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Simulation of losses in autonomous inverter circuits with pulse-width and pulse-frequency modulation

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The article discusses the issues of sinusoidal pulse-frequency modulation in autonomous voltage inverters instead of sinusoidal pulse-width modulation. Analytical expressions describing static and dynamic power losses in power semiconductor diodes and transistors are also given. It is shown that the use of the method of frequency-pulse modulation will reduce dynamic losses in semiconductor switches.

Keywords: autonomous voltage inverter, pulse-frequency modulation, simulation, losses.

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Introduction

Conversion of DC voltage to AC voltage can be carried out using an inverter made on transistor modules IGBT [1]. One of the simplest converters of this type is a three-phase two-level autonomous voltage inverter (AVI) with pulse-width modulation (PWM) [2, 3], the scheme of which is presented in Fig. 1.

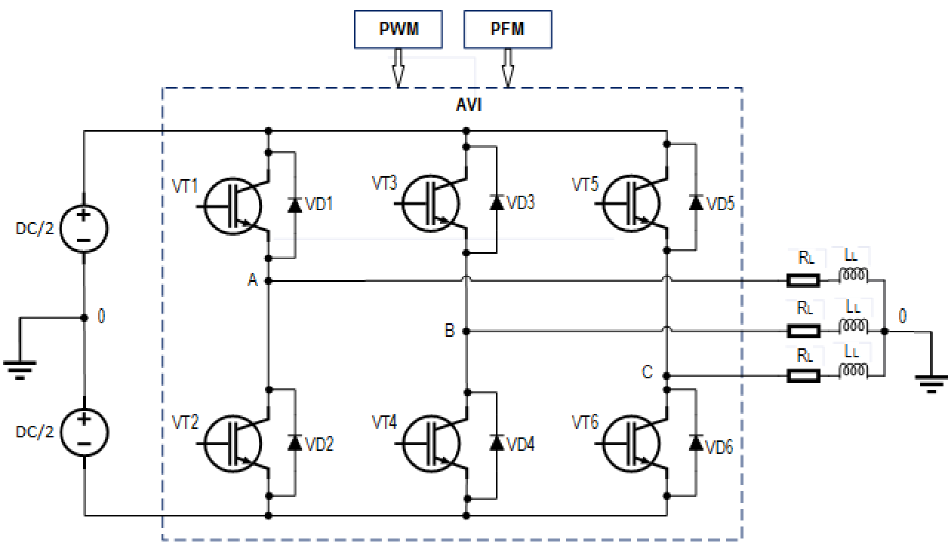

Fig. 1. Three-phase AVI circuit with PWM or PFM modulation

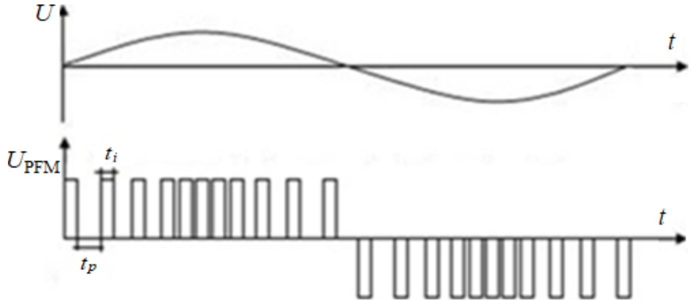

Fig. 2. Diagrams of pulse-frequency modulation formation

Pulse-frequency modulation is a type of modulation where the pulse width of the t_i remains constant and only the pause time changes t_p. Voltage generation diagrams shows in Fig. 2 for controlling semiconductor inverter switches by pulse-frequency modulation (PFM). The sinusoidal signal $U(t)$, which has undergone frequency-pulse modulation, will be represented by a sequence of pulses of the same duration t_i, the width of the pause t_p between which will change with the change in the amplitude of $U(t)$ [4–7].

