



Article

A New Approach for Power Losses Evaluation of IGBT/Diode Module

Hossein Hafezi ^{1,*}  and Roberto Faranda ² 

¹ Faculty of Information Technology and Communication Sciences, Tampere University, 33100 Tampere, Finland

² Department of Energy, Politecnico di Milano, 20156 Milan, Italy; roberto.faranda@polimi.it

* Correspondence: hossein.hafezi@tuni.fi

Abstract: Electric power systems are facing tremendous changes and power electronic devices are playing an increasingly crucial role in this transformation. In this context, the study of power electronic devices behavior becomes of the utmost importance, and in particular, evaluation of their losses to understand their performance. Several methods can be found in literature to evaluate power or energy losses, but each of them is associated with shortcomings (such as missing an important factor or having narrow current or voltage range) that in practice become a strong limit to implement them or in a simulation process. To overcome this problem, this paper evaluates existing methods and proposes new loss calculation methods for power electronics losses that can be used within simulation tools at any converter configuration and application range, splitting power electronic losses into switching and conduction losses. The proposed new approach formulates each loss calculation procedure in a systematic way. The presented methods are implemented in Matlab Simulink and simulation results are compared with data obtained from the Semikron SemiSel v4 online tool, which is used as a benchmark. The outcomes reveal that, with this new approach, the proposed methods can cover wider working operation range compared to the existing methods having better accuracy.



Citation: Hafezi, H.; Faranda, R. A New Approach for Power Losses Evaluation of IGBT/Diode Module. *Electronics* **2021**, *10*, 280. <https://doi.org/10.3390/electronics10030280>

Academic Editor: Gabriele Grandi
Received: 28 December 2020
Accepted: 21 January 2021
Published: 25 January 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Keywords: power electronics; conduction losses; switching losses; IGBT module

1. Introduction

Electric power systems have seen tremendous changes during recent years. One of the main reasons behind these changes is the huge diffusion of power electronics technology in electric power and energy systems. For example, to manage energy storage systems [1], renewable energy sources [2], to increase the performance of electric motor drives, electric vehicles [3], in transportation systems [4] and to give services to the mains or final user such as power quality services, energy management and demand response [5–8].

Therefore, it is essential to study the power converters' behavior in detail aiming to design the best hardware and software solution able to improve their performance and efficiency. In this context, power electronics converter losses evaluation studies are becoming always more and more important.

For example, to reduce power electronics converters losses, zero voltage and zero current switching topologies have been developed and it is a topic of several research works e.g., in [9] and [10]. Some other studies proposed switching losses reduction and closed form solution to reduce conduction losses, in [11] and [12] respectively. Losses reduction in active power filters with a new pulse width modulation (PWM) strategy has been proposed in [13]. The authors in [14] and [15] also aimed to design different power electronics devices with reduced losses.

Therefore, it is becoming essential to design power converter, not only selecting proper switching and heatsink devices according to power rating [16], but also studying the behavior of each single component to evaluate its performance [17]. As described in the IEC

62751 2 standard, which presents general principles, practical steps and recommendations for calculating the power losses in the converters and their switches [18].

In this regard, it is fundamental to note that power electronics losses calculation is tied up with switches and components physical characteristics. Therefore, even if it is not possible to develop a generic model for losses calculation (because it is necessary to consider the selected components used in the power converter), it is possible to define a common approach which can be used for power electronics converters' behavior and losses evaluation at their components level.

Considering this inescapable implementation limit, all the developed/proposed methods in literature have additional constraints. Indeed, these methods need extra time-consuming procedure which should be carried out in addition to the hardware and software design and development. Moreover, in most cases, it is very difficult to implement these methods into simulation tools and when the method permits this implementation, it is not possible to obtain a good power losses evaluation in a wide voltage and current operation range.

Therefore, an agile and handy new approach, able to evaluate, in a preliminary design phase, the power electronic converter losses with good accuracy and in a wide working operation range (covering wide range of current and voltage variations), is mandatory for designing better hardware and software (controller) solutions that could improve the performance of the power electronic converter.

This paper aims to fill in these gaps and solve these strong constraints adopting a new approach. Following this new approach, it is possible to evaluate power electronic converter losses of any hardware configuration and operating working condition, by simulation software tools, so it can reduce the extra efforts, the time spent on further analysis and/or the need to develop separate simulation models for loss evaluation.

To achieve this result, starting from the power losses evaluation methods available in the literature, new methods, that can cover a wide range of current and voltage variations, have been proposed. Comparison has been made to illustrate the better overall accuracy of proposed new methods over a wider operating range.

This new approach, gives the possibility to evaluate, unlike some available approaches in literature, the switching and conduction losses separately for each component, so the contribution of each power losses component to the total power losses can be discovered in the simulation environment during a preliminary design process.

Moreover, all methods are presented in a systematic way, so it is quite straight forward and easy for researchers to build their own models following the steps provided in the paper.

The rest of the paper is organized as follows: Section 2 introduces the device losses. Section 3 describes several methods (available basic method and the new methods) for power electronics switching losses evaluation, and Section 4 does the same for conduction losses. Section 5 describes the new approach introducing all the implementation steps that permits us to evaluate the total power electronics losses in a simulation environment. Section 6 verifies the proposed methods adopted in this new approach and compares the results with Semikron SemiSel v4 online tool and Section 7 points out the conclusion of the work.

