBT). Krzywe wydajności IGBT zostały przybliżone w celu obliczenia strat. Otrzymane krzywe dość dokładnie opisują krzywe zastosowanego tranzystora IGBT (CM800HC-66H firmy MITSUBISHI). Wykazano, że przy zastosowaniu przekształtników impulsowo-częstotliwościowych można zmniejszyć straty dynamiczne i zwiększyć sprawność konwersji w porównaniu z przekształtnikami o szerokości impulsu. Stwierdzono, że dla wartości współczynnika wypełnienia w zakresie od 0,1 do 0,5 sprawność przetwornika częstotliwości impulsów jest znacznie wyższa niż przetwornika szerokości impulsu. (**Analiza i porównanie wskaźników energetycznych przetworników impulsowych DC-DC**)*

Keywords: pulse converter, pulse-width modulation, pulse-frequency modulation, approximation, dynamic losses, efficiency, frequency.
Słowa kluczowe: konwerter impulsów, modulacja szerokości impulsu, modulacja częstotliwości impulsów, aproksymacja, straty dynamiczne, sprawność, częstotliwość.

Introduction

To date, application of the DC converters plays a major role in a number of industries, such as industrial facilities automatization, electric transport, welding machines, domestic appliances, radio-frequency engineering and etc. It is in these areas, where the new demand appeared – the demand for energy different from that from the grid in frequency, output current or voltage, number of phases, possibility to control energy parameters. These are the most common development challenges for the AC and DC electric drives, which takes about 60% of all energy consumption in the Russian Federation [1].

Nowadays power-width modulation (PWM) is the best control method [1, 4]. Pulse-width converters (PWC) are used to control the DC drives. This control method allows to set required form and shape of voltage and power supply of the motor. In addition, the controlling range of angular velocity is smoother and wider during load change in high variation [4, 5].

Semiconductor converters with pulse-width and pulse-frequency control

Power-width modulator (PWM) is the main cell block of power-width converter (PWC). PWC converts direct voltage [7, 19] to pulsating one. Its average value (i.e. constant component of load obtained by filters) can be controlled. The principle of controlling output voltage of PWC is based on periodic closing-opening gates – transistors and thyristors. Figure 1 shows the simplest basic circuit of pulse semiconductor converter (PSC) with pulse-width or pulse-frequency control.

The circuit consists of transistor VT1, which works in key mode, DC power supply Uп. and resistive load Rн. The circuit (Fig.1) ensures only unipolar modulation. When the transistor VT1 is on (the key mode) the load voltage forms positive pulse. When VT1 is off the load voltage forms pause (Fig.2).

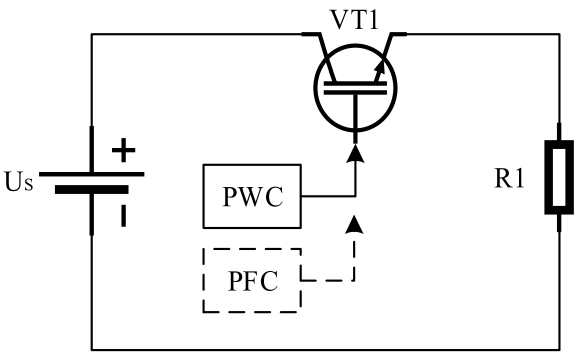

Fig.1. Pulse semiconductor converter with pulse-width or pulse-frequency control

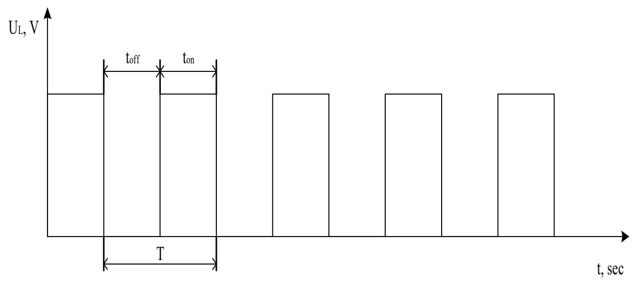

Fig.2. PWC voltage diagram at duty cycle 0.5 and frequency 5 Hz.

