

Article

Influence of Parasitic Elements and Operating Conditions of Semiconductor Switches on Power Losses and the Junction Temperature of These Switches

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Abstract: This article presents the results of computer analysis of selected switching networks. In these analyses, the influence of selected parasitic components of electronic switches on the total and active power losses in these switches is considered. Analyses are performed using the SPICE software for two models of semiconductor switches: an ideal switch with RC parasitic components and the SPICE model of an IGBT. The influence of parasitic capacitances and resistances of these devices operating with the control signal of different parameters values on the total and active power dissipated in these switches is analyzed. On the basis of the obtained computations the average and peak-to-peak values of the junction temperature of electronic switches at the steady state are calculated using a compact thermal model. It is shown that parasitic elements visibly influence waveforms of the active and total power. It is proved that the simplified model using the total power in computations of the junction temperature makes it possible to obtain a high accuracy of computations only in a situation when the transistor operates with a resistive load. For an inductive load, such simplification can cause an unacceptably high computation error exceeding even 30%. Such an error is a result of big differences between the active and total powers during switching-on and switching-off processes.

Keywords: DC–DC converters; self-heating; power semiconductor devices; power losses; junction temperature; parasitic capacitances; parasitic resistances



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1. Introduction

Switch-mode power converters are an important component of electrical and electronic equipment [1–3]. The tendency towards miniaturizing this equipment has resulted in an intensification of research aimed at enabling the operation of the considered class of power electronic systems at increasingly higher frequency values [1,4]. As has been discussed in the literature [5,6], an increase in the switching frequency causes an increase in the value of power losses in semiconductor devices [5] and magnetic components, e.g., inductors [7,8]. On the other hand, an increase in the value of the lost power causes an increase in the junction temperature of the electronic components under consideration due to the self-heating phenomenon [8,9].

Computer programs are commonly used in the design and analysis of electronic circuits. In the case of power electronic systems, SPICE and PLECS programs are most often used [10,11]. In order to take into account self-heating in these simulations, special models called electrothermal models are needed. Such models make it possible to determine waveforms of voltages and currents in the system and the junction temperature of its individual components [4,12]. When calculating the value of the junction temperature T_j a compact thermal model of the following form [6,8] is typically used

$$T_j(t) = T_a + \int_0^t Z'_{th}(t-v) \cdot p(v) dv \quad (1)$$

where T_a denotes the ambient temperature, $Z'_{th}(t)$ denotes the time differentiation of transient thermal impedance $Z_{th}(t)$, while $p(t)$ is the power dissipated in the device under consideration.

Typically, the Equation (1) uses the total power, i.e., the product of the voltage at the terminals of the semiconductor device and the current flowing through this device [6,10,13,14]. However, in actual semiconductor devices, electrical inertia associated with the occurrence of parasitic capacitances of this device is observed [15]. The effect of the use of the total power or the active power dissipated only in the resistive part of the equivalent circuit of the transistor on the waveforms of the junction temperature of the CoolMOS transistor was analyzed in paper [16]. The results presented in the cited paper show that there are visible differences in the total and active power waveforms. However, determination of the active power requires the use of a more complicated formula.

Such a formula causes an increase in the computation time and even can cause problems with the convergence of computations. On the other hand, in paper [17], it is proved that at the period of the control signal lower than the thermal time constant, the value of the transistor junction temperature at the steady state depends on the average value of the dissipated power. An important problem is to identify in which situations the total power can be used when calculating the junction temperature of a semiconductor device and when it is necessary to take into account the existence of parasitic capacitances of the device when determining this temperature and to use the active power [18–21].

Table 1 collects the most important information about the type of power used in computations of the junction temperature of semiconductor devices, as used in selected papers.

Table 1. Total power versus active power in selected papers.

Reference	Total Power	Active Power
[4,6,8,11,13,17,18,22–25]	YES	NO
[12,16]	NO	YES
[14,15,19–21,26,27]	No data	No data

Evidently, in many papers the total power is used in order to simplify the applied model and to shorten the computation time. Only a few papers use the active power in the thermal model.

The aim of this article is to analyze the relations between the active and total power dissipated in semiconductor devices operating in switching networks. In order to find such a relation, computer simulations of an electronic switch with a resistive load and a boost converter were carried out. The calculations were made in a wide range of changes in the frequency of the control signal and the parameters of the tested devices. In the calculations carried out using the SPICE program, two kinds of switches were used: (a) a simple switch model with a linear RC system, and (b) a non-linear compact model of the IGBT described in [22]. Using the obtained waveforms of the active and total power the values of the junction temperature of the switches under consideration were calculated and compared. On the basis of the obtained results, it is shown when the differences between the values of the total power and active power are negligible and when the differences cannot be omitted. It is also investigated whether the nonlinearities of the model being used influence the difference between the total and active power. It is shown that only for switching networks operating with an inductive load and a high value of peak-to-peak value of current flowing through the switch, the use of active power in the computations of device junction temperature is indispensable.

Section 2 describes the method of the analysis used. Section 3 presents the models of electronic switches used. The results of the calculations of power losses in switches are presented and discussed in Section 4. Based on the determined waveforms of the power lost in these switches, a thermal analysis described in Section 5 is carried out. The results of this analysis are presented in Section 6.

2. Analysis Method

In order to assess the influence of parasitic capacitances on power losses in electronic switches, a transient analysis was carried out for two networks. The first was an electronic switch with a resistive load, and the other was a boost converter. In both the cases, there was an electronic switch controlled by a sequence of rectangular pulses with the adjustable frequency f and the duty cycle d .

The waveforms of the power dissipated in the switch were determined using the classic transient analysis in the SPICE program. On the basis of the determined current and voltage waveforms in the analyzed networks, the waveform of the total power $P_{\text{tot}}(t)$ dissipated in the switches under consideration and the active power waveform $P_{\text{act}}(t)$ were determined. Power $P_{\text{tot}}(t)$ is the product of the time waveforms of the switch current and the voltage at its terminals. In turn, power $P_{\text{act}}(t)$ is the difference between power $P_{\text{tot}}(t)$ and the products of the currents and voltages on the capacitors representing the parasitic capacitances of the switches under consideration.

The analysis compares both the power waveforms $P_{\text{tot}}(t)$ and $P_{\text{act}}(t)$, as well as the average values of these waveforms in the steady state. The dependence of the difference of powers $P_{\text{tot}}(t)$ and $P_{\text{act}}(t)$ on frequency f , the slopes of the control signal and selected parameters of the model of the tested switches were determined.

3. Used Models of Electronic Switches

The analysis of properties of the switch networks under consideration was carried out for two models of electronic switches, hereinafter called linear switch and IGBT. The first one was based on the properties of the power MOS transistor operating at control voltage much lower and much higher than the threshold voltage, respectively. Of course, in order to simplify presented considerations, the actual dependence of on-state resistance on the transistor control voltage was omitted. This device was modeled using a voltage-controlled switch, which took into account the resistance of this component in the on and off state, the series resistance and the parasitic capacitance. This model used the built-in SPICE model of a voltage-controlled switch as well as a linear resistor and a linear capacitor. The other model considered was a non-linear model of the IGBT described in [22]. This model took into account the non-linearity of the DC characteristics of this transistor and its internal capacitances, the values of which were described by non-linear functions of the voltages between the terminals of this transistor.

Figure 1 shows a network representation of a linear switch model.

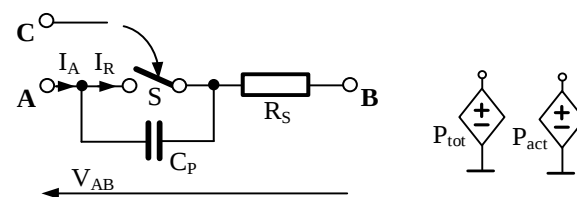


Figure 1. Network representation of a linear switch model.

The output terminals of the modeled switch are marked as A and B. The control signal is applied between terminal C and the ground. The controlled voltage sources are used to calculate the total power P_{tot} in the switch and the active power P_{act} . Power P_{tot} is the product of current I_A and voltage V_{AB} marked in Figure 1. In turn, power P_{act} is the sum of the product of current I_R and voltage V_{AB} and the product of the square of the difference of currents $I_A - I_R$ and resistance R_s .

This model uses the voltage-controlled switch S model built-in in the SPICE program. It is a non-inertial component and its DC characteristics are determined by 4 parameters: on-state resistance R_{ON} , off-state resistance R_{OFF} , on-state voltage V_{ON} and on-state voltage V_{OFF} [28]. The following values of these parameters were assumed in the calculations: $R_{\text{ON}} = 10 \text{ m}\Omega$, $R_{\text{OFF}} = 100 \text{ k}\Omega$, $V_{\text{ON}} = 4.8 \text{ V}$, $V_{\text{OFF}} = 0.2 \text{ V}$. These values of parameters are

selected arbitrarily, but selected values of voltage V_{OFF} and V_{ON} guarantee switching-on and switching-off of the device under consideration if the control signal has a form of a rectangular pulses train with the values equal to 0 and 5 V, respectively. The value of R_{OFF} corresponds to the opened channel and R_{ON} corresponds to the resistance of the switching-on channel for power MOS transistors dedicated to low voltage applications. Resistor R_S models the output resistance of the switched-on transistor. Capacitor C_P represents the capacitance of the switch.