2. Device Power and Energy Losses

The efficiency evaluation of a power electronic converter, even if it is fundamental for designing better hardware and software (controller) solutions, is always a very expensive activity (both in terms of time and resources) to conduct. Losses evaluation of a power electronic device and, in particular, of a semiconductor switch, can be performed adopting one of the following approaches [19]:

- Experimental tests. Adopting this approach, it is not possible to perform a converter losses evaluation in the preliminary design phase and it is possible to obtain only the

total power electronic converter losses for a single (or limited number of) operation point with dedicated laboratory setup;

- Physics-based simulations. A detailed physics-based simulation is mostly undertaken by finite element analysis which models the semiconductor switches in detail. This simulation method gives very precise and accurate results and matches very well with experiments, even if the simulation of a single switching cycle with a typical workstation may take one or a couple of days. Moreover, the simulation is mostly performed in open loop, so it is nearly impossible to perform losses analysis within the simulation model adopted to study a system or controller;
- Behavior models. A behavior model is based on parameters and models provided by manufacturers, which also allows good losses analysis results (normally less accurate than physics-based simulations). These models can be used in simulation tools to simulate a power electronic converter (so, they can be a good trade-off between accuracy and simulation time), even if a complete losses analysis must be performed separately with respect to the design simulations;
- Analytical (or mathematical) models. These models are very fast and simple, so they allow wide use implementation into simulation tools. However, usually they do not possess good accuracy and they cannot cover a wide operation range (of current and voltage).

Hence, it should be clear that the development of an accurate, complete, fast and simple approach, as a definitive solution for power electronic devices losses calculation, is becoming increasingly important.

Based on the above discussions, an analytical or mathematical approach is well suited to this contest because it can be adopted into simulation tools.

To develop analytical or mathematical power electronics losses calculation methods, simulation model-based approaches can be classified in two different categories:

- The first one is to build a 3D look-up table from datasheet info and use it for dynamic losses calculation [20–22];
- The second is to approximate the losses with analytical formula and matching the formula with datasheet information by adjusting some coefficients [16,23–28].

The first approach is very complicated to use and generally does not have good accuracy (unless a look up table is provided by manufacturer), because it is necessary to evaluate the losses directly by datasheet and in a small working operation range. The second one is preferable because it offers a systematic approach to study power converter losses and it is easy to implement even if it needs extra time to obtain good accuracy and adequate working operation range.

In the following, power electronics module losses are split up into three components namely:

- switching losses;
- conduction losses;
- blocking (leakage) losses.

The last component normally is negligible (comparing to switching and conduction losses) and its evaluation is also very difficult [24]. Therefore, as normally happens in this kind of analysis, only switching and conduction losses are explained and modelled in the following Sections 3 and 4.

It is important to note that in a real prototype, parasitic inductors and capacitances affect the voltage/current turn-on/off curves and consequently they can have effects on switching losses calculation [19,29]. Those parasitic effects are not considered in this study, because the focus of the paper is to propose an agile and simple new approach compromising the accuracy and computation burden (simulation speed and time). Therefore, the results are compared with similar studies. More accurate results are possible with more detailed modelling which needs more complex modelling and time-consuming simulations. Parasitic components' effects can be considered as future studies.

Therefore, in the next sections switching losses and conduction losses methods are evaluated considering the datasheet info for the SEMIKRON “SKM400GB12T4” module (SEMIKRON, Nuremberg, Germany) with the nominal current of 400 A, the maximum collector-to-emitter voltage (V_{CES}) of 1200 V (at $T_j = 25\text{ }^\circ\text{C}$), and the switch operation temperature range between $-40\text{ }^\circ\text{C}$ to $175\text{ }^\circ\text{C}$.

3. Switching Losses Calculation and Modeling

Switching losses are present in a real switch during turning on and off intervals, because voltage and current waveforms do not perform a stepwise change, but have rising and falling shapes and slopes.

Considering the insulated-gate bipolar transistor (IGBT) with a freewheeling diode (FWD) module reported in Figure 1a, it is possible to identify the following losses:

1. IGBT turn on energy losses (E_{on});
2. IGBT turn off energy losses (E_{off});
3. FWD reverse recovery energy losses (E_{rr}).

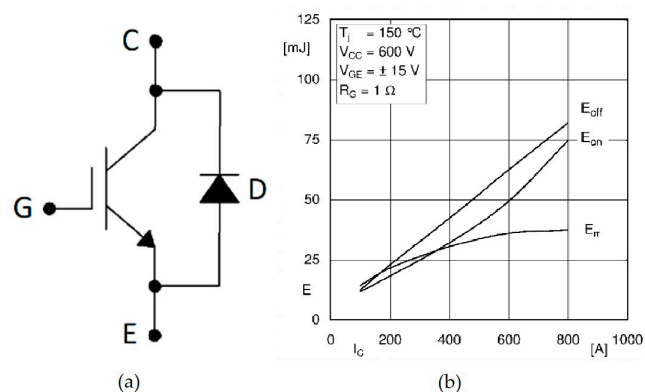


Figure 1. (a) Insulated-gate bipolar transistor (IGBT) and anti-parallel freewheeling diode (FWD) module; (b) a datasheet graphs example of switching energy losses.

Each power electronic module has its own manufacturing characteristics which defines its losses specifications. Therefore, for any power electronic device, extracting info from the manufacturer and the device datasheet is an unavoidable part in power electronics losses calculation.

Usually, the datasheet reflects information about average energy losses of the module versus the operating collector current [26] in three different graphs, E_{on} for IGBT turn-on energy losses, E_{off} for IGBT turn-off energy losses and E_{rr} for anti-parallel FWD reverse recovery energy losses, as in the example reported in Figure 1b.

These graphs are realized by the manufacturer with experimental tests. They are obtained by measuring the instantaneous values of: collector current i , the supply (direct current (DC) bus) voltage v_{DC} and junction temperature T_j (normally the last two parameters are constant in the experimental test so $v_{DC} = V_{DC,ref}$ and $T_j = T_{j,ref}$) for a whole switching cycle. Then, the average of all the measures is reported in the graph to represent the switching energy losses of the device.