1. Calculation of power losses in AVI

Power losses during switching of the IGBT transistor for the specified forms of current and voltage signals are divided into three parts, as shown in Fig. 3. Total energy losses include static and switching losses in the IGBT transistor and in the reverse diode [8]. Static losses of IGBT transistors and diodes occur when the state is on. This $P_{cond.\,loss}$ can be calculated as the product of collector current and collector-emitter voltage according to formula (1):

$$P_{cond.\,inv} = \int_{t_1}^{t_2} (U_{ce}(I_c)I_c)dt, \tag{1}$$

where I_c — collector current; U_{ce} — collector-emitter voltage. Dynamic losses in IGBT transistors occur during the transition from one steady state to another in Fig. 3, when switching from the off state to the included state and vice versa [9–13]. Power losses when

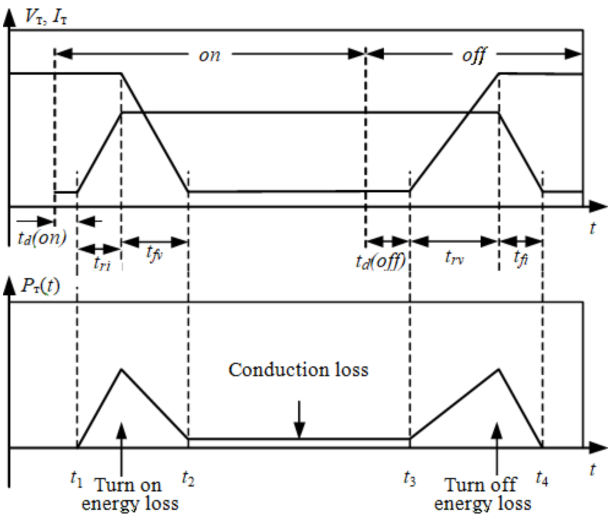

Fig. 3. IGBT transistor switching process: turn on energy loss; turn off energy loss; conduction loss (static losses in the included state); $t1$–$t2$ — power-on interval, $t2$–$t3$ — on state interval, $t3$–$t4$ — shutdown interval

switching the device may vary depending on current, voltage, gate resistance and transition temperature [8].

The value of the average power of switching losses is determined by formulas (2) or (3):

$$P_{sw.\,inv} = [E_{on}(I_c) + E_{off}(I_c)]\, f, \tag{2}$$

$$P_{sw.\,inv} = \int_{t_1}^{t_2} (I_c U_{ce}) dt + \int_{t_3}^{t_4} (I_c U_{ce}) dt, \tag{3}$$

where $E_{on}(I_c)$ is the energy at switching on, which depends on the amount of collector current; $E_{off}(I_c)$ — energy when turned off, which also depends on the value of the collector current; f — switching frequency.

Total losses in AVI can be determined by the expression (4):

$$P_{AVI} = P_{con.\,inv} + P_{sw.\,inv}, \tag{4}$$

where P_{AVI} — power loss in AVI; $P_{con.\,inv}$ — static power loss in the transistor and in the reverse diode; $P_{sw.\,inv}$ — switching power losses in the IGBT transistor and in the reverse diode.

AVI switching losses make a significant contribution to total losses. To assess the efficiency of the AVI and the reliability of its design, it is necessary to accurately calculate the switching losses.

2. Mathematical simulation of AVI with PWM and PFM

In the MATLABR2019 environment, using blocks from the Simulink library [14, 15], the AVI scheme with PFM is simulated, which is shown in Fig. 4. In the work [8] the losses in AVI with PWM modulation are modelled and shown.