In turn, the other model under consideration has a network representation shown in Figure 2.

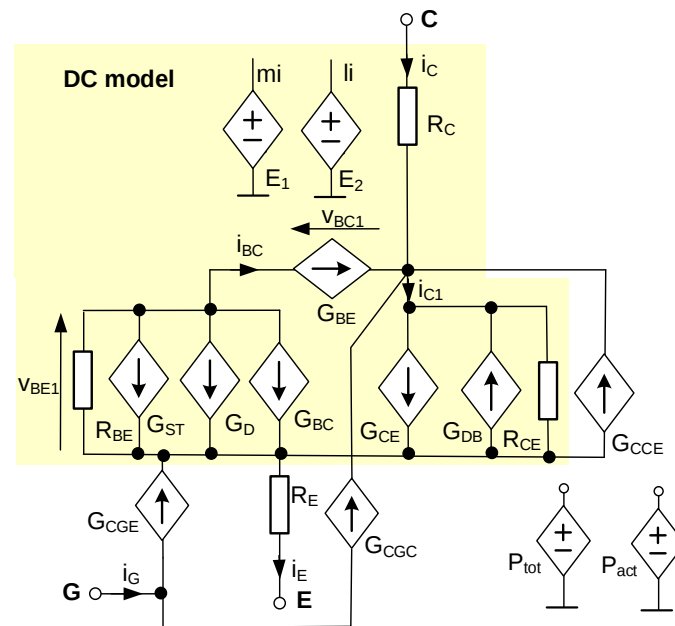


Figure 2. Network representation of the IGBT model used.

In Figure 2, electronic components describing DC characteristics of the IGBT are marked in yellow and labeled as a DC model. In turn, the controlled current sources G_{CGE} , G_{CCE} and G_{CCG} model the currents flowing through the internal capacitances C_{GE} , C_{CE} and C_{CC} of the transistor. In this model, the IGBT is represented by the connection of a MOS transistor and a BJT.

In the DC model of the IGBT, the drain current of the internal MOS structure is represented by two controlled current sources: G_D describing the channel current and G_{ST} modeling the sub-threshold component of this current. To compute the values of currents and voltages in the model of the internal MOS structure, the auxiliary controlled voltage sources (E_1 and E_2) are used.

The controlled current source G_{BE} represents the current flowing between the base and the emitter of the BJT contained in the structure of the modeled IGBT. The controlled current source G_{BC} describes the current flowing between the base and the collector of this BJT.

The controlled current source G_{CE} models the main current of the IGBT. The controlled current source G_{DB} models the DC characteristic of the diode. All the equations used to describe all the mentioned controlled current sources are described and discussed in papers [22,29].

In order to model the internal capacitances of the IGBT, the controlled current sources G_{CGE} , G_{CCE} and G_{CCG} are used. The mentioned current sources model the current flowing through the parasitic capacitances of the transistor C_{GE} , C_{CE} and C_{CC} , respectively. These currents are described with the formulas presented in [29]. In order to simplify the considerations, the influence of temperature on the characteristics of the modeled transistor was omitted in the model under consideration.

The controlled voltage sources P_{tot} and P_{act} enable calculation of the total power and the active power lost in this device. The parameter values of this model were selected for the IRG4PC40UD type transistor, and the correctness of the values of these parameters and the equations of the model was experimentally demonstrated in [29]. The power of P_{tot} is given by the formula of the form

$$P_{\text{tot}} = i_C \cdot V_{\text{CE}} + i_G \cdot V_{\text{GE}} \quad (2)$$

whereas P_{act} is given by the formula

$$P_{\text{act}} = i_C^2 \cdot R_C + i_E^2 \cdot R_E + (i_{\text{BC}} + i_{\text{C1}}) \cdot (V_{\text{BC1}} - V_{\text{BE1}}) \quad (3)$$

where currents i_{BC} , i_{C1} , i_C , i_G and voltages V_{CE} , V_{GE} , V_{BC1} , V_{BE1} are marked in Figure 2.

In the literature, e.g., [28,29], one can see that parasitic elements of semiconductor devices depend on temperature. In the cited papers, detailed formulas describing such dependences are given. In this paper, in order to reduce the number of parameters taken into account in the analyses and to more clearly obtain dependences in both models of electronic switches being used, the influence of temperature of their parameters is neglected. This assumption corresponds to the case when the temperature of these switches is constant.

4. Computation Results

Using the models described in Section 3 and the analysis method shown in Section 2, transient analyses in two networks were carried out. The first is a switch with a resistive load (shown in Figure 3) and the other is a boost converter (shown in Figure 4). The calculations focused on determining the P_{tot} and P_{act} power waveforms in the electronic switches under consideration.

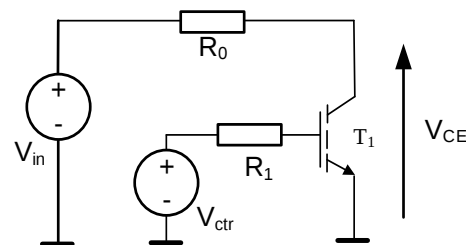


Figure 3. Tested network of the switch with the IGBT and a resistive load.

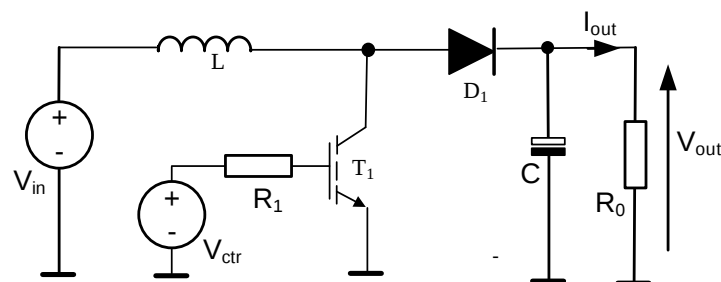


Figure 4. Tested network of the boost converter.

The properties of the power converters strongly depend on the parasitic elements of semiconductor devices and related gate drive circuit. Meanwhile, parasitic elements also influence the performance of the semiconductor switches, especially at high values of the time derivative of the current. This problem is considered in papers [30,31], which analyze the mechanism causing the voltage oscillation in such networks. A sensitivity study was performed in the cited papers to identify the critical impact factors causing the voltage oscillation.

In Figures 3 and 4, the symbol of the IGBT is used. In the case of the analyses performed for a linear switch, its terminal A was connected to the place of the collector, terminal B was for the emitter, and terminal C was in place of the gate of this transistor.

The following part of this section presents the results of computer analyses of the networks under consideration. Section 4.1 describes the results obtained using the linear switch model, and Section 4.2 describes the results obtained using the IGBT model from paper [22]. In all the figures included in this section, solid lines indicate the total power waveforms P_{tot} , and dashed lines indicate the active power waveforms P_{act} .

4.1. Results of the Computations with the Model of a Linear Switch

The figures in this section illustrate the power P_{tot} and P_{act} waveforms obtained for the circuit presented in Figure 3 using a linear switch model. Individual figures illustrate the influence of the factors such as rise time t_R and fall time t_F of the control signal (Figure 5), series resistance R_S (Figure 6), parasitic capacitance C_P (Figure 7) and frequency f (Figure 8) on the waveforms under consideration. The calculations were made with the duty cycle of the control signal $d = 0.5$, the supply voltage $V_{in} = 200$ V and the resistance of resistor $R_0 = 30$ Ω . Unless stated otherwise in the figures, the following nominal parameter values were used in the calculations: $f = 100$ kHz, $R_S = 50$ m Ω , $C_P = 3$ nF, $t_R = t_F = 0.3$ μ s.

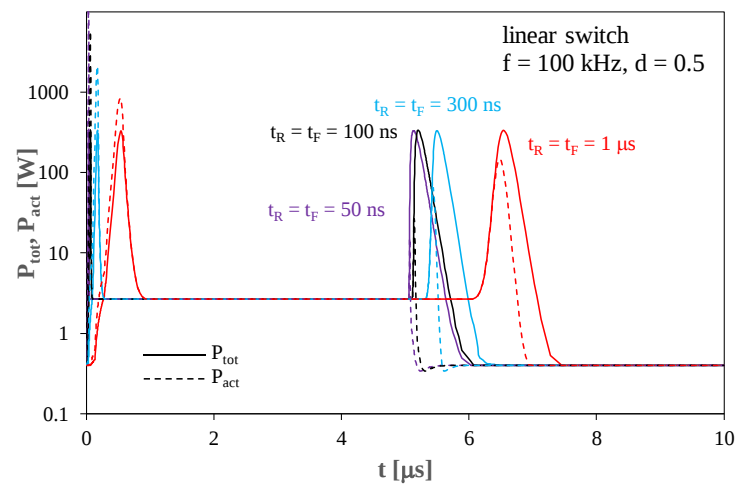


Figure 5. Computed waveforms of the total power and the active power dissipated in the linear switch at different values of times $t_R = t_F$.