3.1. Method SW1

A typical analytical formula, described by Equation (1), allows a rough calculation of any energy losses effect [27].

$$E_{sw1_T}(i, v_{DC}, T_j) = E_{sw,ref} \cdot \left(\frac{i}{I_{ref}}\right)^{K_i} \cdot \left(\frac{v_{DC}}{V_{DC,ref}}\right)^{K_v} \cdot \left[1 + TC_{sw} \cdot (T_j - T_{j,ref})\right] \quad (1)$$

in particular, in Equation (1), the term E_{sw1_T} represents the IGBT turn-on (E_{on}), or the IGBT turn-off (E_{off}) and the FWD reverse recovery (E_{rr}) energy losses respectively.

In this way it is possible to represent the IGBT energy losses ($E_{sw,IGBT} = E_{on} + E_{off}$) and the FWD energy losses ($E_{sw,FWD} = E_{rr}$) in function of the instantaneous values of: collector current i , supply (DC bus) voltage v_{DC} and junction temperatures T_j .

Therefore, to use Equation (1) for IGBT and FWD energy losses, it is mandatory to identify:

- all the parameters $E_{sw,ref}$, I_{ref} , $V_{DC,ref}$ and $T_{j,ref}$, that are the reference test condition values [27];
- two exponents K_i and K_v , and one coefficient TC_{sw} .

Unfortunately, it is impossible to find the losses representation by Equation (1) in a wide range of working conditions. Indeed, Equation (1) gives a good losses approximation only when the real working condition of the power electronics is very close to the reference one, because the single exponents and coefficient values are evaluated close to the reference test condition only. Therefore, when the reference condition is close to the nominal one, it is possible to consider the exponents and coefficient suggested by manufacturers in their application note, as reported in the following [27]:

- K_i : exponent of current dependency (IGBT~1; FWD~0.5–0.6);
- K_v : exponent of supply voltage (DC bus voltage) dependency (IGBT~1.2–1.4; FWD~0.6);
- TC_{sw} : temperature coefficient of switching losses (IGBT~0.003; FWD ~0.005–0.006).

Information in the device datasheet about energy losses of the module are mostly in function of the instantaneous or average current i or I value; instead, in some cases, it can be also observed that only two or three values for different voltage and for different temperature (always very close to their respective reference) are available. This is due because normally the DC bus voltage cannot change too much to avoid damaging the DC bus capacitors, and the junction temperature is controlled by means of heatsink and cooling systems (air or liquid cooling).

Therefore, considering $v_{DC} = V_{DC,ref}$ and $T_j = T_{j,ref}$, it can be seen that the value of the exponent K_v and coefficient TC_{sw} , do not have any effect on Equation (1). It can be simplified into the following:

$$E_{sw1_T}(i) = E_{sw,ref} \cdot \left(\frac{i}{I_{ref}} \right)^{K_i} \tag{2}$$

To understand the accuracy of this method, energy losses values are evaluated considering the datasheet info for the SEMIKRON “SKM400GB12T4” module. Using this device into the following working condition, $I_{rms} = 400$ A, $v_{DC} = 600$ V and nominal test temperature of $T_j = 150$ °C, the reference $E_{sw,ref}$ and exponents K_i values, suggested by manufacturer in the application note, that can be used in Equation (2), are reported in Table 1.

Table 1. Energy losses reference values and exponents used in Equation (2).

E_{sw}	$E_{sw,ref}$ [mJ]	K_i
E_{on}	33.0	1.00
E_{off}	42.0	1.00
E_{rr}	30.5	0.55

Using values reported in Table 1, Figure 2 compares the datasheet graphs of E_{on} , E_{off} and E_{rr} in solid black lines and their representation by Equation (2) in dashed colour lines.

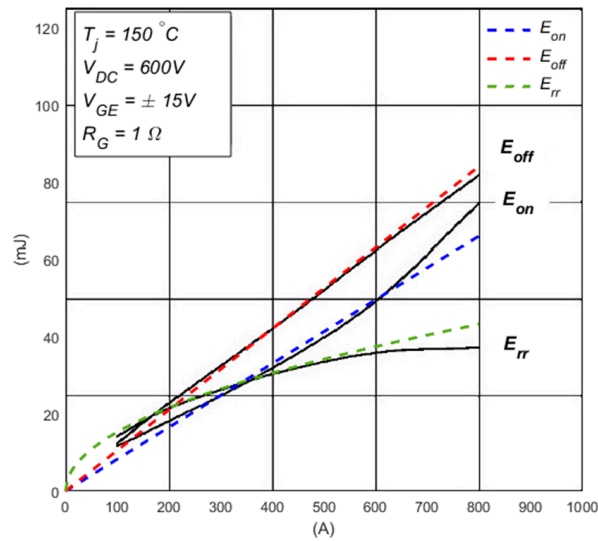


Figure 2. Switching energy losses graphs, comparison between the method SW1 and datasheet.

From Figure 2, it can be seen that Equation (2) can estimate the switching energy losses with quite good accuracy from about 200 A (50% of module nominal current) to about 600 A (150% of module nominal current) only. Therefore, in this simplified case, it can be observed that it is impossible to cover a wide range of current accuracy with a single exponent, so when this method is used in simulation tools using the instantaneous value of the current i , it could give less accurate results. Moreover, when the working condition is far from the nominal one (e.g., $v_{DC} \neq V_{DC,ref}$ and/or $T_j \neq T_{j,ref}$) method SW1 cannot have a good accuracy.

3.2. Method SW2

When the real working condition of the power electronics is not close to the reference one, the losses representation by Equation (1) can still be used, even if the suggested value by the manufacturer in the application note for exponents K_i and K_v , and the coefficient TC_{sw} cannot cover whole application range.