Modules consisting of insulated-gate bipolar transistors (IGBT) became one of the most frequently used power semiconductor devices in converters of high voltage and capacity [7-9]. However, rapid development of power semiconductor equipment leads to increasing rated capacity and reduction in size, what entails inevitable heat problems of power electronic converters.

Increasing heating affects connections and link quality, which reduces lifetime of power semiconductor components.

Losses of PSC are basically caused by IGBT-transistors and diodes. They are divided into static (conduction losses) and dynamic (switching losses) losses [10].
Static losses appear if IGBT is on (or in steady-state). Static losses (Pcond) can be calculated as collector current (IC) multiplied by collector-emitter voltage (Uce).

(1) $$P_{cond.} = \frac{1}{2\pi}\int_{0}^{\pi}\left(I_c \cdot U_{ce}\right)\cdot dt$$

where: *Ic* - collector current; *Uce* - collector-emitter voltage.

Dynamic losses of IGBT-transistors appear in time of transition from one state mode to another i.e. in off-on process (dynamic on-losses) and vice-versa from on to off mode (dynamic off-losses) [8-11].

Average switching power can be described as:

(2) $$P_{sw.} = \frac{1}{2\pi}\cdot\int_{0}^{\pi}\left[\left(E_{on}\left(I_c\right)+E_{off}\left(I_c\right)\right)\cdot f\right]\cdot dt$$

where: $E_{on}(I_c)$ - on-mode energy, which depends on collector current ; $E_{off}(I_c)$ - off-mode energy, which depends on collector current too; *f* - switching frequency.

In power convertor the switching losses make substantial contribution to the total losses of the circuit. The switching losses should be accurately calculated in order to increase reliability of the machine.

As it may be inferred from formula 2, dynamic losses are directly proportional to commutation frequency.
Another control method can be used in order to decrease dynamic losses and therefore increase efficiency of a PSC, which based on using pulse-frequency modulation (PFM). PFM control method is used in pulse-frequency convertor (PFC) [11, 14, 19].

When duty cycle changes the duration of the output PWC voltage pulse tи changes as well, while the pulse period T doesn't change. Therefore, PWC frequency is constant.

In case of PFC, pulse duration tи is constant. Meanwhile the switching frequency of PFC is less than that of PWC. Decreasing switching frequency leads to decreasing dynamic losses and increasing efficiency of a converter.

The Figure 3 describes how pulse width depends on pulse frequency. As is obvious, while pulse width changing, pulse frequency is constant. At the same time, in the case of PFC, while pulse width is changing, pulse frequency is changing proportionally.

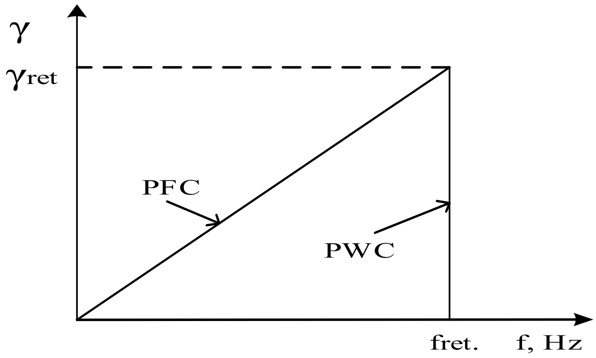

Fig.3. Duty cycle-frequency curve

Basic differences between PFC and PWC [2, 14, 19]:
- duration of the output PFC voltage pulse is constant (duration of the output PWC voltage pulse is changing);
- period of output PFC voltage is changing (period of output PWC voltage is constant);
- PFC output frequency is changing (PWC output frequency is constant).

Model of the PSC circuit with PWC and PFC

The PWC and PFC circuits were modelled using blocks from the Matlab library Simulink/SimPowerSystem/Simscape [15-18] (Fig.4).