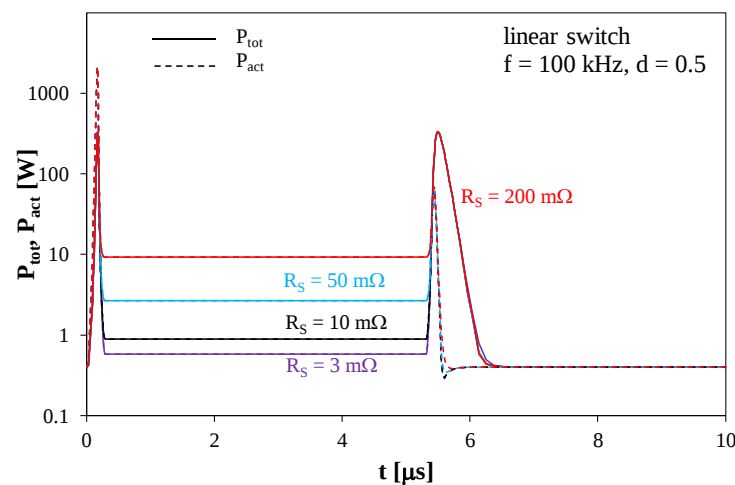


Figure 6. Computed waveforms of the total power and the active power dissipated in the linear switch at different values of resistance R_S .

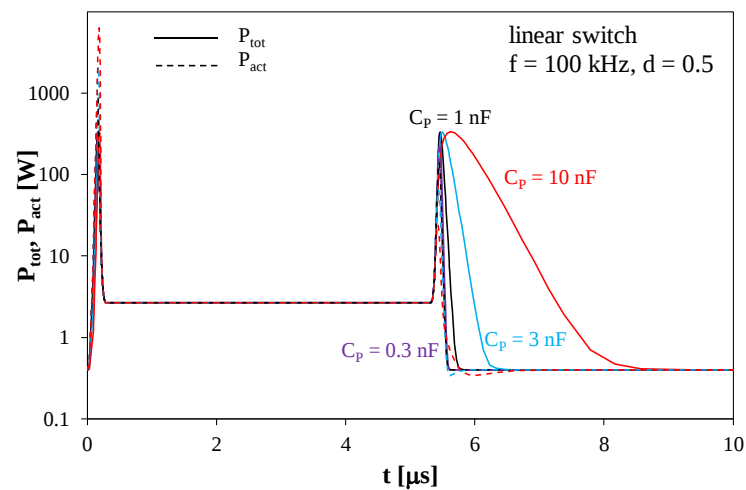


Figure 7. Computed waveforms of the total power and the active power dissipated in the linear switch at different values of capacitance C_p .

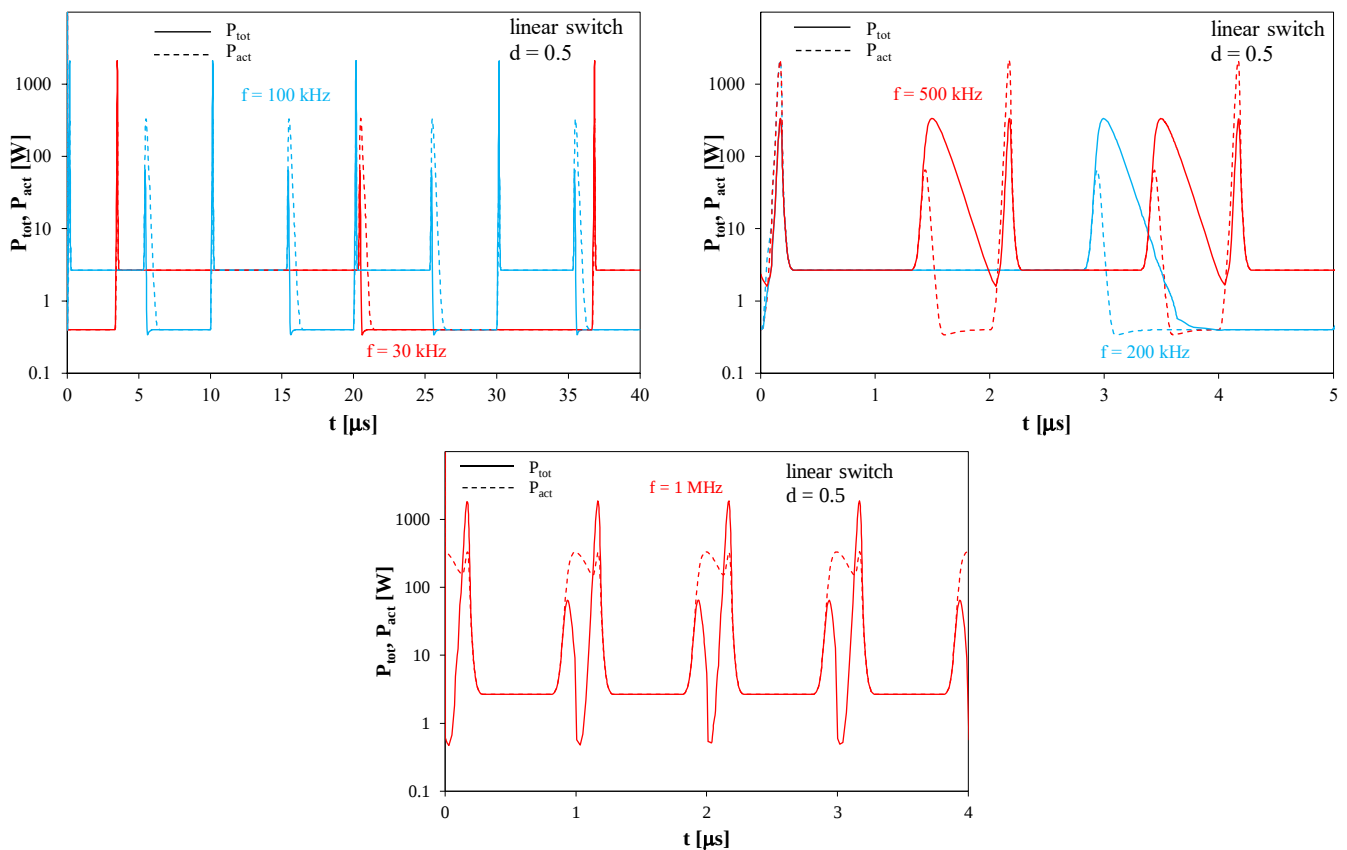


Figure 8. Computed waveforms of the total power and the active power dissipated in the linear switch at different values of frequency f .

Table 2 collects the values of the parameters of the linear switch and the control signal for computations, the results of which are presented in the following figures.

As can be seen, in the on state and in the off state, the power waveforms $P_{tot}(t)$ and $P_{act}(t)$ have identical values, and the influence of the times $t_R = t_F$ on these values is imperceptible. Of course, in the on state the power dissipated in the linear switch is much greater than in the off state. When switching, the instantaneous values of the powers under consideration are much (even 1000 times) higher than the values observed in the steady state. This is due to the simultaneous occurrence of high voltage at the terminals of the

switch and the high current flowing through the switch while switching. When switching on the switch (for time t from 0 to 1 μs) power P_{act} is greater than power P_{tot} , which is related to the discharge of capacitor C_P . On the other hand, when the switch is off (for time t from 5 to 8 μs), power P_{tot} is greater than power P_{act} due to the charging of capacitor C_P at that time. With an increase in the value of times $t_R = t_F$, the duration of the process of switching on and off increases.

Table 2. Values of the parameters of the linear switch and control signal used in the computations, the results of which are shown in the following figures.

Figure Number	f [kHz]	$t_R = t_F$ [ns]	R_S [m Ω]	C_P [nF]
Figure 5	100	50, 100, 300, 1000	50	3
Figure 6	100	300	3, 10, 50, 200	3
Figure 7	100	300	50	0.3, 1, 3, 10
Figure 8	30, 100, 200, 500, 1000	300	50	3

It is worth emphasizing that the maximum value of power P_{act} when switching on decreases with increasing times $t_R = t_F$, whereas when switching off it decreases. No influence of the times under consideration on the maximum values of power P_{tot} during the switching time was observed. Based on the obtained power waveforms $P_{\text{tot}}(t)$ and $P_{\text{act}}(t)$, the average values of these powers were determined for individual times $t_R = t_F$. The obtained results are summarized in Table 2.

As can be seen from Table 3, the average power values P_{tot} and P_{act} increase with increasing times $t_R = t_F$. In the range of changes of these times under consideration, the average power values almost doubles. Despite the differences in the $P_{\text{tot}}(t)$ and $P_{\text{act}}(t)$ waveforms shown in Figure 5, the average values of both the powers are practically identical and the differences between them do not exceed 1%.

Table 3. Average values of the total and active powers for the waveforms shown in Figure 5.

$t_R = t_F$ [ns]	50	100	300	1000
P_{tot} [W]	7.72	7.98	9.15	14.80
P_{act} [W]	7.67	7.89	9.10	14.75

The $P_{\text{tot}}(t)$ and $P_{\text{act}}(t)$ waveforms shown in Figure 6 prove that the series resistance R_S significantly affects the values of these powers in the switch on state, but it has practically no effect on the waveforms under consideration when the switch is turned on and off. There are clearly visible differences between the $P_{\text{tot}}(t)$ and $P_{\text{act}}(t)$ waveforms when switching on and off. The average values of the powers under consideration in the steady state are presented in Table 4.