The new proposed method, for accurate losses modelling, divides the switching losses of the power electronic device in several small ranges.

As before, it is necessary to determine, the energy losses reference values $E_{sw,ref}$, collector current reference value I_{ref} , supply (DC bus) voltage reference value $V_{DC,ref}$ and junction temperatures reference value $T_{j,ref}$, that will be used for any range k .

After that to evaluate the correct parameters (for current, voltage and temperature), it is possible to use the following procedure for each range k .

By setting v_{DC_k} and T_{j_k} to their reference values in Equation (1), it is possible to evaluate the current exponent K_{i_k} , so Equation (1) can be rewritten as:

$$E_{sw2_k} = E_{sw,ref} \cdot \left(\frac{i_k}{I_{ref}} \right)^{K_{i_k}} \cdot 1 \cdot 1 \tag{3}$$

Using log function, Equation (3) can be linearized to find K_{i_k} values for both IGBT and FWD.

By setting i_k and T_{j_k} to their reference values in Equation (1), it is possible to evaluate the voltage exponent K_{v_k} , so Equation (1) can be rewritten as:

$$E_{sw2_k} = E_{sw,ref} \cdot 1 \cdot \left(\frac{v_{DC_k}}{V_{DC,ref}} \right)^{K_{v_k}} \cdot 1 \tag{4}$$

Once again, using log function, Equation (4) can be linearized to find $K_{v,k}$ values for both IGBT and FWD.

In similar manner, by setting i_k and $v_{DC,k}$ to their reference values in Equation (1), it is possible to evaluate the temperature coefficient $TC_{SW,k}$, so Equation (1) can be rewritten as:

$$E_{sw2,k} = E_{sw,ref} \cdot 1 \cdot \left[1 + TC_{sw,k} \cdot (T_{j,k} - T_{j,ref}) \right] \quad (5)$$

Temperature coefficients can be found following similar procedure unless in this case, there is no need for linearization and the solution is straightforward.

As previously reported, it is not common to have wide variation of DC bus voltage (usually it is kept quite constant) and junction temperature (because it is controlled below a certain value by means of heatsink or cooling systems). Moreover, investigation reveals that switching losses have minor variation with respect to supply voltage (DC bus) change. Therefore, the suggested value in the application guide for voltage exponent K_v and temperature coefficient TC_{SW} , can be used in all the defined intervals k . It is necessary to evaluate the correct exponent $K_{i,k}$ for each selected range k , only.

Taking into consideration that to get a better accuracy it is better to consider the supply voltage and temperature variations, Equation (1) changes into the following:

$$E_{sw2,T}(i, v_{DC}, \theta_j) = E_{sw,ref} \cdot \left(\frac{i}{I_{ref}} \right)^{K_{i,k}} \cdot \left(\frac{v_{DC}}{V_{DC,ref}} \right)^{K_v} \cdot \left[1 + TC_{sw} \cdot (T_j - T_{j,ref}) \right] \quad (6)$$

In Equation (6) only $K_{i,k}$ is function of the reference current i_k used to represent the IGBT module, while the parameters $E_{sw,ref}$, I_{ref} , $V_{DC,ref}$, K_v , TC_{sw} , and $T_{j,ref}$ are constant and equal to the reported values in the application note.

To understand the accuracy of this new method, the same IGBT module, "SKM400GB12T4", is used. To represent the switching energy losses in any different range k , the reference current i_k (extracted from the datasheet) and the best operating current exponents $K_{i,k}$ obtained by Equation (3) are reported in Table 2.

Table 2. Current exponents in different ranges used in Equation (6).

	Range k	i_k (A)	$E_{on,k}$ (mJ)	$K_{i,k}$	$E_{off,k}$ (mJ)	$K_{i,k}$	$E_{rr,k}$ (mJ)	$K_{i,k}$
1	$i < 150$ A	100	11.9	0.729	12.5	0.904	14.3	0.562
2	$150 \text{ A} \leq i < 250$ A	200	18.5	0.835	22.5	0.900	22.0	0.471
3	$250 \text{ A} \leq i < 450$ A	300	25.0	0.965	34.0	0.735	26.5	0.488
4	$450 \text{ A} \leq i < 550$ A	500	40.0	0.862	53.0	1.042	33.0	0.487
5	$550 \text{ A} \leq i < 650$ A	600	50.0	1.025	64.0	1.039	35.0	0.339
6	$650 \text{ A} \leq i < 750$ A	700	61.9	1.155	72.0	0.963	36.9	0.296
7	$750 \text{ A} \leq i$	800	75.0	1.184	82.0	0.965	37.0	0.278

It can be noticed that most of $K_{i,k}$ exponents do not match the suggested values by the manufacturer unless close to the nominal current.

The other parameters adopted in this test are $v_{DC} = V_{DC,ref} = 600$ V and $T_j = T_{j,ref} = 150$ °C, and so the value of K_v and TC_{SW} cannot affect the energy losses evaluation.

To verify the accuracy of the proposed method and considering these parameters, Figure 3 reports the datasheet graphs of E_{on} , E_{off} and E_{rr} in solid black lines and their representation by Equation (6) in dashed colour lines.

