Calculation of power losses in a frequency inverter

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ABSTRACT

This study's main goal is to make a new simulation model of the power losses calculation block for frequency converter power switches that can correctly figure out the transistors and diodes' static and dynamic power losses in a 1.5 kW SIEMENS SINAMICS G110 semiconductor converter (SSG110SC). We use simulation modeling tools in the MATLAB/Simulink environment to look at the semiconductor circuits of a rectifier and an autonomous pulse-width modulation voltage inverter. The study presents analytical expressions describing static and dynamic power losses in power semiconductor diodes and transistors. We used polynomials to get close to the power characteristics of insulated-gate bipolar transistor or IGBTs and then used mathematical expressions to show how they depend on Erec (Ic), Vse (Ic), Vf (If), Eon (Ic), and Eoff (Ic). By utilizing the acquired expressions, a MATLAB/Simulink block was constructed to calculate static and dynamic power losses. as well as power loss dependences on switching frequency and load current, were computed utilizing the developable block system. By comparing the simulation outcomes of the present study to the data provided by the manufacturer, the results were validated. Specific diode and transistor characteristics can be accounted for by the method developed in the present study.

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1. INTRODUCTION

AC mains voltage with fixed magnitude and frequency can be converted into alternating voltage with controlled magnitude and frequency parameters using a DC-link-based frequency converter. Such a frequency converter is composed of an input uncontrolled rectifier with a smoothing filter (SF) at its output and an autonomous voltage inverter (AVI) that applies the pulse width modulation (PWM) technique [1]–[7], built using IGBT modules [8]–[14]. One prevalent application of this category is the SSG110FC converter. The power circuit of SSG110FC is shown in Figure 1.

Figure 1 is powered by alternating current mains with 220 V and 50 Hz as voltage (Uc) and frequency (Fc), respectively. A bridge rectifier (BR) with diodes VD7–VD10 and no control is made up of them. A smoothing filter (SF) with capacitor C is also present. There is also a 3-phase bridge AVI with six IGBTs (VT1–VT6) and diodes (VD1–VD6) connected across the IGBTs in an antiparallel way. AC diagonally connected to the inverter load (Rn, Ln) of the AVI. The rectifier is made up of diodes, and the AVI modules consist of IGBTs with free-wheeling diodes. A considerable amount of loss occurring in the converter (FC) takes place in the rectifier. It should be noted that the current study does not address the losses that occur in the filter capacitor, cooling, and control systems. In high-power FCs, losses arising in the uncontrolled rectifier and autonomous voltage inverter may be critical [15], [16]. The current investigation deals with studying power losses in the inverter and rectifier circuits. Currently, these losses can be accurately calculated using various methods. However, such methods involve rather complex formulas and parameters and are therefore difficult to implement in practical applications.

Here, authors describe the determination of losses in the rectifier and AVI circuits by modelling. The reliability of the proposed power loss modelling method is assessed by comparing the simulation results obtained for the frequency converter in the MATLAB environment with the losses specified in the technical documentation of the 1.5 kW SSG110FC. The technical specifications of the 1.5 kW SSG110FC are shown in Table 1. The 1.5 kW SSG110FC is built using GBPC2508W module as the uncontrolled rectifier (specifications of the module in Table 2) and FS15R06XE3 IGBT module with free-wheeling diodes as the autonomous voltage inverter specifications of the module in Table 3.