Table 4. Average values of the total and active powers for the waveforms shown in Figure 6.

R_S [m Ω]	3	10	50	200
P_{tot} [W]	8.05	8.21	9.15	12.60
P_{act} [W]	8.01	8.17	9.10	12.56

The average values of both powers under consideration shown in Table 3 have practically the same values. It is worth noticing that at low values of resistance R_S , the dominant component of losses in the linear switch is related to the switching process. This component of losses for the operating conditions under consideration reaches up to 8 W.

Calculations were also carried out to examine the impact of changes in resistance R_{ON} on the waveforms and the average values of the powers under consideration. The results were analogous to the calculation results presented above for the respective resistance R_S values.

The waveforms of the powers under consideration presented in Figure 7 and calculated for different values of capacitance C_P indicate that an increase in the value of this capacitance may significantly extend the switching-off time of the switch. At $C_P = 10$ nF, this time exceeds even 3 μ s. The waveforms $P_{act}(t)$ show a large pulse when switching on the switch, the value of which increases with an increase of capacitance C_P , exceeding even 6 kW at $C_P = 10$ nF. On the other hand, when the switch is turned off, an increase in this capacitance results in an increase in the turn-off time and a significant difference between the waveforms $P_{tot}(t)$ and $P_{act}(t)$ in this range.

The comparison of the average values of the powers for the values of capacitance C_P is shown in Table 5. It can be seen that an increase in the value of this capacitance can cause a significant (even almost fivefold) increase in the value of the average power lost in the switch under consideration. As in the previous considerations, there is practically no difference in the average values of P_{tot} and P_{act} determined in the considered conditions.

Table 5. Average values of the total and active powers for the waveforms shown in Figure 7.

C_P [nF]	0.3	1	3	10
P_{tot} [W]	4.83	5.67	9.16	22.79
P_{act} [W]	4.84	5.65	9.12	22.63

The effect of frequency on the waveforms $P_{tot}(t)$ and $P_{act}(t)$ shown in Figure 8 indicates that an excessive increase in frequency can lead to switching problems. At $f = 1$ MHz, the switch cannot be turned off. In the on state, the switch remains on all the time and the pulses of the powers under consideration are observed only at the moments of switching on the control signal. Switching is performed correctly for the frequency not exceeding 500 kHz.

The average values of the powers under consideration for selected frequency values are summarized in Table 6. It can be seen that an increase in frequency causes an almost proportional increase in the values under consideration. The discrepancies between the average values of power P_{tot} and P_{act} are below 1%.

Table 6. Average values of the total and active powers for the waveforms shown in Figure 8.

f [kHz]	30	100	200	500
P_{tot} [W]	3.789	9.147	16.702	39.441
P_{act} [W]	3.78	9.096	16.645	39.29

4.2. Results of the Computations with the Model of the IGBT Switch

This section presents the results of calculations of the power waveforms P_{tot} and P_{act} in the IGBT operating in the circuit shown in Figure 3, determined at different values of the parameters of the signal controlling the gate of this transistor. The calculations were made using the model of this transistor described in [22], and the parameter values of this model were used for the transistor type IRG4PC40UD [32]. The correctness of this model was demonstrated experimentally in [29]. Although the manufacturer recommends using this transistor at a switching frequency not exceeding 40 kHz, a frequency of 100 kHz was used in the calculations. This procedure was used to emphasize the influence of transistor parasitic capacitances on the p_{tot} and p_{act} power waveforms.

The dependence of the internal capacitances of this transistor, C_{GE} , C_{GC} and C_{CE} , on the voltage between the collector and the emitter V_{CE} as determined by the applied model at the control voltage $V_{GE} = 0$ is shown in Figure 9.

As can be seen, when switching on transistor capacitances C_{GC} and C_{CE} are the decreasing functions of voltage V_{CE} . The capacitance between the gate and the emitter C_{GE} in the conditions under consideration practically does not depend on voltage V_{CE} .

Table 7 collects the values of the parameters of the control signal for computations, the results of which are presented in Figures 10 and 11.

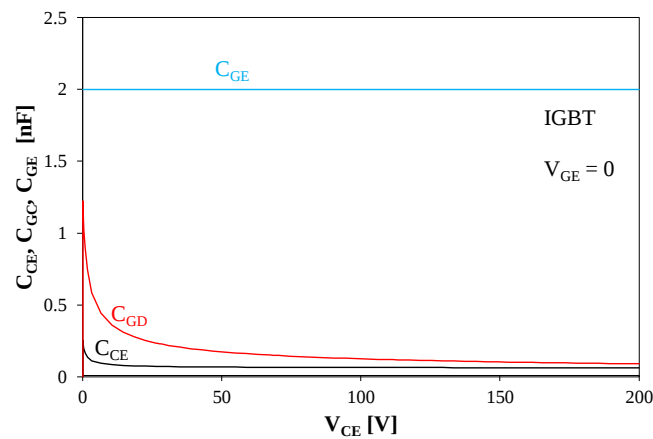


Figure 9. Dependences of parasitic capacitances of the tested IGBT on voltage V_{CE} at $V_{GE} = 0$.

Table 7. Values of the parameters of the IGBT switch and control signal used in the computations, the results of which are shown in the following figures.

Figure Number	f [kHz]	$t_R = t_F$ [ns]
Figure 10	100	100, 300, 700, 1000
Figure 11	50, 100, 200, 400	300

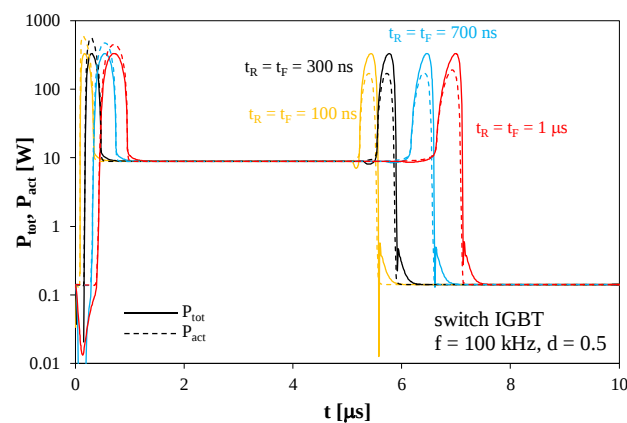


Figure 10. Computed waveforms of the total and active power dissipated in the IGBT switch at different values of times $t_R = t_F$.

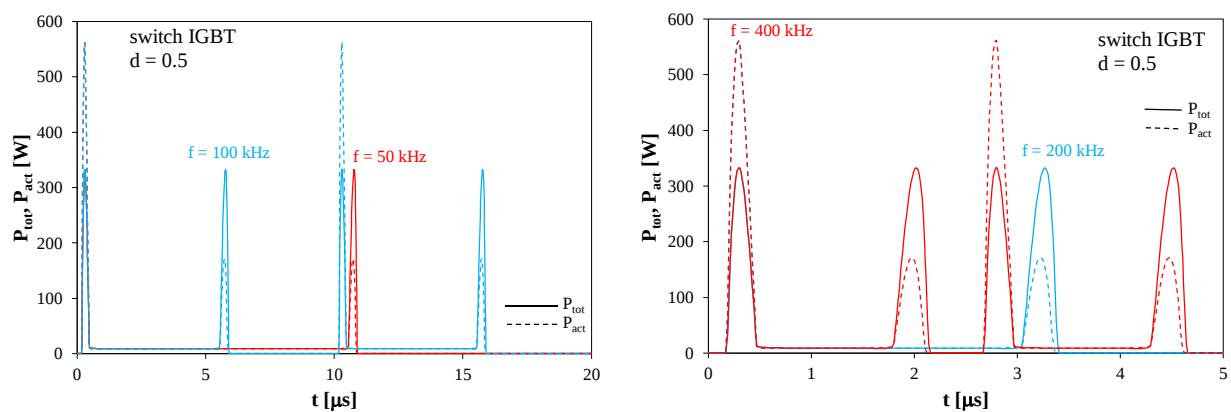


Figure 11. Computed waveforms of the total and active powers dissipated in the IGBT switch at different values of frequency f .

Figures 10 and 11 illustrate the influence of rise and fall times $t_R = t_F$ (Figure 10) and frequency (Figure 11) on the power waveforms P_{tot} and P_{act} in the IGBT transistor under consideration operating in the switch network shown in Figure 3. The calculations assumed the following test circuit parameter values: $V_{in} = 200$ V, $R_0 = 30$ Ω , $R_1 = 10$ Ω . The voltage source V_{ctr} produces a trapezoidal signal of the levels 0 and 15 V and the duty cycle $d = 0.5$.

In the case of the IGBT switch, the $P_{tot}(t)$ and $P_{act}(t)$ waveforms shown in Figure 10 do not differ significantly. The waveforms of these powers determined for different values of times $t_R = t_F$ show only a shift on the time axis, while no significant change in the maximum value or pulse duration of these powers associated with switching the transistor on and off is visible. The differences between the maximum values of $P_{tot}(t)$ and $P_{act}(t)$ determined for the times $t_R = t_F$ under consideration do not exceed 15%. The average values of both powers under consideration for individual values of times $t_R = t_F$ are summarized in Table 8.