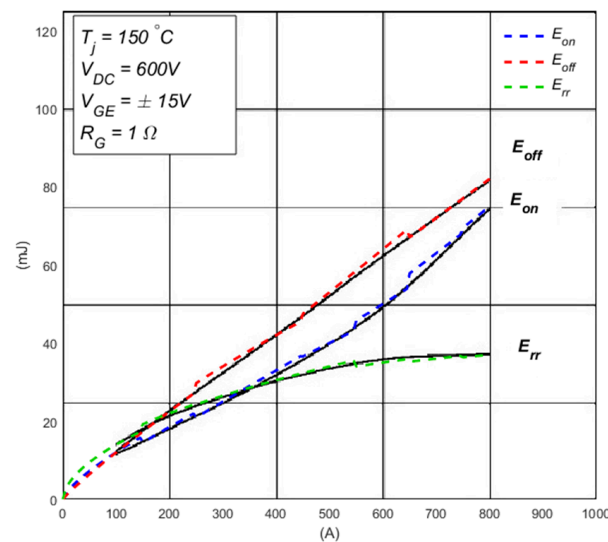


Figure 3. Switching energy losses graphs, comparison between the method SW2 and datasheet.

It can be seen that with this new method Equation (6) can estimate the switching energy losses with good accuracy in a range wider than the method SW1, covering from about almost zero current up to about 800 A (200% module nominal current), so it can be used in simulation tools using the instantaneous value of the current i .

Obviously when the working condition is quite far from the nominal one ($v_{DC} \neq V_{DC,ref}$ and/or $T_j \neq T_{j,ref}$), it is possible to evaluate the right exponent K_v and coefficient TC_{SW} by using Equations (4) and (5) or using the average values suggested in the application guide of the exponent K_v and coefficient TC_{SW} .

3.3. Method SW3

An interesting method, suggested by literature in [16], is to use analytical second order polynomial formulas to represent the switching losses. Authors in [16] illustrated that second order approximation is a good compromise between computation burden and accuracy, even if it is possible to match the switching losses curves more accurately by choosing high order approximation.

It is important to underline that in the switching losses evaluation in [16], the supply voltage (DC bus) variation is considered linear (the voltage exponent is equal to one) and the temperature variation is ignored (junction temperature coefficient equal to zero). As reported in the datasheet supply voltage (v_{DC}) and temperature variations have a significant impact on losses evaluations when the device works far from its reference value. Therefore, to deal with these shortcomings, authors suggest using the following new method which is a combination of second order polynomial approximation and suggested formula by manufacturer.

The new completed method, which is a combination of second order polynomial approximation of [16] and suggested formula by manufacturer, can be written as reported in Equation (7).

$$E_{sw3_T}(i, v_{DC}, T_j) = E_{sw3}(i) \cdot \left(\frac{V_{DC}}{V_{DC,ref}} \right)^{K_v} \cdot \left[1 + TC_{sw} \cdot (T_j - T_{j,ref}) \right] \quad (7)$$

where $E_{sw3}(i)$ represents each switching energy losses $E_{on}(i)$, $E_{off}(i)$ or $E_{rr}(i)$, obtained by the generic analytical second order polynomial formula reported in Equation (8).

$$E_{sw_3}(i) = A_{sw} + B_{sw} \cdot i + C_{sw} \cdot i^2 \quad (8)$$

Second-order polynomial approximation can be done with Matlab curve fitting toolbox, MS Excel Trendline option or by measuring three different points from the losses datasheet curve around 25%, 100% and 175% of the nominal operating collector current value.

As for previous cases, the proposed model has a good accuracy using the exponent K_v and coefficient TC_{SW} suggested in the application guide.

To understand the accuracy of this method, the switching losses are evaluated for the same IGBT module "SKM400GB12T4". Here the Matlab curve fitting toolbox is used with the four points reported in Table 3.

Table 3. Measurement points to characterize the switching losses.

Point	i (A)	E_{on} (mJ)	E_{off} (mJ)	E_{rr} (mJ)
0	0.00	0.00	0.00	0.00
1	100	11.9	12.5	14.3
2	400	33.0	42.0	30.5
3	700	61.9	72.0	36.9

The starting point (0,0,0,0) is very important otherwise the losses could have high error when the collector instantaneous current i is close to zero.

Using the data reported in Table 3 and Matlab curve fitting toolbox, it is possible to obtain the result reported in system (9).

$$\begin{aligned} E_{on}(i) &= 0.00171 + 7.42 \times 10^{-5} \cdot i + 1.81 \times 10^{-8} \cdot i^2 \\ E_{off}(i) &= 0.00049 + 1.08 \times 10^{-4} \cdot i - 9.09 \times 10^{-9} \cdot i^2 \\ E_{rr}(i) &= 0.00148 + 1.11 \times 10^{-4} \cdot i - 8.86 \times 10^{-8} \cdot i^2 \end{aligned} \quad (9)$$

As it is possible to observe in Figure 4, system (9) fits quite well the datasheet info of the component, therefore, it can accurately represent the $E_{on}(i)$, $E_{off}(i)$ and $E_{rr}(i)$ at constant supply voltage and temperature in wide current application range so it can be used in simulation tools using the instantaneous value of the current i .

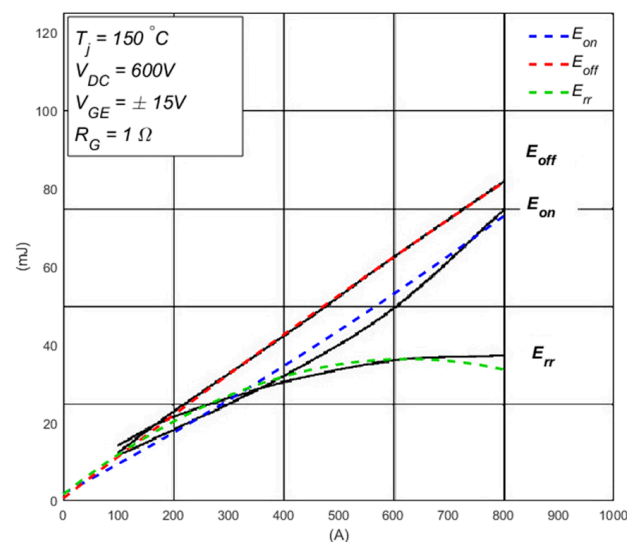


Figure 4. Switching energy losses graphs, comparison between the method SW3 and datasheet.