Table 1. Main specifications of SSG110FC

Parameter	Value
Line voltage, V	230
Line frequency, Hz	50
Output power, kW	1.5
Power loss*, W	118
Efficiency (at PWM Frequency of kHz)	0.927
PWM Frequency kHz	Standard factory setting -8 adjustment range 2-16 (in 2 kHz increment)

Table 2. Main technical specifications of FS15R06XE3 IGBT module with free-wheeling diodes

Parmeter	Symbol	Value
Maximum repetitive peak voltage, V	URPM	800
Continuous direct current, A	Io	25
Maximum one-cycle non repetitive peak forward current, A	IFSM	400
Maximum forward voltage drops, V	UFM	1.1

Table 3. Main technical specifications of FS15R06XE3 IGBT module with free-wheeling diodes

Parameter	Condition	Symbol	Value
Maximum collector emitter voltage, V	At temperature of IGBT module T_{vi}	U_{CES}	600
Collector current, A	At ambient temperature T_c 80 $°C$ and temperature of IGBT module T_{vi} 175 $°C$	I_{cnom}	15
Repetitive peak collector current, A	At puls duration t_p =1ms	I_{CRM}	30
Saturation voltage of collector-emitter, V	I_C=15 A, U_{GE}=15 V T_{vi}=25 $°C$	U_{CEsat}	1.55
	I_C=15 A, U_{GE}=15 V T_{vi}=125 $°C$		1.7
	I_C=15 A, U_{GE}=15 V T_{vi}=150 $°C$		1.8
Turn-on energy loss, mJ	I_C=15 A, U_{CE}=300 V	E_{on}	
	T_{vi}=25 $°C$		0.25
	T_{vi}=125 $°C$		0.32
	T_{vi}=150 $°C$		0.36
Turn-off energy loss, mJ	I_C=15 A, U_{CE}=300 V	E_{off}	
	T_{vi}=25 $°C$		0.34
	T_{vi}=125 $°C$		0.44
	T_{vi}=150 $°C$		0.46
Repetitive peak reverse wheeling diode, A	T_{vi}=25 $°C$	U_{RPM}	600
DC forward current of free-wheeling diode, A		I_F	15
Forword voltage, V	I_F=15 A, U_{GE}=0 V T_{vi}=25 $°C$	U_F	1.6
	I_F =15 A, U_{GE}=0 V T_{vi}=125 $°C$		1.55
	I_F =15 A, U_{GE}=0 V T_{vi}=150 $°C$		1.5
Reveres recovery energy of the diode, mJ	I_F=15 A, U_R=300 V	E_{rec}	
	T_{vi}=25 $°C$		1.6
	T_{vi}=125 $°C$		0.28
	T_{vi}=150 $°C$		0.37