Table 8. Average values of the total and active powers for the waveforms shown in Figure 10.

$t_R = t_F$ [ns]	100	300	700	1000
P_{tot} [W]	17.18	18.16	22.04	25.34
P_{act} [W]	17.18	18.17	22.03	25.33

It can be seen that the average values of both the powers are practically identical. The differences between them are less than 0.06%. The influence of times $t_R = t_F$ on the values under consideration is weak. With changes of these times from 100 ns to 1 μ s, the average values of the powers under consideration increase by about 50%.

The $P_{tot}(t)$ and $P_{act}(t)$ waveforms shown in Figure 11 indicate that frequency changes do not cause changes in the waveform of these powers when switching the transistor on/off. Frequency affects only the average values of the powers under consideration, which are collected in Table 9.

Table 9. Average values of the total and active powers for the waveforms shown in Figure 11.

f [kHz]	50	100	200	400
P_{tot} [W]	11.35	18.17	31.83	59.09
P_{act} [W]	11.35	18.17	31.81	59.08

It can be seen that the average value of both powers under consideration increases almost proportionally to frequency. The differences between the obtained average values of both the powers are practically invisible.

4.3. Results of the Computations of the Boost Converter

The results presented in the previous sections concerned switches with resistive loads. However, electronic switches are often used in DC–DC converters. The next part of the section presents the results of analyses of a boost converter containing a linear switch on the IGBT. The calculations were carried out for the frequency of the control signal $f = 100$ kHz and different values of a load resistance R_0 . The input voltage V_{in} is equal to 100 V, inductance $L = 100$ μ H and capacitance $C = 100$ μ F. Figure 12 is for a converter with the linear switch and Figure 12 is for a converter with the IGBT.

For the converter with a linear switch, the load resistance values were selected in such a way as to examine the operation of the converter in the continuous conduction mode (CCM) and the discontinuous conduction mode (DCM). In the case under consideration, the CCM mode was obtained for R_0 values of 10 Ω , 50 Ω and 100 Ω , while the DCM mode was obtained for R_0 values of 200 and 300 Ω , respectively. It is worth noting in Figure 12 that in the CCM mode, as the load resistance increases, the power dissipated in the switch in its on state decreases, while in the DCM mode, the opposite tendency is observed. Due to the low value of the resistance of the switched-on switch, the power pulses have a very high maximum value, reaching up to 80 kW when switching on the switch and up to

10 kW when switching it off. The short switching time of the linear switch means that the switching losses do not have a significant influence on the average values of P_{tot} and P_{act} .

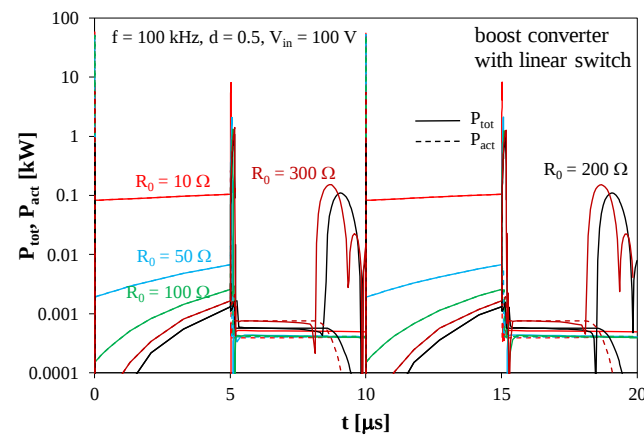


Figure 12. Computed waveforms of the total and active powers dissipated in the linear switch operating in the boost converter at different values of load resistance R_0 .

Table 10 compares the average values of the total and active powers dissipated in the linear switch operating in the converter under consideration and the values of the output voltage of this converter V_{out} . For all the resistance values R_0 under consideration, the average value of the P_{act} power is lower than the P_{tot} power. The relative deviation of power P_{tot} and P_{act} values increases with an increase of the load resistance R_0 . When working in the DCM mode for $R_0 = 500 \Omega$ this deviation exceeds as much as 18%. In the CCM mode, an increase in the resistance R_0 value causes a decrease in the value of both powers under consideration, whereas when switching to the DCM mode, the value of these powers increases. This is caused by an increase in the amplitude of the current switched by the switch.

Table 10. Average values of the total and active powers for the waveforms shown in Figure 12.

R_0 [Ω]	10	50	100	200	300	500
P_{tot} [W]	54.44	8.63	6.99	0.592	1.427	1.38
P_{act} [W]	54.36	8.56	6.93	0.558	1.267	1.132
V_{out} [V]	197.23	200.1	200.95	237.7	272.63	367

Figure 13 shows the waveforms of the powers under consideration, dissipated in the IGBT during the operation in the boost converter.

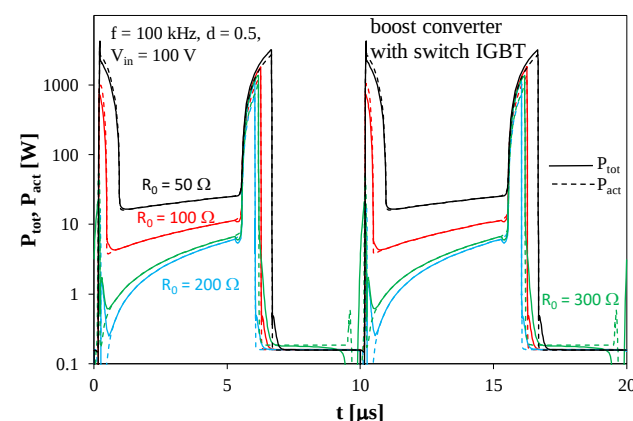


Figure 13. Computed waveforms of the total and active powers dissipated in the IGBT operating in the boost converter at different values of load resistance R_0 .

As can be seen, the switching process of the IGBT transistor is much slower than that of the linear switch. The waveforms $P_{\text{tot}}(t)$ and $P_{\text{act}}(t)$ shown in Figure 13 clearly show that the maximum value of the power pulses decreases with an increase of load resistance R_0 . An increase in the value of this resistance also results in shortening the switching process and a decrease in the average value of the power. When the transistor is turned on, power P_{tot} is less than power P_{act} , whereas when the transistor is turned off, the relation between these powers is opposite. When operating in the DCM mode (at $R_0 = 200 \, \Omega$ and $R_0 = 300 \, \Omega$), the transistor current when switching it on is close to zero, and therefore in this mode the power pulses when switching on the transistor are even thousand times smaller than when working in the CCM mode. The average values of both the powers are presented in Table 11.

Table 11. Average values of the total and active powers for the waveforms shown in Figure 13.

$R_0 \, [\Omega]$	50	100	200	300	500
$P_{\text{tot}} \, [\text{W}]$	290.28	83.23	31.73	42.83	46.72
$P_{\text{act}} \, [\text{W}]$	281.32	73.44	20.60	28.20	30.72
$V_{\text{out}} \, [\text{V}]$	219.4	222.52	223	256.8	275.4

It can be seen that for all the load resistance values under consideration, the average power P_{tot} is greater than the average power P_{act} . The differences between these values range from 9 to 16 W, which is from 3% to as much as 34% of the average power P_{tot} . The relative differences between the average values of the powers under consideration are the greatest when the converter operates in the DCM mode. In this mode, the current flowing through the IGBT when switching it on is much lower than the current of this transistor when switching it off, because it is equal to the inductor current in this time interval, the waveform of which is in the shape of a triangle signal. The peak-to-peak value of this waveform depends, among others, on the operating frequency of the converter and the inductor inductance.

In the CCM mode, a slight decrease in the difference between the average values of the powers under consideration can be noticed with an increase in the inductor inductance L . In the case of the converter operating in the DCM mode, an increase in inductance L causes a decrease in the peak-to-peak value of the inductor current, and in extreme cases it may result in switching to the CCM mode [7,33].

The calculation results presented in this section prove that the IGBT switches are much slower than the linear switch under consideration. In the case of the operation of both the switching devices under consideration with a resistive load and with an inductive load, it can be seen that when switching on, power P_{act} is greater than power P_{tot} , and when switching off the relation between these powers is opposite. With a resistive load, the average values of both the powers are practically identical, while with an inductive load, the average power P_{tot} is significantly higher than the average power P_{act} . The differences between these values increase as the peak-to-peak value of the inductor current increases. These differences are particularly big when the DC–DC converter is operating in the DCM mode, exceeding even 33%.

5. Thermal Analysis

In order to determine the waveform of the junction temperature of an electronic switch during its operation, it is necessary to perform a thermal analysis. Typically, the compact thermal model described by the Equation (1) is used in such an analysis. Active power P_{act} should be used in this model. However, the total power P_{tot} is often used in such a model for simplicity [23,24,27]. The calculations, and the results of which are presented in the further part of this paper, will show what error is made with such a simplification.