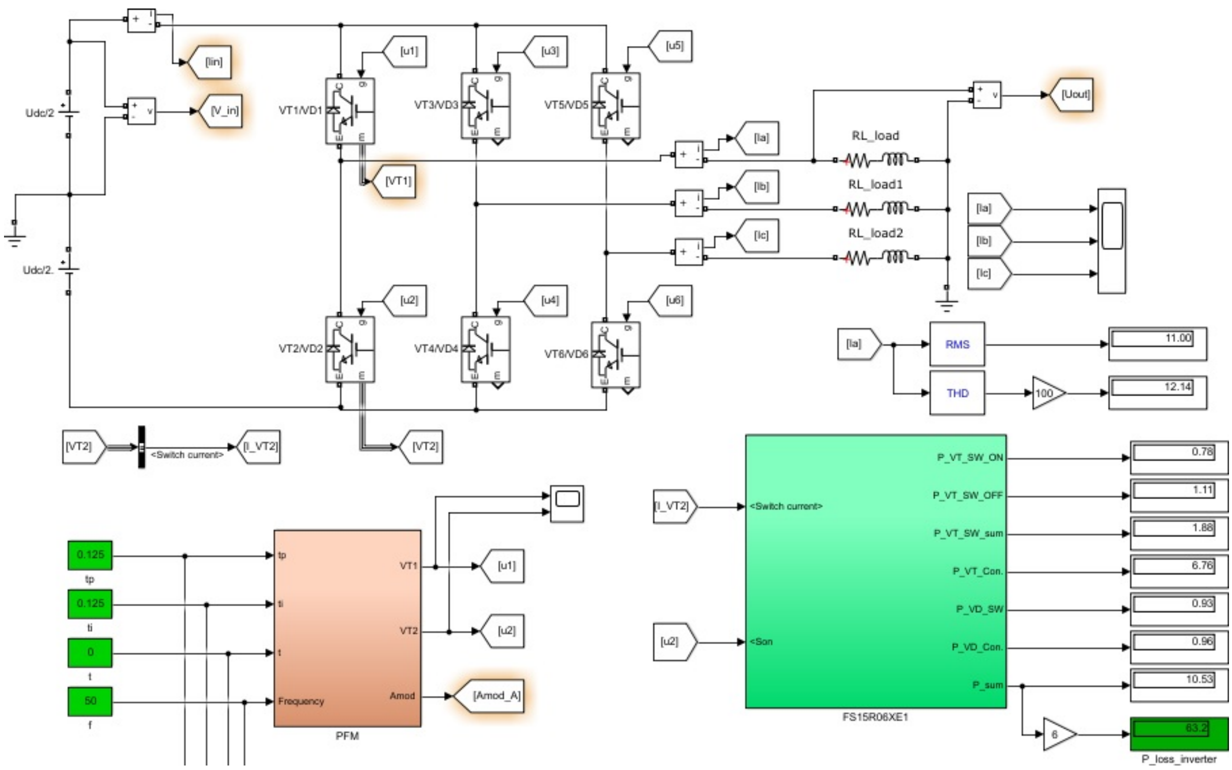

Fig. 4. Model AVI with PFM in MATLAB environment

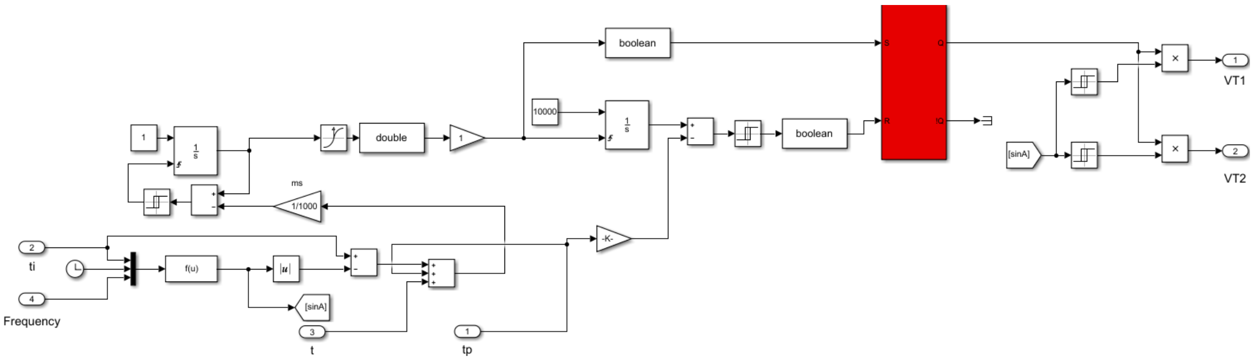

Fig. 5. Model AVI with PFM in MATLAB environment

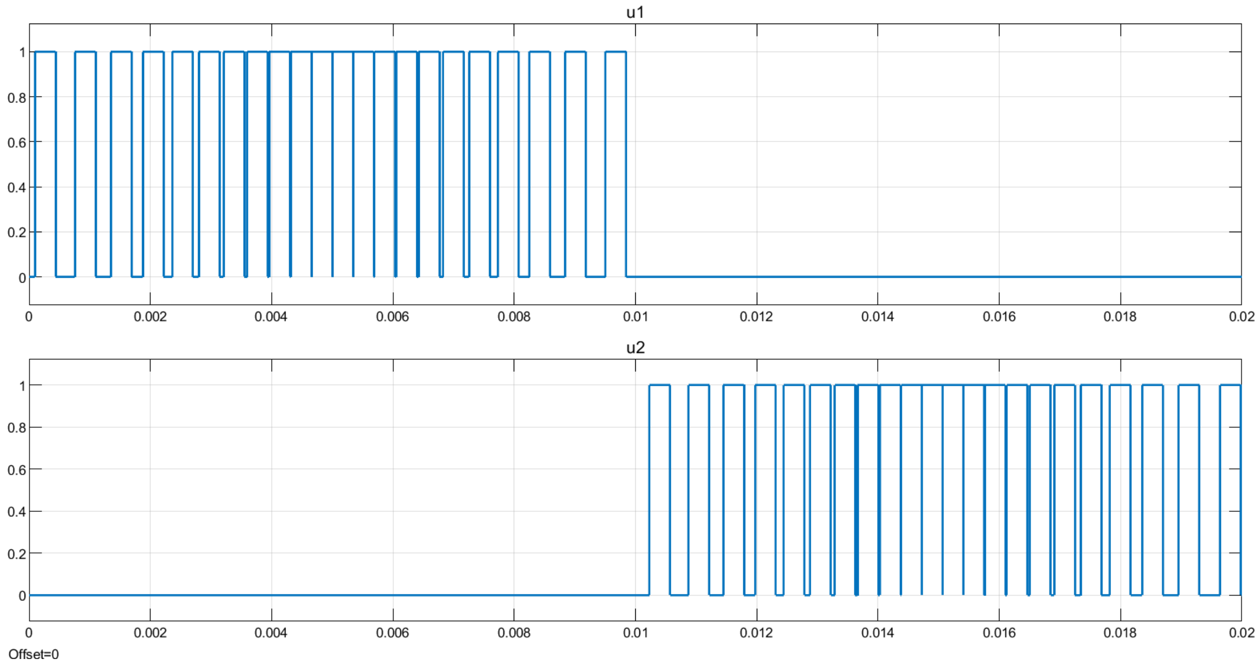

Fig. 6. Simulation results: u1, u2 — control voltages of transistors AVI in PFM mode