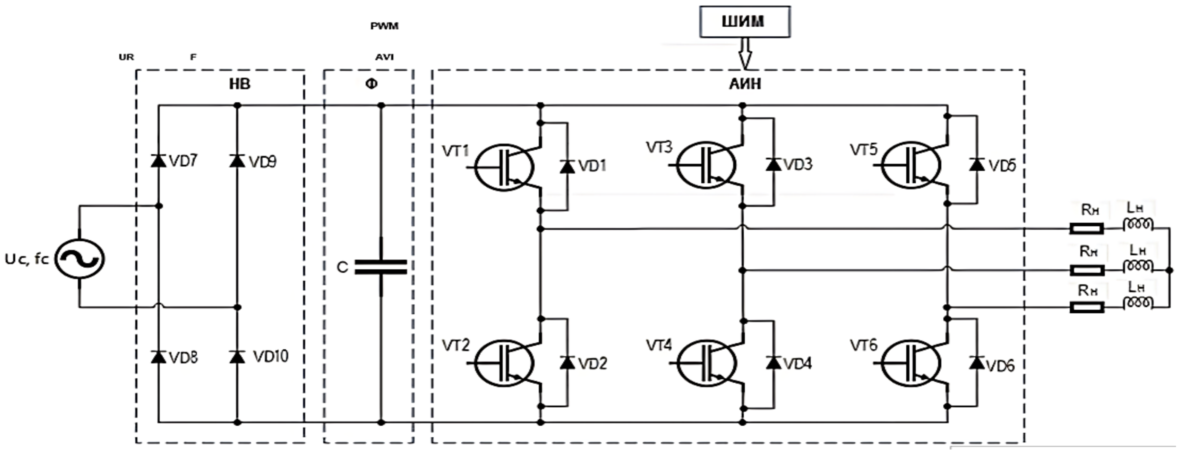


Figure 1. Power circuit of a SSG110FC

2. CALCULATION OF POWER LOSSES

2.1. Calculation of static power losses

Power losses at switching for an IGBT for given current and voltage waveforms can be split into three phases, as seen in Figure 2 [17], [18]. The total power losses include static and switching losses in IGBT and in the associated free-wheeling diode. Static losses occur in IGBTs and diodes when they are in the turned-on condition. This conduction loss (P_{cond}) is multiplication result of the collector 's current (I_c) and the collector-emitter's voltage (U_{ce}), which can be calculated by (1).

$$P_{cond.inv} = \int_{t_2}^{t_3} (U_{ce}(I_c) \cdot I_c) \cdot dt \quad (1)$$

Static losses in the uncontrolled diode rectifier and in the free-wheeling diode of the IGBT module can be calculated using (2). Losses also occur in the diodes during turn ON to OFF [19], These losses are known as switching losses. The switching losses in the uncontrolled diode rectifier at low network frequencies are minor and can be neglected. The conduction losses in a single-phase uncontrolled diode bridge rectifier are four times higher than losses in a single diode.

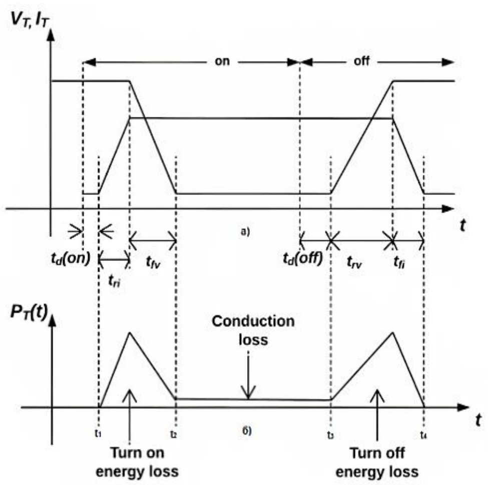


Figure 2. IGBT switching process

2.2. Calculations of dynamic power losses

Dynamic losses in IGBTs occur at transitions between steady state modes as seen in Figure 2, at transitions from off to on states (dynamic turn-on energy loss), and then from on to off (dynamic turn-off energy loss) [20]–[22] It depends on the voltage, gate resistance, junction temperature [23]–[26] and the amount of current flowing through the device to determine how much switching energy it loses. It depends on the voltage, gate resistance, junction temperature, and the amount of current flowing through the device to determine how much switching energy it loses. The value of average switching power losses is determined by (2) or (3):

$$P_{sw.inv} = \left[E_{on}(I_c) + E_{off}(I_c)\right] \cdot f \quad (2)$$

$$P_{sw.inv} = \int_{t_1}^{t_2}[(I_c * Uce)] \cdot dt + \int_{t_3}^{t_4}[(I_c * Uce)]\, dt \quad (3)$$

where $E_{on}(I_c)$ is the turn-on energy; $E_{off}(I_c)$ is the turn-off energy; f is the switching frequency. The total FC losses can be determined using (4):

$$P_{fc} = P_{con.rec.} + P_{con.inv} + P_{sw.inv.} \quad (4)$$

where P_{fc} power losses in the frequency converter; $P_{con.rec.}$ is the static power losses in the uncontrolled rectifier; $P_{con.inv.}$ is the static power losses in the free-wheeling diode; and $P_{SW.inv.}$ is the switching power losses in IGBT. As a result of variations in current, voltage, gate resistance, and junction temperature, the switching energy losses of the device may differ [23]. The switching losses occurring in AVI make a contribution to the total FC losses. Accurate calculations of the switching losses are a prerequisite for the correct evaluation of the frequency converter efficiency and reliability.