In the Equation (1) there is transient thermal impedance $Z_{th}(t)$ typically described by the formula [25,34,35]

$$Z_{th}(t) = R_{th} \cdot \left(1 - \sum_{i=1}^N a_i \cdot \exp\left(-\frac{t}{\tau_{thi}}\right) \right) \quad (4)$$

where R_{th} is thermal resistance, a_i is the weighting factor related to the thermal time constant τ_{thi} and N is the number of thermal time constants.

Depending on the construction of the cooling system of the semiconductor device under consideration, in Equation (2) there are from three to seven thermal time constants [36,37]. The values of these time constants range from a few tenths of a millisecond to several thousand seconds [17,37]. These values are much higher than the typical values of the control signal period of the switching systems under consideration. This period is usually much less than 100 μ s. As was shown in [17], due to the big difference between the values of thermal time constants and the period of the control signal, the peak-to-peak values of the steady-state junction temperature do not exceed 1% of the average excess of the junction temperature T_j over the ambient temperature T_a . Therefore, the average value of the junction temperature in the steady state can be calculated from the formula of the form

$$T_j = T_a + R_{th} \cdot p_{avg} \quad (5)$$

where p_{avg} is the average value of the power dissipated in the tested switch.

The next section illustrates the effect of substituting the average power P_{tot} and P_{act} with p_{avg} on the average value of temperature T_j at the steady state. The effect of substituting the P_{act} or P_{tot} power waveforms in the Equation (1) on the peak-to-peak value of temperature T_j is also analyzed.

6. Results of the Investigations

In order to show that the model of the IGBT being used makes it possible to properly compute the average values of the junction temperature of this device operating in both the tested networks some measurements and computations were performed. The results obtained at the steady state are presented in Figures 14 and 15. In these figures, points denote the results of measurements and lines denote the results of computations. Solid lines were obtained using the active power in the thermal model, whereas dashed lines were obtained using the total power. The results of the measurements shown in these figures were presented previously in papers [5,22]. During the measurements the tested IGBT was situated on the big heat sink.

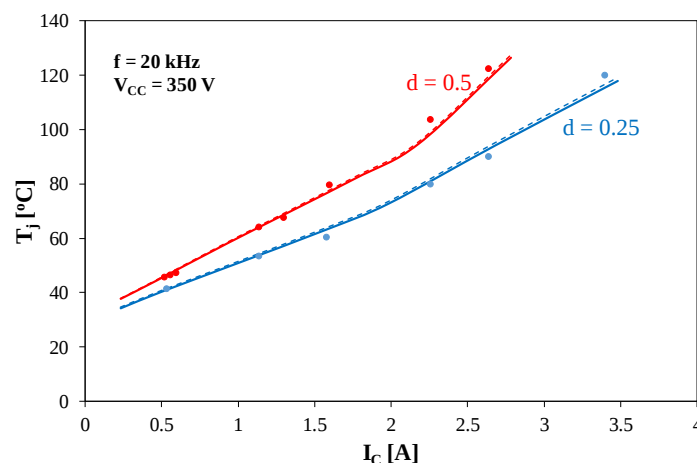


Figure 14. Computed and measured dependences of the average values of the junction temperature of the IGBT operating in the switch with a resistive load at different values of the duty cycle on the value of the collector current in the on state.

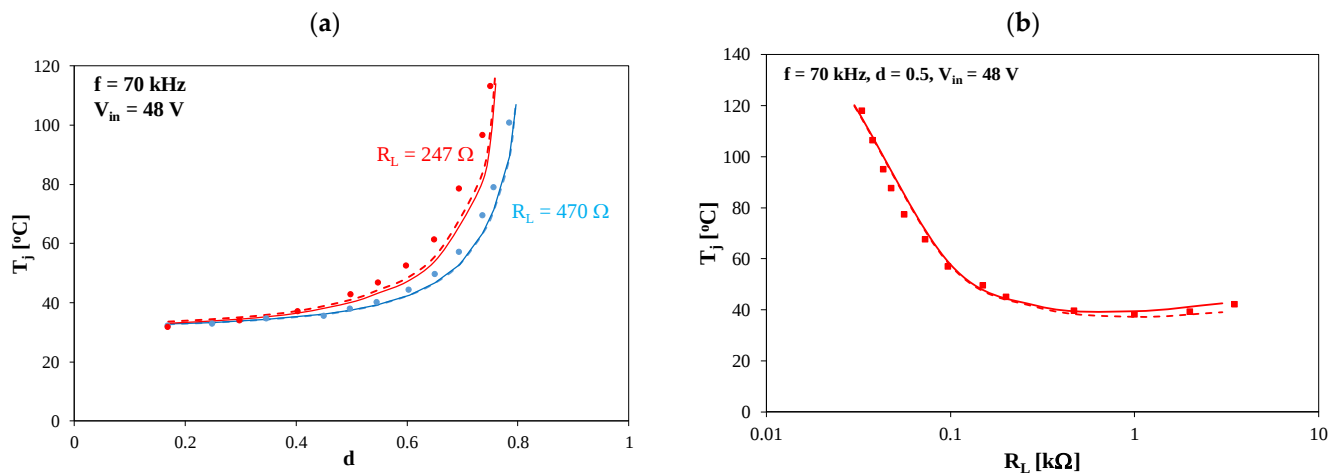


Figure 15. Computed and measured dependences of the average values of the junction temperature of the IGBT operating in the boost converter on the value of the duty cycle at different values of the load resistance (a) and on load resistance (b).

Figure 14 illustrates the dependence of the average values of the junction temperature of the IGBT operating in the switch with a resistive load on the value of the collector current in the on state at different values of the duty cycle. In turn, in Figure 15a the dependences of the average values of the junction temperature of the IGBT operating in the boost converter at different values of the load resistance on the value of the duty cycle are shown, whereas Figure 15b shows the dependence of such temperature on the load resistance of the converter under consideration.

Evidently, in both cases under consideration, a good agreement between the results of measurements and computations was obtained. This confirms the correctness of the electrothermal model of the IGBT used. Furthermore, Figures 14 and 15a demonstrate that the use of the active or total power in the analyses of the switch with a resistive load and a boost converter operating in the CCM mode does not cause any visible differences in the computations results. In Figure 15a it is evident that for both values of the load resistance under consideration the tested boost converter operates in the CCM mode.

Figure 15b show all the results of the investigations of the tested boost converter operating both in the CCM (for $R_L < 500 \Omega$) and DCM modes (for $R_L > 500 \Omega$). In both the modes the value of the junction temperature computed by using the total power in the thermal model is higher than the value of such temperature obtained using active power. In the CCM mode the differences between the mentioned values of junction temperature do not exceed 0.5°C , whereas in the DCM they are up to 3.5°C . The dependence $T_j(R_L)$ has a minimum at $R_L = 1 \text{ k}\Omega$.

The thermal analysis of both the systems described in Section 4 was carried out using a compact thermal model. Two sets of parameters of such a model, given in [17], were used in the computations. The cited paper shows that the junction temperature oscillations of an electronic component excited by the power of the rectangular pulses train are bigger when the thermal time constants are smaller. Therefore, for the linear switch and the IGBT, the following values of the thermal model parameters are adopted, corresponding to the ideal cooling of the semiconductor device case: $a_1 = 0.2$, $\tau_{th1} = 0.4 \text{ ms}$, $a_2 = 0.15$, $\tau_{th2} = 4.5 \text{ ms}$, $a_3 = 0.65$, $\tau_{th3} = 6 \text{ ms}$. In turn, the values of thermal resistance R_{th} of both the switches were selected in such a way that the maximum junction temperature increase at the steady state reached about 100 K ; for the linear switch $R_{th} = 10 \text{ K/W}$, and for the transistor 0.5 K/W .

The following figures show, in the form of bar charts, the computed values of an excess in the junction temperature T_j of the linear switch and the IGBT operating in the conditions considered in Section 4 above the ambient temperature T_a . Both the average values of this excess $(T_j - T_a)_{avg}$ and the peak-to-peak values $(T_j - T_a)_{pp}$ at the steady state are presented. In the computations of the mentioned parameters, the waveforms of power P_{tot} (full bars)

and power P_{act} (empty bars) obtained at the steady state were used. Section 6.1 presents the results achieved for the switch with a resistive load, whereas Section 6.2 presents the results obtained for the boost converter.

6.1. Results of the Calculations for the Switch with a Resistive Load

Figure 16 illustrates the effect of rise time $t_R = t_F$ (Figure 16a) and capacitance C_P (Figure 16b) on the value of $(T_j - T_a)_{avg}$ for the linear switch operating in the circuits shown in Figure 6, while in Figure 17 illustrates the effect of frequency f (Figure 17a) and resistance R_S (Figure 17b) on the value of $(T_j - T_a)_{pp}$.