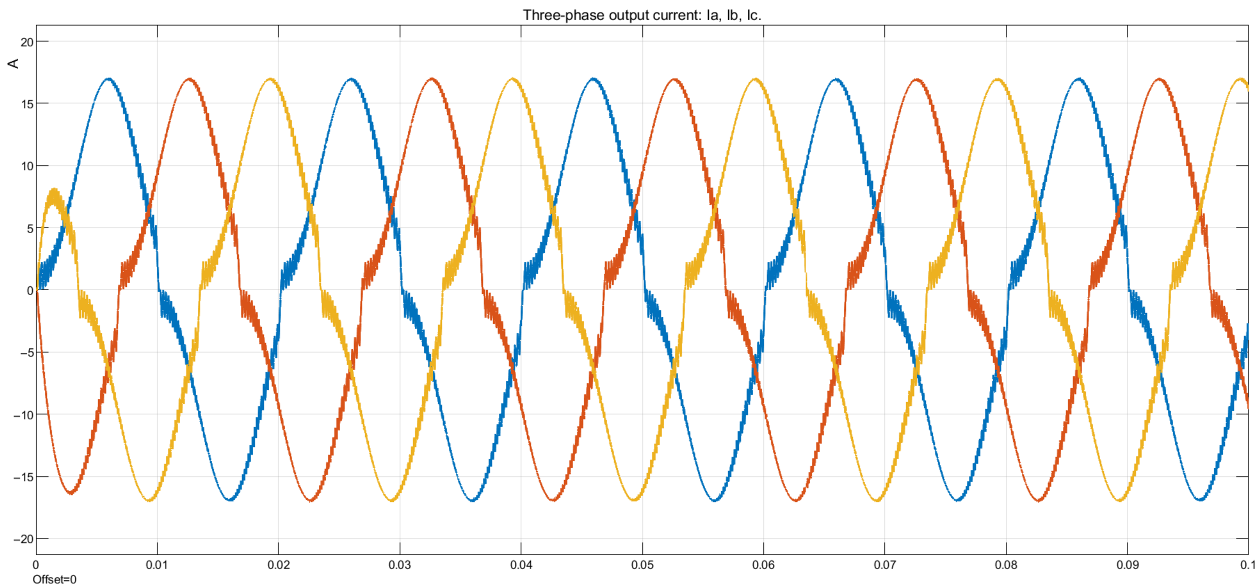

Fig. 7. Simulation result: output currents AVI with PFM

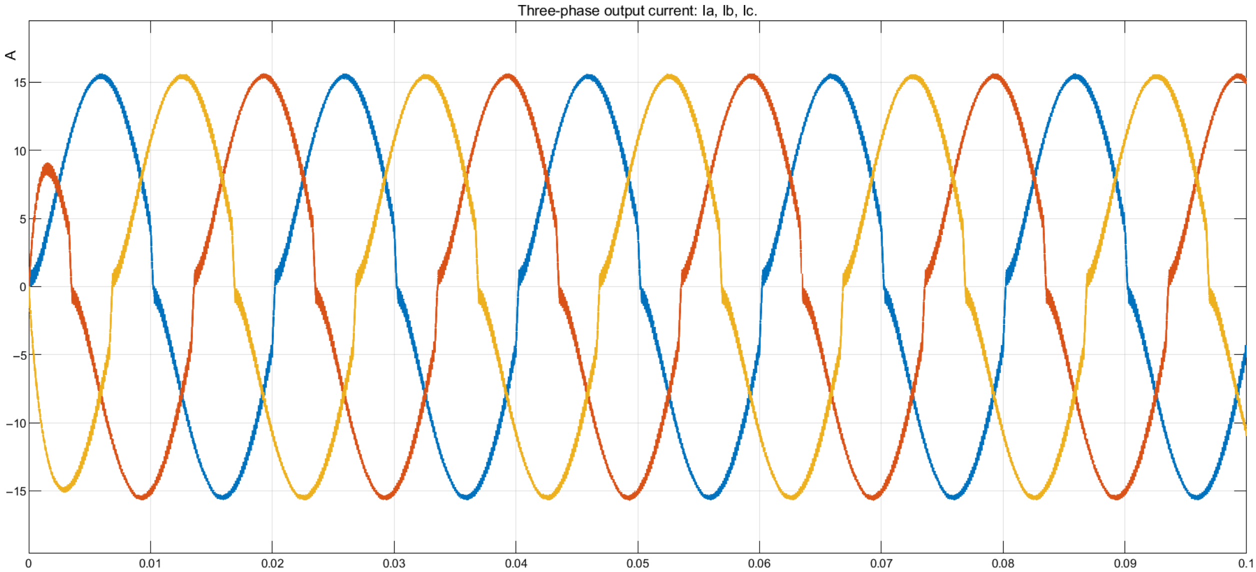

Fig. 8. Simulation result: output currents AVI with PWM

The model in Fig. 4 contains the following units: a unit of an autonomous three-phase bridge voltage inverter on six IGBT/Diode modules (VT1/VD1–VT6/VD6); PFM control system unit; automatic calculation unit for losses in the inverter (FS15R06XE1); load block (Yn, Lh); set of measuring instruments.

The model of the control system with sinusoidal PFM is shown in Fig. 5.

Time diagrams of the control system in Fig. 5 are shown in the Fig. 6. In PFM, the pulse duration remains constant, and the pulse repetition periods are variable and change according to the sinusoidal law.

Figures 7 and 8 show current diagrams in AVI with PFM and PWM.

3. Automatic calculation unit for losses in inverter

Currently, there are various methods for calculating losses in IGBT transistors that use rather complex formulas using numerous parameters. Consequently, these methods of calculation are not easy to implement in practice. In this article, the losses in the AVI are determined by the method of computer modelling, in which graphs of energy dependencies of semiconductor diodes and transistors were used.