3. SIMULATION AND CALCULATION OF LOSSES FOR SINAMICS G110 FREQUENCY CONVERTER

SSG110FC with a power of 1.5 kW was simulated in MATLAB R2019 [24]. Figure 3 shows the model's structure. The following blocks are illustrated in this model: i) Uncontrolled bridge rectifier consisting of diodes VD7-VD10 (type GBPC2508W), including the smoothing circuit with capacitor C1 and resistor R; ii) Self-commutated 3-phase bridge voltage inverter consisting of 6 diodes od IGBT modules VT1/VD1 to VT6/VD6 (type FS15R06XE3); iii) Power loss analyzer for the rectifier (GBPC2508W); iv) Power loss analyzer for the inverter (FS15R06XE3); v) Three-phase load R_H, L_H; vi) A set of measuring instruments to measure effective (RMS) currents and voltages, and the total harmonic distortion (THD); and vii) Power supply (U_c).

The approximation method was used to derive mathematical functions that most accurately describe V_{ce} (I_c), V_f (I_f), E_{on} (I_c), E_{off} (I_c), E_{rec} (I_c) dependence graphs, which are shown in Figures 4 and 5. You can use this method to figure out static losses in an uncontrolled rectifier, dynamic and static losses in IGBTs, and free-wheeling diodes of AVIs. You can also use it to get a rough idea of how efficient the frequency converter is as a whole. The (5)-(10) were obtained by approximation of power losses graphs for GBPC2508W uncontrolled diode rectifier and FS15R06XE3 IGBT module. Equation for uncontrolled diode rectifier type GBPC2508W; the model as shown in Figure 3 contains the following blocks:

$$U_F(I_F) = 0.0277 \cdot \left(\frac{I_F}{100}\right)^5 - 0.2812 \cdot \left(\frac{I_F}{100}\right)^4 + 0.9917 \cdot \left(\frac{I_F}{100}\right)^3 - 1.4921 \cdot \left(\frac{I_F}{100}\right)^2 + 1.6057 \cdot \left(\frac{I_F}{100}\right) + 0.6551 \quad (5)$$

Equations for IGBT module type FS15R06XE3 are:

$$U_{CE}(I_C) = -102775 \cdot \left(\frac{I_C}{100}\right)^6 + 98467 \cdot \left(\frac{I_C}{100}\right)^5 - 36327 \cdot \left(\frac{I_C}{100}\right)^4 + 6505.8 \cdot \left(\frac{I_C}{100}\right)^3 - 590.76 \cdot \left(\frac{I_C}{100}\right)^2 + 32.772 \cdot \left(\frac{I_C}{100}\right) + 0.3152 \quad (6)$$

$$U_F(I_F) = -72672 \cdot \left(\frac{I_F}{100}\right)^6 + 71308 \cdot \left(\frac{I_F}{100}\right)^5 - 27122 \cdot \left(\frac{I_F}{100}\right)^4 + 5045.3 \cdot \left(\frac{I_F}{100}\right)^3 - 481.84 \cdot \left(\frac{I_F}{100}\right)^2 + 27.018 \cdot \left(\frac{I_F}{100}\right) + 0.4514 \quad (7)$$

$$E_{on}(I_C) = 4.8894 \cdot \left(\frac{I_C}{100}\right)^4 + 7.928 \cdot \left(\frac{I_C}{100}\right)^3 + 0.0715 \cdot \left(\frac{I_C}{100}\right)^2 + 1.8573 \cdot \left(\frac{I_C}{100}\right) + 0.0486 \quad (8)$$

$$E_{off}(I_C) = -15.198 \cdot \left(\frac{I_C}{100}\right)^4 + 16.984 \cdot \left(\frac{I_C}{100}\right)^3 - 8.0363 \cdot \left(\frac{I_C}{100}\right)^2 +$$

$$3.6428 \cdot \left(\frac{I_C}{100}\right) + 0.0456 \quad (9)$$

$$E_{rec}(I_F) = 5.4932 \cdot \left(\frac{I_F}{100}\right)^3 - 5.7025 \cdot \left(\frac{I_F}{100}\right)^2 + 2.6764 \cdot \left(\frac{I_F}{100}\right) + 0.0792 \quad (10)$$