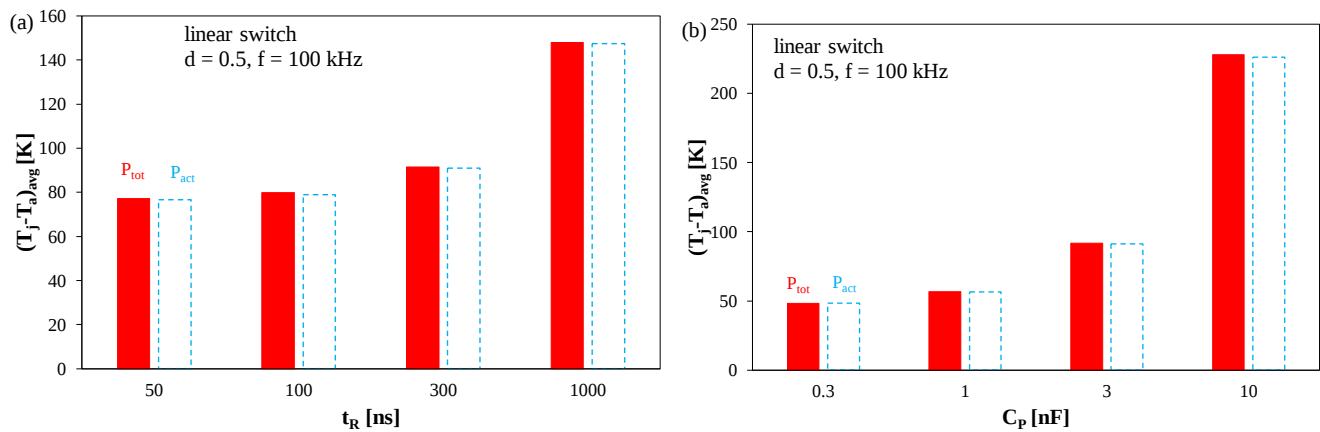


Figure 16. Computed average values of a temperature increase $(T_j - T_a)_{avg}$ of the linear switch operating in the network shown in Figure 3 at selected values of time t_R (a) and capacitance C_P (b).

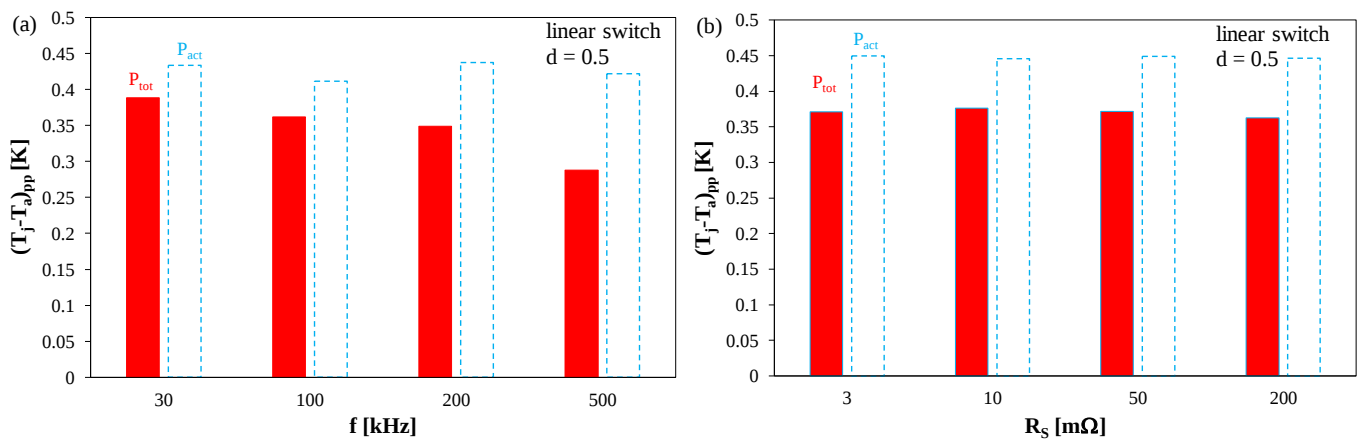


Figure 17. Computed peak-to-peak values of a temperature increase $(T_j - T_a)_{pp}$ of the linear switch operating in the network shown in Figure 3 at selected values of frequency f (a) and resistance R_S (b).

In Figure 16 it can clearly be seen that the average values of the excess of temperature T_j over temperature T_a calculated using power P_{tot} and P_{act} are practically identical. It can be observed that an increase in both time t_R and capacitance C_P cause an increase in the value of $(T_j - T_a)_{avg}$. In the range of changes in time t_R under consideration, the increase in temperature under study doubles, and with changes in capacitance C_P in the range under study, this increase is more than fourfold.

In Figure 17 there are visible differences between the values of a temperature increase under consideration which are calculated using the total power P_{tot} and the active power P_{act} . In all the considered cases, the values of $(T_j - T_a)_{pp}$ calculated using power P_{act} are higher (even by 50%) than the values calculated using power P_{tot} . An increase in frequency causes a decrease in the value of $(T_j - T_a)_{pp}$ by up to 30%, while a change in the value

of resistance R_S practically does not affect the value of $(T_j - T_a)_{pp}$. The results of the calculations shown in Figure 17 prove that the peak-to-peak value of a temperature increase $(T_j - T_a)_{pp}$ in the steady state is significantly (even 100 times) lower than the average value of this increase. This means that in the considered range of frequency the ripples in the junction temperature can be omitted and an error of such simplification does not exceed 1%. The accurate results of the junction temperature can be obtained using either the total or active power in computations.

Figure 18 shows the influence of time $t_R = t_F$ (Figure 18a) and frequency f (Figure 18b) on the value of $(T_j - T_a)_{avg}$ for the IGBT operating in the circuit shown in Figure 3, while Figure 19 shows the influence of these quantities on the value of $(T_j - T_a)_{pp}$.

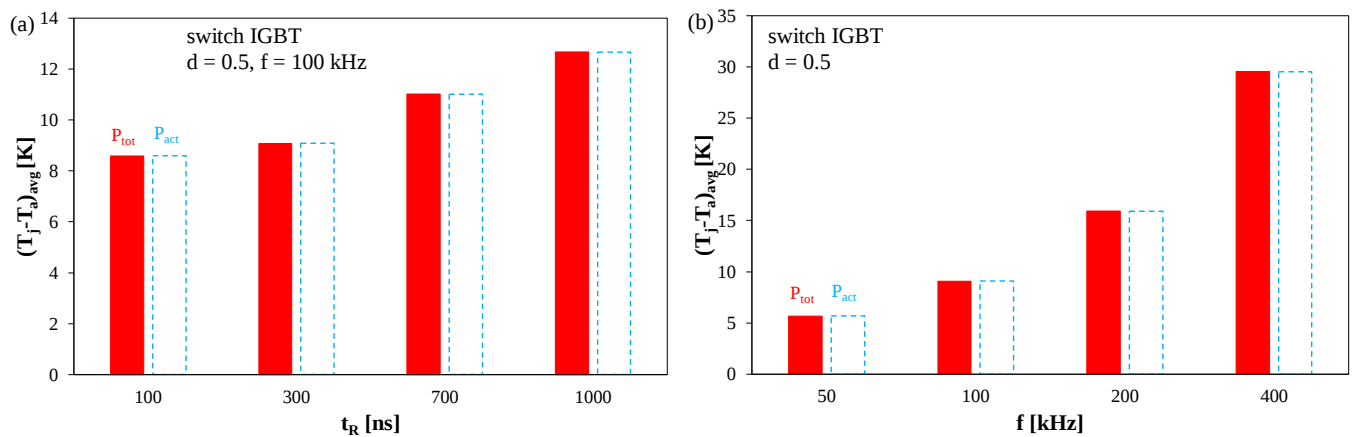


Figure 18. Computed average values of a temperature increase $(T_j - T_a)_{avg}$ of the IGBT operating in the network shown in Figure 3 at selected values of time t_R (a) and frequency f (b).

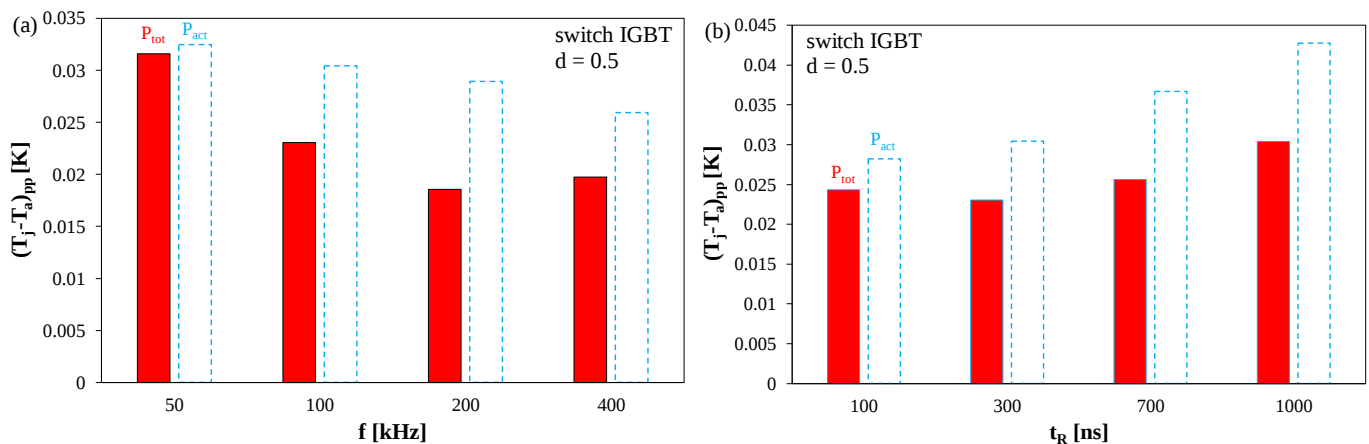


Figure 19. Computed peak-to-peak values of a temperature increase $(T_j - T_a)_{pp}$ of the IGBT operating in the network shown in Figure 3 at selected values of time t_R (a) and frequency f (b).