It is important to underline that this new method can be used also when DC bus voltage and temperature are different to their reference value, indeed Equation (7) follows manufacturer's suggestions updating the method [16] representing the correlation between power losses and supply voltage (DC bus) and temperature variation.

3.4. Final Consideration

The use of the instantaneous current i to calculate switching losses allows a great flexibility in a simulation process. This permits to evaluate different control methods in transitory conditions, to evaluate the losses of each element during the design process, and so on. Using the instantaneous value of the current i , it is possible to evaluate the total power switching losses following each one of the described methods. Therefore, following the discussions in this section, method SW1 has limited current application range and owns lower accuracy, while both new methods, method SW2 and method SW3, have better accuracy for similar current range. Method SW2 is quite complicated to use in simulation software tools with respect to method SW3 because it is necessary to define several parameters with good accuracy (at least two values for each range).

In all the described methods, the parameters $V_{DC,ref}$, K_v , TC_{sw} and $T_{j,ref}$, which are necessary to describe each model, can be evaluated from the datasheet using the manufacturer's suggested values.

Overall, it is possible to write that for switching losses evaluation, that needs instantaneous current values, it is very important to cover a wide current range, and in particular, it is very important to represent correctly the losses equation when the instantaneous current i is close to zero.

To evaluate the total power switching losses, it should be noted that the described methods calculate E_{on} , E_{off} and E_{rr} every switching cycle, but Equations (1), (6) or (7) are meant to estimate E_{on} , E_{off} and E_{rr} graphs reported by manufacturer and those are averaged values. Therefore, to evaluate the total power switching losses, it is necessary to make an average of evaluated E_{SW} over one switching cycle.

$$\bar{E}_{SW} = \frac{1}{\Delta t} \cdot \int_{t_0}^{t_0+\Delta t} E_{sw} dt = f_{sw} \cdot \int_{t_0}^{t_0+\frac{1}{f_{sw}}} E_{sw} dt \quad (10)$$

where Δt is the switching period and f_{sw} stands for switching frequency in hertz (Hz).

The total energy losses in one period is the sum of E_{on} , E_{off} and E_{rr} energy losses. Moreover, the switching frequency must be considered to evaluate the total power switching losses.

Equation (11) represents the total power switching losses (P_{sw}) as the sum of IGBT power switching losses ($P_{sw,IGBT}$) and FWD switching losses ($P_{sw,FWD}$).

$$P_{sw} = P_{sw,IGBT} + P_{sw,FWD} = (\bar{E}_{on} + \bar{E}_{off}) \cdot f_{sw} + \bar{E}_{rr} \cdot f_{sw} = (\bar{E}_{on} + \bar{E}_{off} + \bar{E}_{rr}) \cdot f_{sw} = \bar{E}_{sw} \cdot f_{sw} \quad (11)$$

where \bar{E}_{on} , \bar{E}_{off} , \bar{E}_{rr} and \bar{E}_{sw} are described before and evaluated in Joule.

4. Conduction Losses Calculation and Modeling

Conduction losses on power electronics switching devices happens because during conduction period, switching devices do not behave as an ideal switch (zero on-state resistance and zero voltage drop). Indeed, they have on-state resistance and an amount of forward voltage drop on the device.

Usually the datasheet reflects information about conduction v - i characteristics of the module for IGBT and for anti-parallel FWD. These data are realized by the manufacturer running experimental tests at some temperatures T_j only (usually at max and min temperatures). Therefore, to evaluate the operational conduction power losses of the module, it is necessary to evaluate v - i characteristics and its dependency on the temperature. Therefore, also in this case a generic losses calculation model is not achievable, because each study must build its model considering the component in the power electronic converter.

Considering the same IGBT with the anti-parallel FWD module reported in Figure 1a, it is possible to identify the following losses:

- IGBT conduction power losses ($P_{con,IGBT}$);
- FWD conduction power losses ($P_{con,FWD}$).

A typical curve of the v - i characteristic of a semiconductor switch at a fixed junction temperature T_j , is shown in Figure 5 (extracted from datasheet).

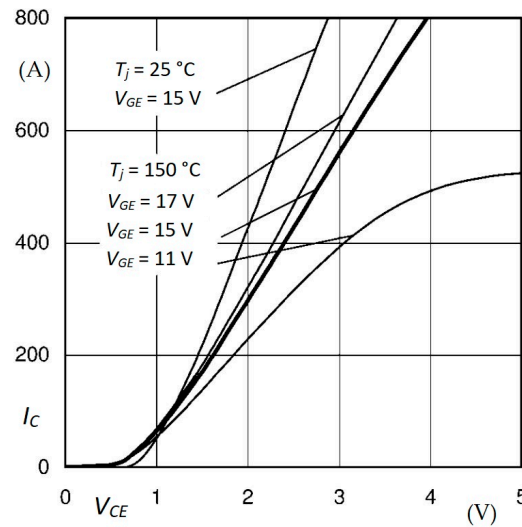


Figure 5. Typical switch forward characteristics representation.

Therefore, by extracting the switching characteristics (of IGBT and FWD) the conduction losses can be calculated using Equation (12), where the subscript X has been used to represent IGBT and FWD because the formula is identical for both.

$$p_{con, X}(t, T_j) = v_X(t, i_X, T_j) \cdot i_X(t) \tag{12}$$

Normally, the datasheet provides v - i characteristic of the switch (IGBT or FWD) in a few points (two different temperatures T_{min} and T_{max}) and not in the whole working temperature range. Therefore, it is quite impossible to get accurate conduction losses evaluation in a function of time t , current i and junction temperature T_j , so Equation (12) cannot be used directly.