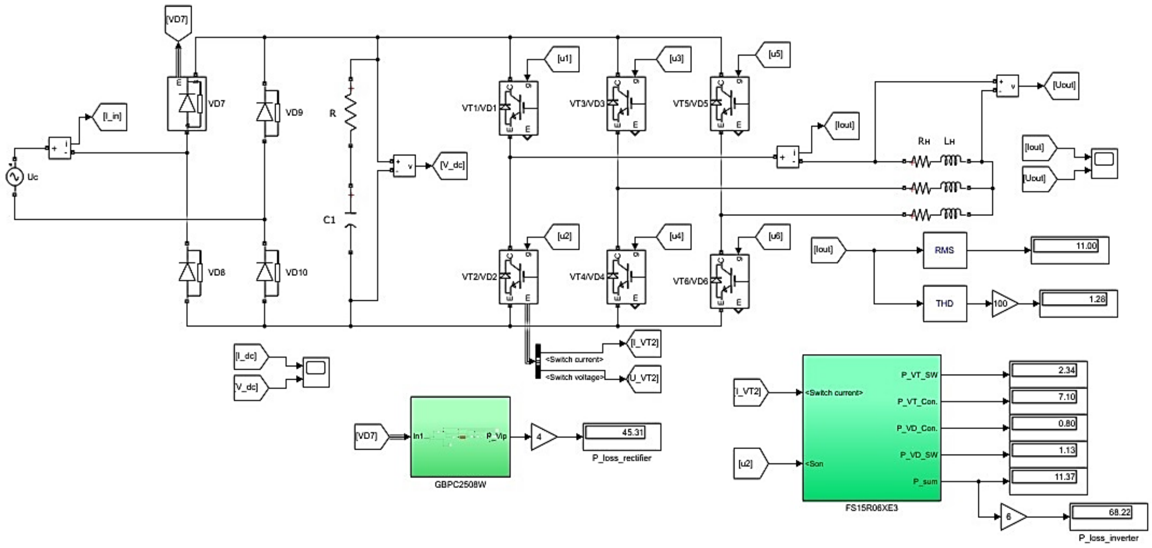


Figure 3. Model of SSG110FC

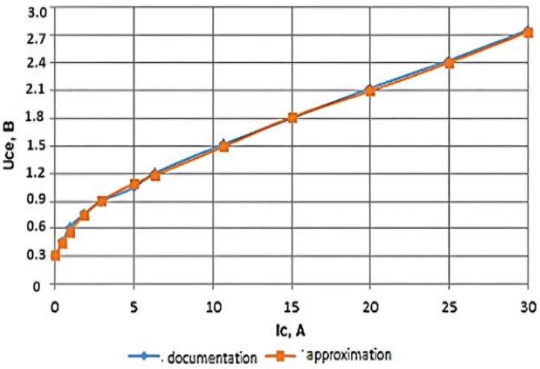


Figure 4. Collector-emitter saturation voltage for FS15R06XE3 power transistor

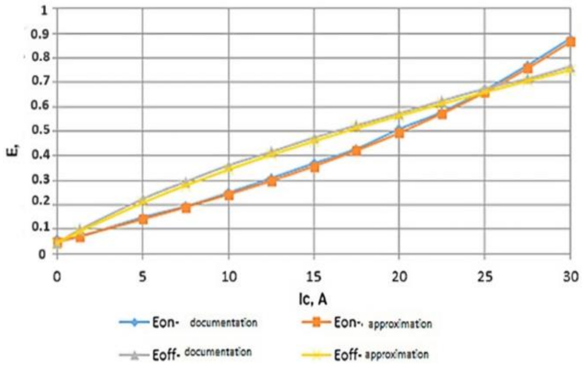


Figure 5. Switching energy loss curves for FS15R06XE3 power transistor

The obtained mathematical dependences describe the energy loss curves for the uncontrolled diode rectifier and IGBT/diode AVI modules with sufficient accuracy. The static and dynamic power losses in IGBTs are determined using transistor voltage and current. The power loss analyzer block in Figure 6 is used to figure out the static and dynamic power losses on the bypass diode of the FS15R06XE3 IGBT/diode module. The analyzer block in Figure 6 contains the following elements: one relay element, one delay element, one limiter, product blocks, one comparator, integral blocks, amplifiers, one conversion block, and function blocks.