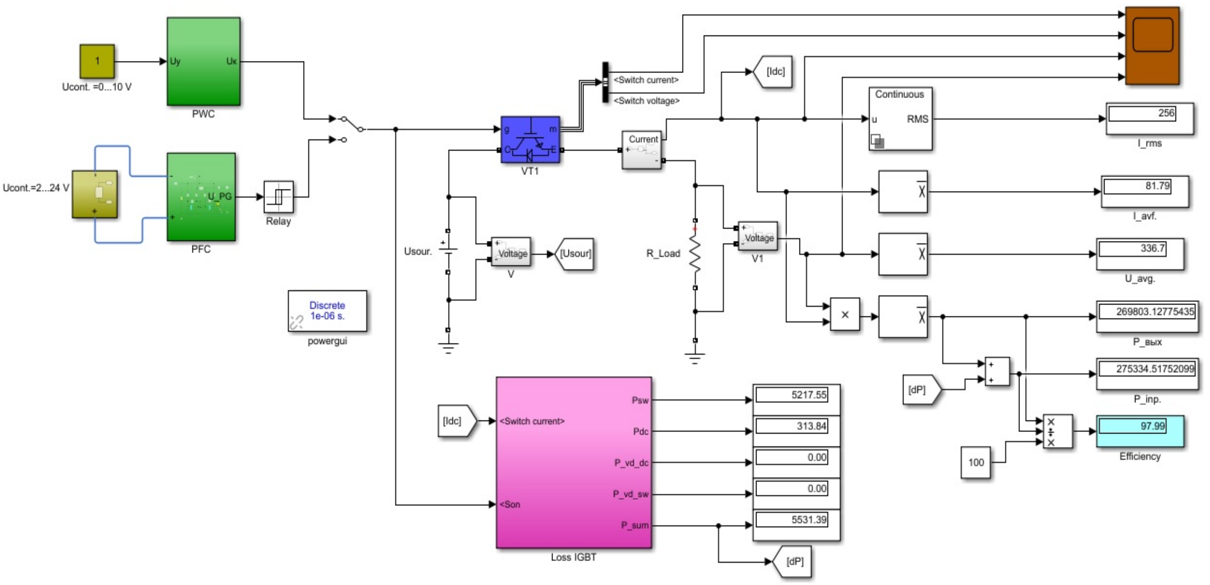

Fig.4. Model of PSC with PWC and PFC control

PSC models with PWC and PFC contain the following blocks:

- A block of duty cycle variation, which is operated by the control voltage. The control voltage of the PWC model changes from 2 to 30 V.

The control system of the PWC model is build using standard Simulink blocks.

The control system of the PFC model is build using with using Simscape library elements [13] (Fig.5).

Simscape is an environment for physical systems simulation. The base Simscape library extends into several specialized libraries such as: Foundation Library, Driveline, Electrical, Fluids, Multibody, etc. In this environment, electronic, electromechanical, electrical, mechanical, hydraulic, thermal and other types of systems can be simulated.