4.1. Method Con1

In Figure 5, it is possible to see that the v - i characteristic of the switch can be linearized with very good accuracy (when the gate-emitter voltage is high enough, $V_{GE} \geq 15$ V, because as shown in Figure 5, with low V_{GE} (=11 V) the v - i characteristic misbehave), except the starting points where the level of current usually stays around few mA. Therefore, linear approximation for switch forward characteristics is considered and the v - i curve can be linearized as:

$$v_X(t, i_X, T_j) = R_X(T_j) \cdot i_X(t) + V_X(T_j) \tag{13}$$

where, the $R_X(T_j)$ is the on-state resistances (proportional to the gradient value) and the $V_X(T_j)$ is the voltage drops (proportional to the intercept value). Replacing Equation (13) into Equation (12) the instantaneous losses expression can be achieved.

$$p_{con, X}(t, i_X, T_j) = R_X(T_j) \cdot i_X(t)^2 + V_X(T_j) \cdot i_X(t) \tag{14}$$

The average conduction losses value in a period (2π) can be calculated by:

$$P_{con, X}(i_X, T_j) = \frac{1}{2 \cdot \pi} \cdot \int_0^{2 \cdot \pi} p_{con, X}(t, T_j) dt \tag{15}$$

With simplification, the equation becomes:

$$P_{con, X}(i_X, T_j) = R_X(T_j) \cdot I_X^2 + V_X(T_j) \cdot i_{X, ave} \tag{16}$$

where I_X and $i_{X,ave}$ are the rms and average forward currents i_X through the switch.

Equation (16) reports the conduction losses at T_j junction temperature. It is imperative to consider the junction temperature variations but, usually datasheet provides v - i characteristics of the switch (IGBT or FWD) in only two different temperatures T_{min} and T_{max} as it is shown in Figure 6 where, as example, a typical forward characteristic of a diode and its linear approximation are shown.

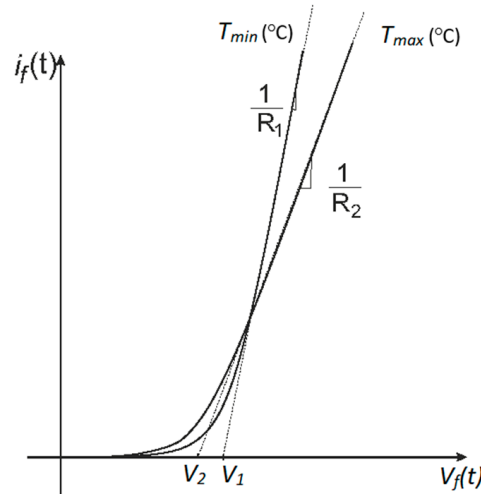


Figure 6. Typical diode forward characteristics and first order (linear) approximation.

Therefore, it can be quite easy to follow this procedure to evaluate conduction losses at these two temperatures but conduction losses value, at different junction temperature, is not achievable yet.

To solve this problem, the linear representation of the variation of resistances R_X and voltage drops V_X in function of junction temperature T_j , can be represented by the first order (linear) functions that have a good accuracy and are widely used in literature as reported in [16] and [28]. These approximated correlations are reported in Equations (17) and (18).

$$R_X(T_j) = \frac{R_2 \cdot T_{min} - R_1 \cdot T_{max}}{T_{min} - T_{max}} + \frac{R_1 - R_2}{T_{min} - T_{max}} \cdot T_j \tag{17}$$

$$V_X(T_j) = \frac{V_2 \cdot T_{min} - V_1 \cdot T_{max}}{T_{min} - T_{max}} + \frac{V_1 - V_2}{T_{min} - T_{max}} \cdot T_j \tag{18}$$

In particular, Equation (17) represents the dynamic resistances of the switch and is the inverse slope of the v - i characteristic of the switch, while Equation (18) represents the voltage threshold which is where the switch starts conducting. These parameters depend on the junction temperature T_j , which means by increasing the junction temperature, the dynamic resistance increases while the threshold voltage decreases.

Extracting T_{min} , T_{max} , $R_1(T_{min})$, $R_2(T_{max})$, $V_1(T_{min})$ and $V_2(T_{max})$ from datasheet graph, the dynamic resistance and the voltage threshold relationships can be expressed by Equations (17) and (18) both for IGBT and FWD. Then the obtained results can be replaced in power conduction losses calculation Formula (16). Equation (19) reports the result.

$$P_{con, X}(i_X, T_j) = \left(\frac{R_2 \cdot T_{min} - R_1 \cdot T_{max}}{T_{min} - T_{max}} + \frac{R_1 - R_2}{T_{min} - T_{max}} \cdot T_j \right) \cdot I_X^2 + \left(\frac{V_2 \cdot T_{min} - V_1 \cdot T_{max}}{T_{min} - T_{max}} + \frac{V_1 - V_2}{T_{min} - T_{max}} \cdot T_j \right) \cdot i_{X,ave} \tag{19}$$

To understand the simplicity and applicability of this method, in the following the conduction losses for the same IGBT module “SKM400GB12T4” have been evaluated. Therefore, its datasheet info has been used to find nominal (reference) values as reported in Table 4.

Table 4. Nominal values used in Equation (19).