The power loss analyzer used to determine the static and dynamic power losses on the IGBT/diode module type FS15R06XE3 is depicted in Figure 7. The analyzer block in Figure 7 contains the following elements: limiters, product blocks, amplifiers, comparators, integral blocks, one conversion block, and function blocks. Static losses resulted from simulation are shown in Figure 8, while the simulation results of dynamic losses are shown in Figure 9. It could be clearly deduced from Figure 9 that the turn-off and turn-on energy values depend on the transistor current magnitude. The modelling of dynamic losses shall be performed using a simulation method with constant calculation increments [25], [27]. Figure 7 shows the power loss analyzer block that was used to figure out the static and dynamic power losses on an IGBT/diode module of type FS15R06XE3.

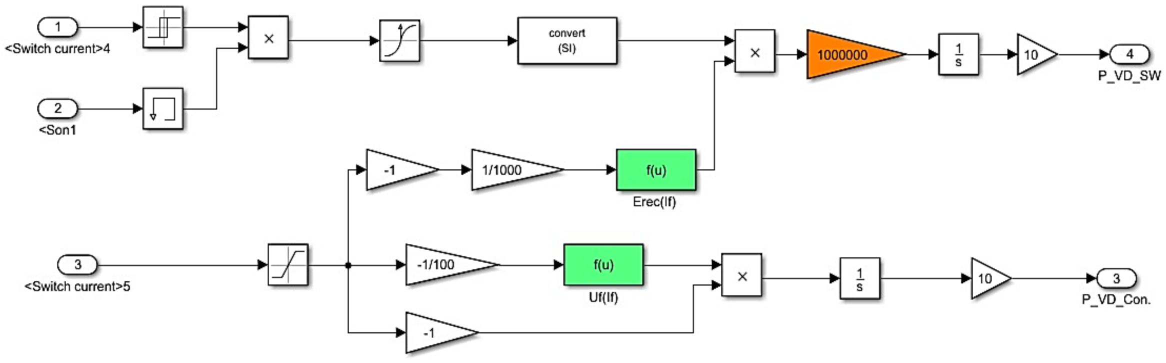
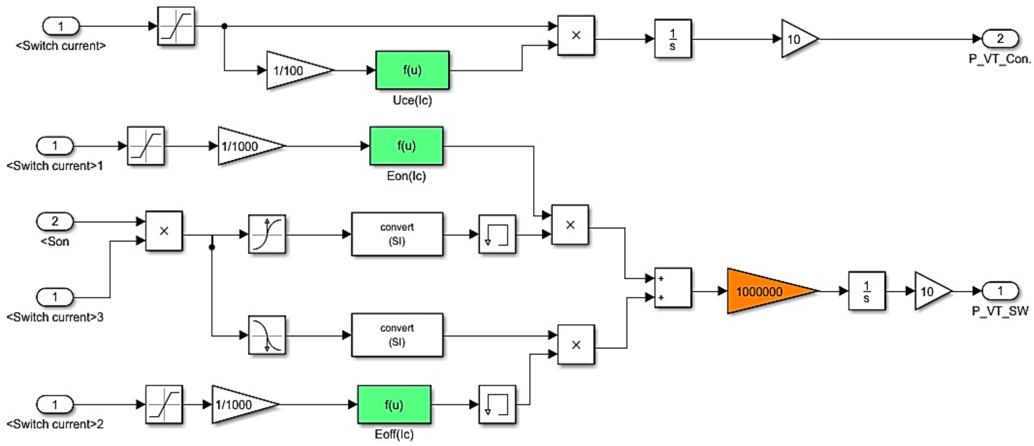