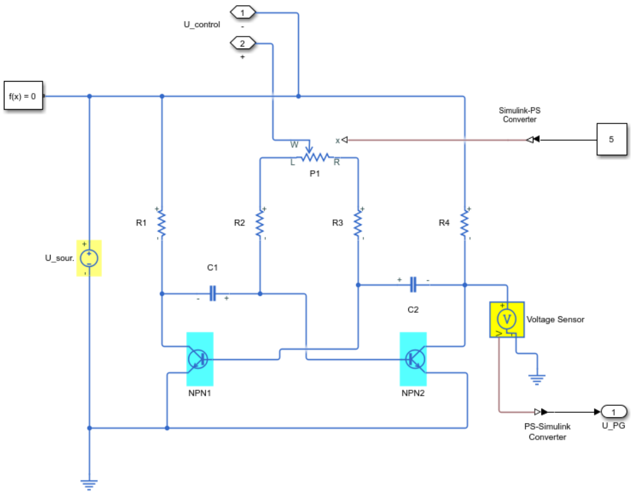

Fig.5. Model of the circuit of the PFC control system

- Block of the power circuit of the PWC or PFC, which consists of a semiconductor power converter, an active load RH and a power (supply) link, presented in the form of a battery with a voltage of 3300 V. the IGBT by MITSUBISHI, type CM800HC-66H was used as a power semiconductor converter, the parameters of which are shown in the table 1.
- The block for calculating the power losses of an SPC based on a PWC and a PFC is shown on the figure 4. The calculation of power losses of the IGBT by different methods is described in detail in [3, 6, 7-13, 15-18, 19]. In [8], the calculation of IGBT power losses was performed by approximating the losses curves. Energy curves Uce (Ic), Eon (Ic), Eoff (Ic) from the datasheet (the characteristics are marked with 1) and the curves after approximation (the characteristics are marked with 2) (Fig.6 and Fig.7 respectively). Using this calculation method, the following parameters can be determined: static losses, dynamic losses, total losses of the IGBT and converter efficiency. Figure 8 shows a block model for calculating the static losses of an IGBT.

Table 1. Main characteristics of IGBT

Model	I_c.n, A	V_{ce}.n, V	$V_{ce.\ sat}$, V	E_{on}, J	E_{off}, J
CM800HC-66H	800	3300	3.6	1.1	1.05

The approximation of the power losses curves of the IGBT is carried out by equations (3-5):

(3) $$U_{ce}(I_c) = -1.29 \cdot I^4 + 5.297 \cdot I^3 - 7.7961 \cdot I^2 + +7.22936 \cdot I + 0.8666$$

(4) $$E_{on}(I_c) = -0.1002 \cdot I^3 + 1.237 \cdot I^2 + 0.5766 \cdot I + +0.138$$

(5) $$E_{off}(I_c) = 1.2243 \cdot I + 0.284$$

The obtained curves (3 - 5) quite accurately describe the energy curves of the IGBT power losses.

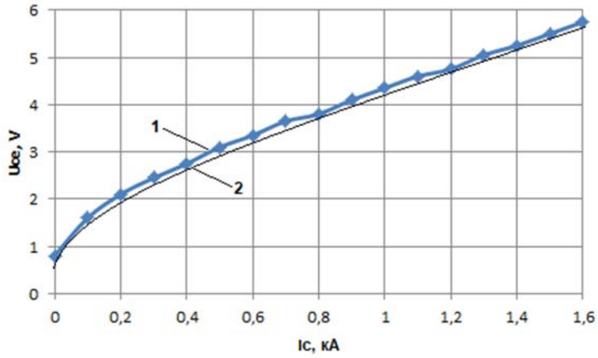

Fig.6. Saturation voltage of the collector-emitter: 1 - from the datasheet; 2-after approximation

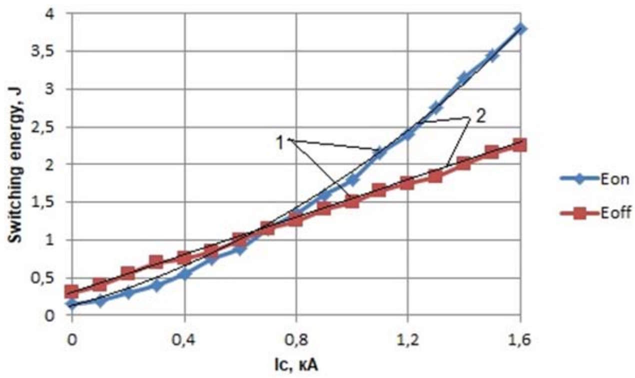

Fig.7. Energy curves: 1 - from the datasheet; 2-after approximation

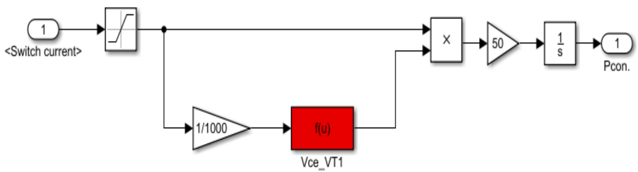

Fig.8. Block for calculating the static losses of the IGBT.

The simulation results of the IGBT static losses are shown on figure 9.