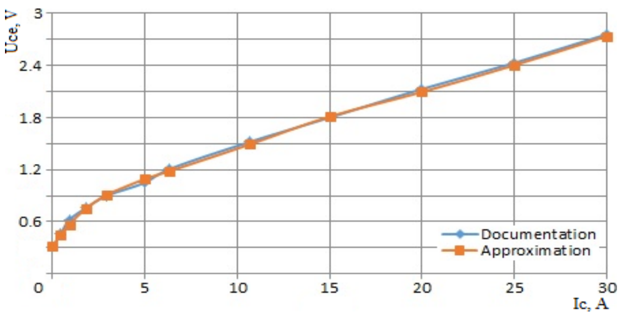

Fig. 9. Saturation voltage collector-emitter transistor type FS15R06XE3

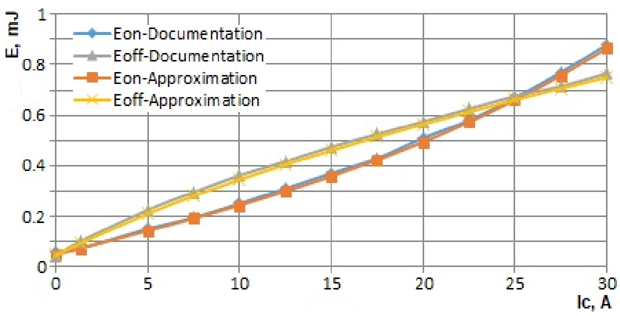

Fig. 10. Power switching characteristics of FS15R06XE3 power transistor

The approximation method defines the mathematical functions that most accurately describe the graphs of energy dependencies [9, 11, 12] $U_{se}(I_c)$, $U_F(I_F)$, $E_{on}(I_c)$, $E_{off}(I_c)$, $E_{rec}(I_c)$. Energy graphs of the dependencies $U_{se}(I_c)$, $E_{on}(I_c)$, $E_{off}(I_c)$ are taken from the documentation for semiconductor diodes and transistors and after approximation are shown in Fig. 9 and 10. Using this calculation method, it is possible to determine static and dynamic losses in IGBT-transistors and reverse diodes [8] AVI, as well as to quantify the efficiency of the converter in general.

After approximation of power loss graphs of IGBT-transistor module type FS15R06XE3 the following equations (5)–(9) are obtained:

$$U_{CE}(I_c) = -102775(I_c/100)^6 + 98467(I_c/100)^5 - 36327(I_c/100)^4 + 6505.8(I_c/100)^3 - \\ -590.76(I_c/100)^2 + 32.772(I_c/100) + 0.3152, \quad (5)$$

$$U_F(I_F) = -72672(I_F/100)^4 + 71308(I_F/100)^5 - 2722(I_F/100)^4 + 5043.3(I_F/100)^3 - \\ -481.84(I_F/100)^2 + 27.018(I_F/100) + 0.4514, \quad (6)$$

$$E_{on}(I_c) = 4.8894(I_c/100)^4 + 7.982(I_c/100)^3 + 0.0715(I_c/100)^2 + 1.8573(I_c/100) + 0.0486, \quad (7)$$

$$E_{off}(I_c) = -15.198(I_c/100)^4 + 16.984(I_c/100)^3 - 8.0363(I_c/100)^2 + \\ +3.6428(I_c/100) + 0.0456, \quad (8)$$

$$E_{rec}(I_F) = 5.4932(I_F/100)^3 - 5.7025(I_F/100)^2 + 2.6764(I_F/100) + 0.0792. \quad (9)$$

The obtained mathematical dependencies (5)–(9) accurately describe the energy graphs of power losses in IGBT/Diode of AVI modules.

To calculate the static and dynamic power losses of the IGBT transistor, the voltage and current of the transistor are used.

Figure 11 shows the unit for calculating static and dynamic power losses of the reverse diode IGBT/Diode module type FS15R06XE3.

Figure 12 shows the block for calculating static and dynamic losses IGBT/Diode module type FS15R06XE3.