Figure 6. Block for calculation of power losses in the free-wheeling diode of FS15R06XE3 IGBT/diode module



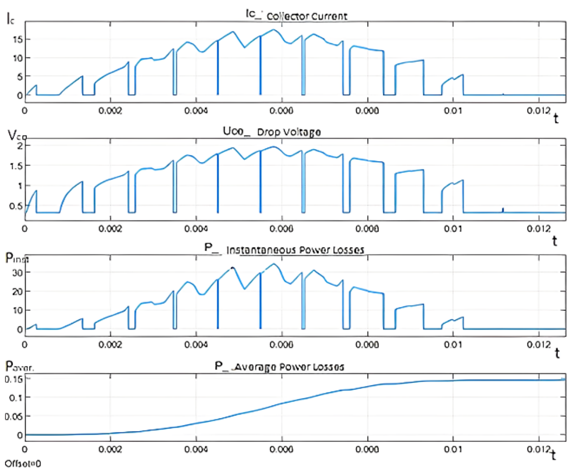


Figure 8. The static loss simulation results for the FS15R06XE3 IGBT/diode module

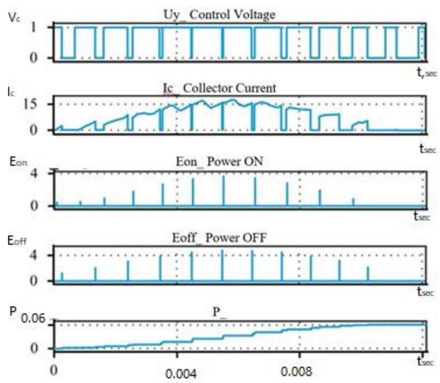


Figure 9. The simulation results of dynamic losses in the FS15R06XE3 IGBT/diode module

4. MODEL VERIFICATION

Table 4 compares the values of losses obtained by simulation in MATLAB/Simulink with those specified in the technical documentation for the 1.5 kW SSG110FC. The frequency converter model that was obtained in MATLAB/Simulink is sufficiently adequate, as evidenced by the simulation error for the losses of 3.78%. By using the suggested method, there was obtained an error of 3.78% compared to manufacturer-supplied data. The results of static and dynamic power loss modeling methods have been used to look into the efficiency of frequency converters and other types of semiconductor converters, as well as technical and scientific power loss estimation. The advantages of this method is that it accounts for particular transistor and power diode characteristics.

Table 4. Power losses calculation in SSG110FC

Parameter	FC documentation	MATLAB	Error
Total losses in frequency converter	118 W	113.53	3.78%

5. CONCLUSION

The current study presents a simulation modeling method that allows for estimating power losses in power semiconductor converters. Researchers developed model blocks to calculate the conduction losses in an unregulated rectifier and the losses in the AVI of the frequency converter. To use the approximation method to figure out power losses, mathematical equations were made for Vce (Ic), Vf (If), Eon (Ic), Eoff (Ic), and Erec (Ic) energy dependence diagrams. The obtained mathematical equations describe the power loss curves with adequate accuracy. We checked how reliable the suggested method for modeling power loss was by comparing the values given in the technical documentation of the 1.5 kW SSG110FC with the simulation results we got from MATLAB. This method yielded an error of 3.78% compared to manufacturer-supplied data. The given static and dynamic power loss modeling methods have been used to look into the efficiency of frequency converters and other types of semiconductor converters, as well as technical and scientific power loss estimation. This method's advantage is that it accounts for particular transistor and power diode characteristics.

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