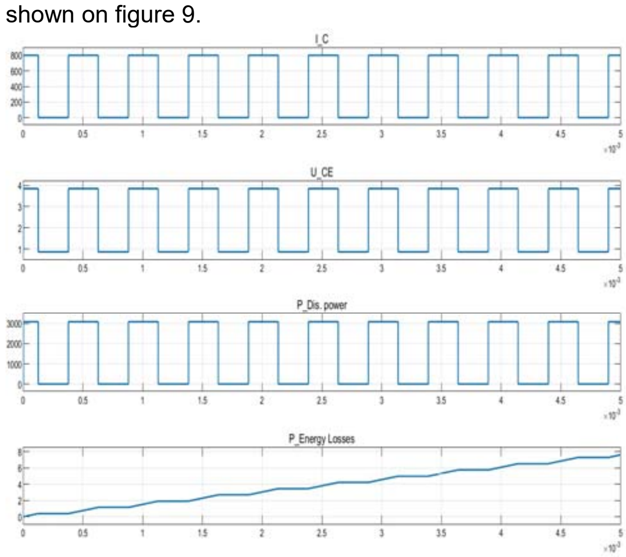

Fig.9. Diagrams of the IGBT static losses.

Comparison and analysis of PWC and PFC circuits

Figures 10 and 11 show the diagrams of currents and voltages for the PWC and PFC circuits respectively. They were obtained as a result of simulation for active load at a duty cycle of 0.5. As it can be seen from the PWC diagram (Fig. 10), the switching frequency is 2 kHz at a duty cycle of 0.5. And in the case of a PFC with a duty cycle of 0.5, the switching frequency decreases by 50%, i.e. it will be equal to 1 kHz.

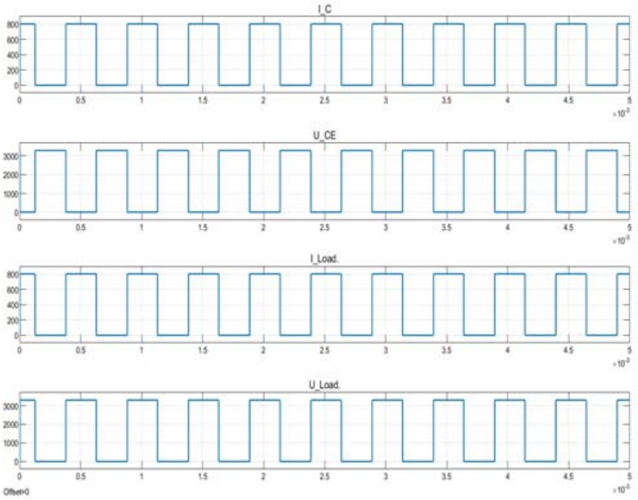

Fig.10. PWC time diagrams with a duty cycle of 0.5 and a switching frequency of 2 kHz.

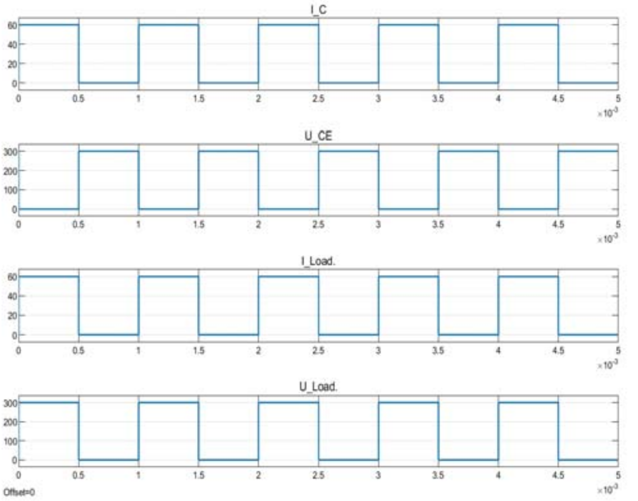

Fig.11. PFC time diagrams with a duty cycle of 0.5 and a switching frequency of 1 kHz.

The analysis of losses obtained in the simulation of semiconductor converters circuits in PWC and PFC modes at different values of duty cycle γ is given in the table 2.