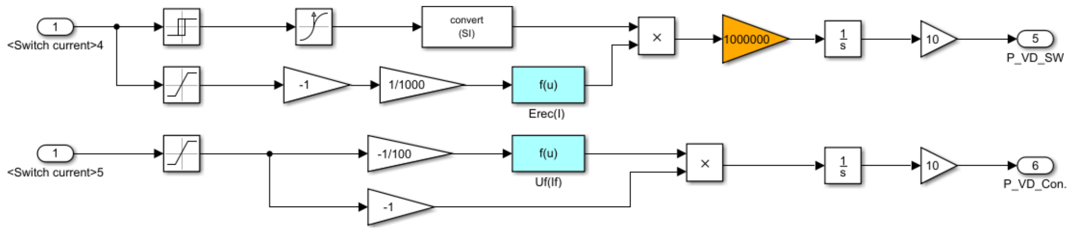

Fig. 11. Reverse diode power loss calculation unit of FS15R06XE3 type module

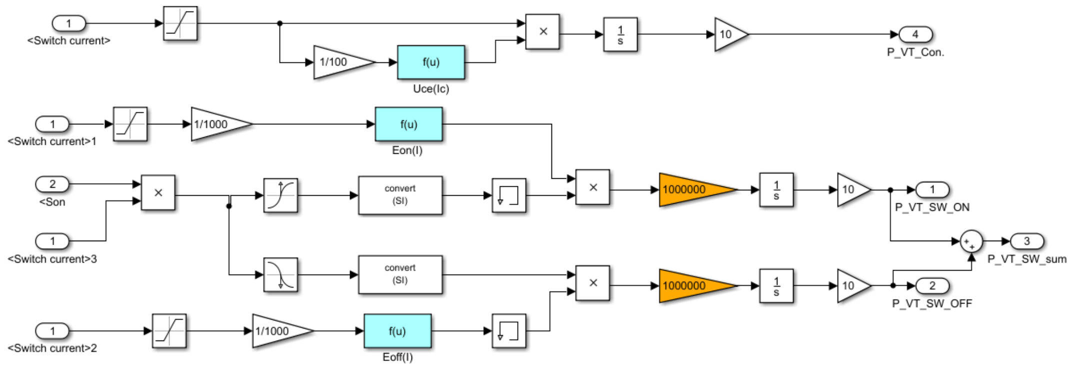

Fig. 12. Block for calculating losses IGBT/Diode module type FS15R06XE3

The results of modelling static and dynamic power losses of the IGBT/Diode module type FS15R06XE3 are shown in Fig. 13 and 14. To simulate dynamic losses, a modelling method with a constant calculation step is used [8, 10, 11].