The dependences visible in Figure 18 show that additionally in the case of a switch with an IGBT, the influence of the use of P_{tot} or P_{act} power in the thermal model on the calculated $(T_j - T_a)_{avg}$ values is not noticeable. The considered temperature difference is an increasing function of time t_R and frequency f . In the range of frequency changes under consideration, the calculated values of a temperature excess increase by even sixfold. In turn, the peak-to-peak value of this temperature excess is more than 300 times lower than the average value of this temperature excess. As with the linear switch, the peak-to-peak value of a temperature rise determined using power P_{act} is up to 50% higher than when power P_{tot} is used in the calculations. The results presented in Figures 18 and 19 prove that

the thermal properties of the switch IGBT operating with a resistive load can be properly modeled using the total power in computations.

6.2. Results of the Calculations for the Boost Converter

Figure 20 illustrates the effect of load resistance R_0 of the boost converter on the value $(T_j - T_a)_{avg}$ for the linear switch (Figure 20a) and the IGBT (Figure 20b), and Figure 21 shows the influence of this resistance on the value $(T_j - T_a)_{pp}$.

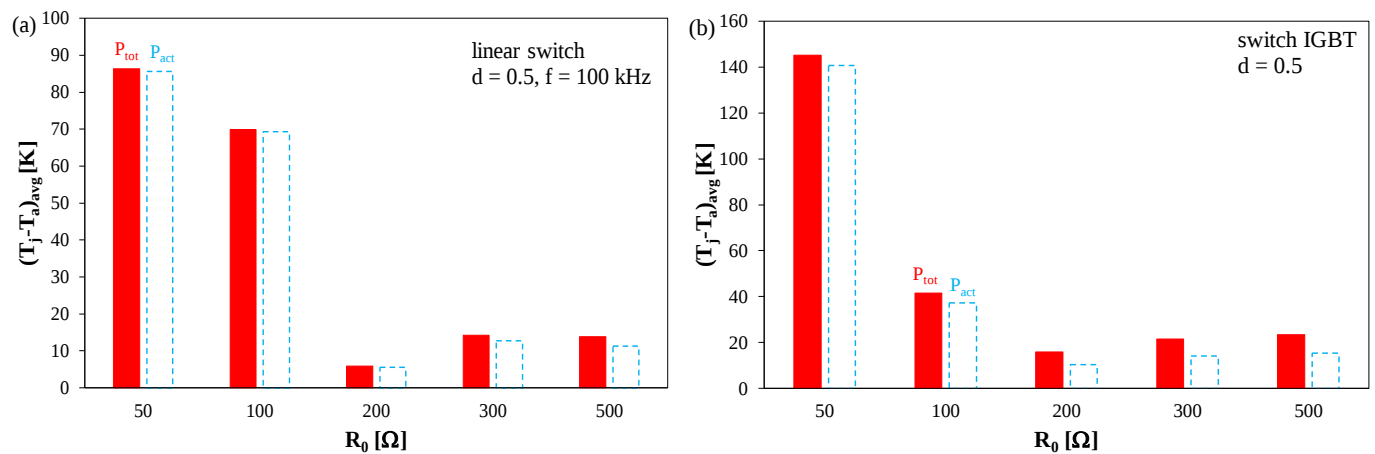


Figure 20. Computed average values of a temperature increase $(T_j - T_a)_{avg}$ of the linear switch (a) and the IGBT (b) operating in the boost converter at selected values of load resistance R_0 .

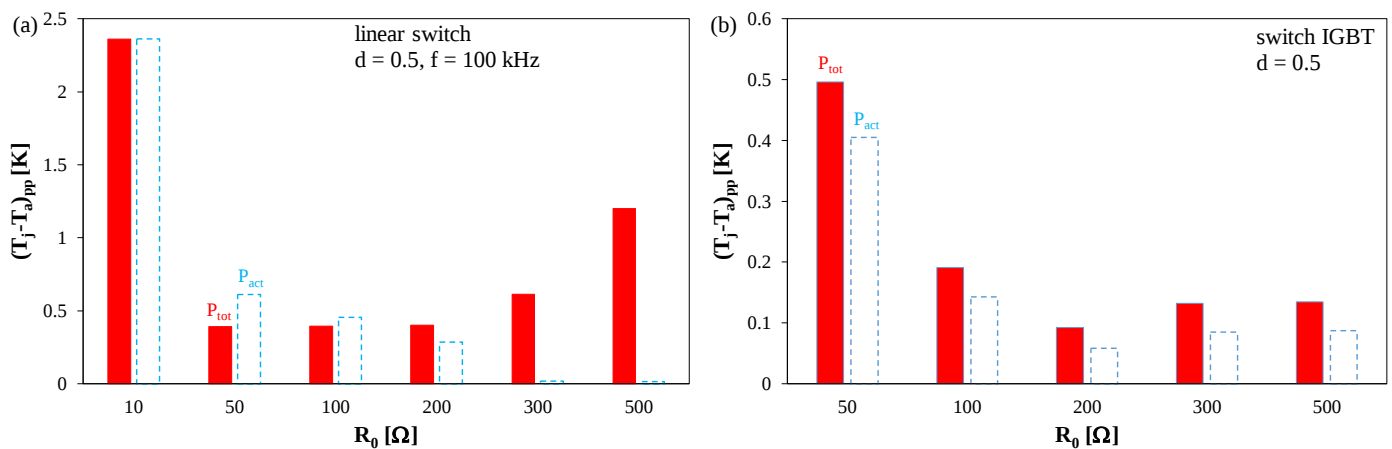


Figure 21. Computed peak-to-peak values of a temperature increase $(T_j - T_a)_{pp}$ of the linear switch (a) and the IGBT (b) operating in the boost converter at selected values of load resistance R_0 .

In the case of the operation of the considered switches in the boost converter, it can clearly be seen in Figure 20 that by determining the average value of a temperature excess $(T_j - T_a)_{pp}$ using power P_{tot} , higher values are obtained than when power P_{act} is used. The differences are particularly visible when the converter is operating in the DCM mode (at high resistance R_0 values). These differences exceed even 30%. It is also worth noting that when working in the DCM mode, despite the lower power delivered to the load, higher transistor junction temperature values are obtained.

In Figure 21 it can be seen that the peak-to-peak value of a temperature excess is negligible in relation to the average value of this excess. In the case of the linear switch operating in the converter in the CCM mode, higher values of $(T_j - T_a)_{pp}$ were obtained using power P_{act} in the thermal model, while in the DCM mode the relation was opposite. For the IGBT, the considered peak-to-peak value of a temperature excess was higher for power P_{tot} .

The results presented in this subsection prove that the use of total power instead of active power causes visible errors in the calculation values of the junction temperature of a semiconductor switch operating in the boost converter. In such a case the obtained values of the junction temperature can be overestimated significantly.

7. Conclusions

This paper presents the results of investigations into the influence of selected parameters on the waveforms of the total and active power dissipated in selected electronic switches. Two kinds of such switches were considered: a linear switch and the IGBT. These switches operate in two networks: the switch with a resistive load and a boost converter.

The influence of selected parameters of the linear switch and parameters of the signal controlling both the switches on the waveforms of the total and active power were analyzed. It was shown that such parameters as the switch parasitic capacitance, the rise time and frequency of the control signal significantly influence the waveforms and the average values of the power dissipate during the switching process. At a resistive load the values of the total power are higher than the values of the active power while switching off, whereas the opposite relation is observed when switching on. In the considered operating conditions, the average values of both these powers are practically the same. This means that the values of the junction temperature at the steady state obtained using the total and active power in the thermal model are the same.

In turn, when the switches under consideration operate with an inductive load, e.g., in a boost converter, the values of the total power are higher than the values of the active power when switching off, whereas the opposite relation is observed when switching on. The differences between the maximum values when switching off and switching on are visible when this converter operates in the DCM mode. The average values of the total power and the active power can differ visibly, even by over 30% when operating in the DCM mode. In this mode such a difference increases with an increase in the load resistance. These differences cause the same differences in the calculated values of the junction temperature. In the operating conditions under consideration, the value of this temperature should be calculated using the active power in the thermal model. The use of the total power can cause visible overestimation of an excess of the junction temperature over the ambient one. The error in the calculations of such an excess can exceed even 30% for boost converters operating in the DCM mode.

The use of the total power in the thermal model is justifiable for analyses of switches operating with a resistive load only. For switches operating with an inductive load the use of the active power in the thermal model is indispensable to obtain accurate results for junction temperature computations.

The presented investigations can be used by designers of power electronics networks. The results obtained make it possible to properly select the thermal model of power switches being used, which guarantees the satisfied accuracy of computations.

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