Table 2. Losses of PWC and PFC circuits at a frequency of 2 kHz

γ	*f*, kHz		Icp., kA	Irms, kA	Imax, kA	Psw, kW		Pdc, kW	efficiency, %	
	PWM	PFC				PWM	PFC		PWM	PFC
1	2	2	0,8	0,8	0,8	5,217	5,217	3,078	99,69	99,69
0.9	2	1,8	0,72	0,76	0,8	5,217	4,695,	2,775	99,67	99,689
0.6	2	1,2	0,48	0,62	0,8	5,217	3,130	1,850	99,56	99,6885
0.3	2	0,6	0,24	0,43	0,8	5,217	1,565	0,925	99,23	99,688
0.1	2	0,2	0,08	0,25	0,8	5,217	0,521	0,308	97,95	99,687

Figures 12-13 show diagrams comparing the dynamic losses as well as the efficiency of PWC and PFC. In the case of PWC, when the duty cycle changes from the maximum value to the decreasing direction, the switching frequency does not change. With a constant switching frequency, dynamic losses remain constant, which leads to a decrease in converter efficiency at low values of duty cycle.

In the case of PFC, as the duty cycle decreases from the maximum value to the minimum value, the switching frequency decreases in direct proportion. This leads to a decrease in dynamic losses and a significantly smaller decrease in efficiency PFC versus PWC.

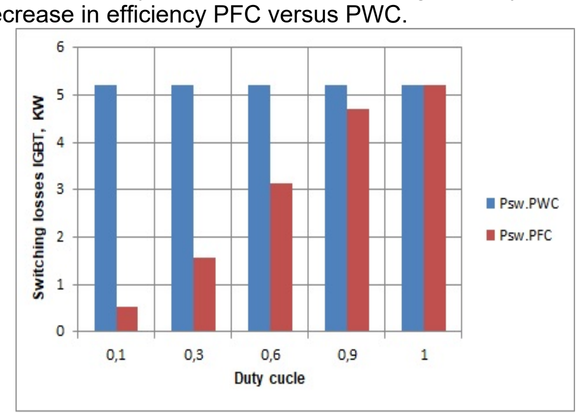

Fig.12. Dynamic losses of the IGBT in PWC mode (switching frequency is 2 kHz) and PFC mode (maximum frequency is 2 kHz)

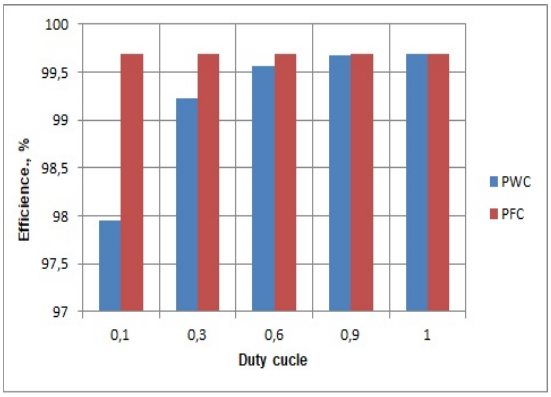

Fig.13. Efficiency in PWC mode (switching frequency is 2 kHz) and PFC mode (maximum frequency is 2 kHz).

It can be seen that when the duty cycle changes from 0.1 to 0.5 efficiency of PFC significantly exceeds that of PWC. This excess is more significant at higher switching frequency of converters. For example, with a duty cycle of 0.1 and a frequency of 2 kHz, the efficiency of the PFC is 1.737% more than that of the PWC; at 4 kHz the efficiency of the PFC is 3.5% higher than that of the PWC.

Conclusion

Models of circuits with PWC and PFC were developed in the Matlab environment using blocks from the Simulink / SimPowerSystem / Simscape library. The block for calculating IGBT power losses (static and dynamic) was created. The method of approximation was used in order to calculate the power losses. The obtained curves quite accurately describe the power losses of the IGBT. The IGBT is a MITSUBISHI power transistor of the CM800HC-66H type. It was shown that when using the PFC circuit, it is possible to reduce the dynamic losses and increase the converter efficiency in relation to the PWC circuit. It can be seen that when the duty cycle changes from 0.1 to 0.5 efficiency PFC significantly exceeds that of PWC. This excess is more significant at higher switching frequency and higher capacity of the power switches of the converters.

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