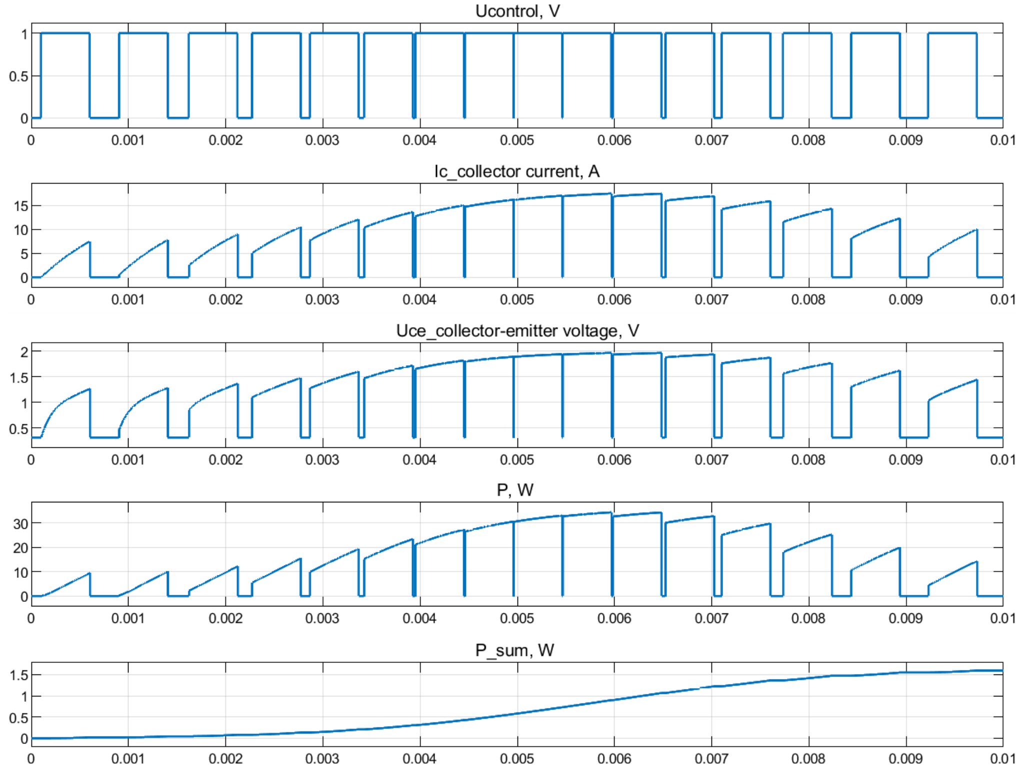

Fig. 13. Results of simulation of static losses of FS15R06XE3 module at PFM

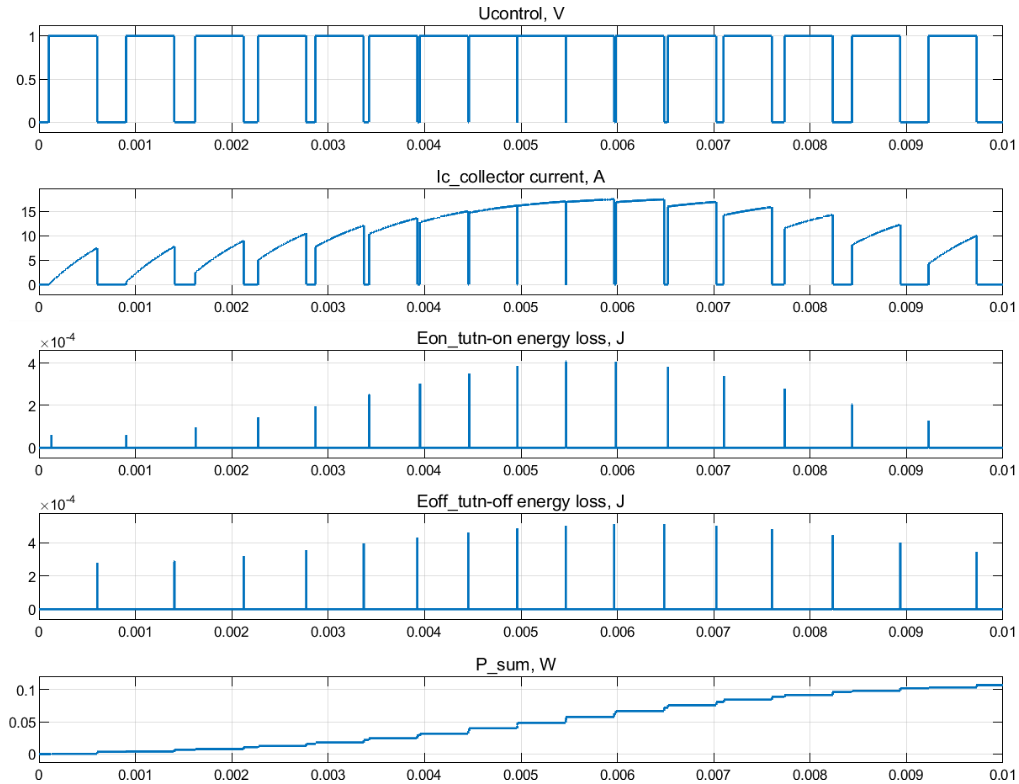

Fig. 14. Dynamic loss simulation results of FS15R06XE3 module at PFM

4. Comparison of losses in AVI with PWM and PFM

The analysis of losses obtained when simulation AVI schemes with PWM and PFM at a maximum frequency of $f_{\max} = 8$ kHz is given. The obtained diagrams of the output pulse voltage AVI with PFM showed that the modulation frequency at the edges of the half-periods of the output pulse voltage is about two times less than in the middle of the half-times of the output pulse voltage. This leads to a decrease in dynamic losses in transistors AVI with PFM compared to AVI with PWM by 21.4 %, because the power of dynamic losses is directly proportional to the modulation frequency.

Conclusion

The article presents the method of mathematical simulation of AVI with PFM and PWM. A model of AVI with sinusoidal PFM, which is set by analog-digital method, has been developed. The above diagrams of the autonomous voltage inverter with PFM show that the modulation frequency at the edges of the half-periods of the output pulse voltage is two times less than in the middle of the half-times of the output pulse voltage. As a result, the dynamic losses in the IGBT modules of the autonomous voltage inverter with PFM will be significantly lower than in a similar scheme with PWM. To calculate the power losses of IGBT transistors by the method of polynomial approximation, mathematical equations describing the graphs of the dependencies $U_{se}(I_c)$, $U_F(I_F)$, $E_{on}(I_c)$, $E_{off}(I_c)$, $E_{rec}(I_c)$ are determined. The obtained mathematical equations accurately describe the graphs of power losses. The use of PFM allows to reduce dynamic losses by 21 % and increase the efficiency of AVI.

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МАТЕМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ

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Моделирование потерь в автономных инверторных схемах с широтно- и частотно-импульсной модуляцией

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Аннотация

Рассмотрены вопросы синусоидальной частотно-импульсной модуляции в автономных инверторах напряжения взамен синусоидальной широтно-импульсной модуляции. Приведены аналитические выражения, описывающие статические и динамические потери мощности в силовых полупроводниковых диодах и транзисторах. Показано, что использование метода частотно-импульсной модуляции позволит снизить динамические потери в полупроводниковых переключателях.

Ключевые слова: автономный инвертор напряжения, частотно-импульсная модуляция, моделирование, потери.

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