Device	T_{min} (K)	T_{max} (K)	R_1 (m Ω)	R_2 (m Ω)	V_1 (V)	V_2 (V)
IGBT	298.15	423.15	2.34	3.90	1.00	0.85
FWD	298.15	423.15	2.40	3.34	1.45	1.05

These parameters can be used in the Equation (19) to evaluate the IGBT power conduction losses ($P_{con,IGBT}$) and the FWD conduction losses ($P_{con,FWD}$) respectively. Equation (20) represents the total power conduction losses (P_{con}) at any junction temperature T_j and current i_X as the sum of these conduction losses.

$$P_{con}(i_X, T_j) = P_{con,IGBT}(i_X, T_j) + P_{con,FWD}(i_X, T_j) \quad (20)$$

This linearization method permits to evaluate power conduction losses in real working conditions in a very simple way because all the parameters can be simply determined. Normally it can be considered very accurate with a very good application range; however, linearization might not fit well to all applications especially where the v - i characteristic of the switch shows high non-linearity.

4.2. Method Con2

When the v - i characteristic of the switch in real working condition shows high nonlinearity, as new proposal, the v - i characteristic in Figure 5, can be approximated by second order polynomial equation.

$$v_X(t, i_X, T_j) = A_X(T_j) + B_X(T_j) \cdot i_X(t) + C_X(T_j) \cdot i_X^2(t) \quad (21)$$

where the representation of $A_X(T_j)$, $B_X(T_j)$ and $C_X(T_j)$ need to be found. Here T_j can be either T_{min} and T_{max} . This can be done, considering the two curves, of Figure 6, reported in the datasheet at T_{min} and T_{max} , with Matlab curve fitting toolbox, MS Excel Trendline option or by measuring three different points for each v - i characteristic curve of the datasheet.

In this work, the last approach is followed by obtaining the value of the v - i curve in the three points around 25%, 100% and 175% of the nominal current value from the datasheet.

Solving the linear system of three equations for the three unknown variables, it is possible to find the coefficients A_1 , A_2 , B_1 , B_2 , C_1 and C_2 , where the subscripts 1 and 2 have been used, as in the example of the previous paragraph, for minimum and maximum junction temperatures respectively (T_{min} and T_{max}) that are not normal working conditions. Therefore, it is fundamentally important to find a strategy to obtain the right coefficient at the working junction temperature T_j .

As previously described, the same linear interpolation for resistant and voltage drop can be used to consider the temperature dynamics variation for the coefficients $A_X(T_j)$, $B_X(T_j)$ and $C_X(T_j)$.

$$\begin{aligned} A_X(T_j) &= \frac{A_2 \cdot T_{min} - A_1 \cdot T_{max}}{T_{min} - T_{max}} + \frac{A_1 - A_2}{T_{min} - T_{max}} \cdot T_j \\ B_X(T_j) &= \frac{B_2 \cdot T_{min} - B_1 \cdot T_{max}}{T_{min} - T_{max}} + \frac{B_1 - B_2}{T_{min} - T_{max}} \cdot T_j \\ C_X(T_j) &= \frac{C_2 \cdot T_{min} - C_1 \cdot T_{max}}{T_{min} - T_{max}} + \frac{C_1 - C_2}{T_{min} - T_{max}} \cdot T_j \end{aligned} \quad (22)$$

Thanks to this new approximation, replacing Equation (21) into Equation (13), the instantaneous losses expression with second order approximation can be achieved.

$$p_{con,X}(t, i_X, T_j) = C_X(T_j) \cdot i_X(t)^3 + B_{ce}(T_j) \cdot i_X(t)^2 + A_{ce}(T_j) \cdot i_X(t) \quad (23)$$

The average conduction losses can be calculated by the following simplified expression.

$$P_{con,X}(i_X, T_j) = \left(\frac{C_2 \cdot T_{min} - C_1 \cdot T_{max}}{T_{min} - T_{max}} + \frac{C_1 - C_2}{T_{min} - T_{max}} \cdot T_j \right) \cdot i_{X,ave}^3 + \left(\frac{B_2 \cdot T_{min} - B_1 \cdot T_{max}}{T_{min} - T_{max}} + \frac{B_1 - B_2}{T_{min} - T_{max}} \cdot T_j \right) \cdot i_X^2 + \left(\frac{A_2 \cdot T_{min} - A_1 \cdot T_{max}}{T_{min} - T_{max}} + \frac{A_1 - A_2}{T_{min} - T_{max}} \cdot T_j \right) \cdot i_{X,ave} \tag{24}$$

where $i_{X,ave}^3$ is the average of cubed switch current.

To understand the method, the conduction losses of the same IGBT module “SKM400GB 12T4”, has been considered. Starting from datasheet info of this device, the three points reported in Table 5 for each curve has been used.

Table 5. Measurement points to characterize the conduction losses.

Point	i (A)	$v_{ce}(T_{min})$ (V)	$v_{ce}(T_{max})$ (V)	$v_f(T_{min})$ (V)	$v_f(T_{max})$ (V)
1	100	1.15	1.15	1.51	1.23
2	400	1.90	2.35	2.35	2.29
3	700	2.60	3.55	2.86	3.14

The obtained coefficients values are reported in Table 6.

Table 6. Nominal values used in Equation (25).

Device	A_1	A_2	B_1	B_2	C_1	C_2
IGBT	0.89	0.75	$2.6 \cdot 10^{-3}$	$4.0 \cdot 10^{-3}$	$-2.77 \cdot 10^{-7}$	$-5.35 \cdot 10^{-21}$
FWD	1.15	0.83	$3.7 \cdot 10^{-3}$	$4.1 \cdot 10^{-3}$	$-1.85 \cdot 10^{-6}$	$-1.16 \cdot 10^{-6}$

In this way, the power conduction losses of IGBT ($P_{con,IGBT}$) and FWD ($P_{con,FWD}$) with second order approximation method can be evaluated by Equation (24). Equation (25) represents the total power conduction losses (P_{con}) at any junction temperature T_j and current i_X , as the sum of these two conduction losses for IGBT and FWD.

$$P_{con}(i_X, T_j) = P_{con,IGBT}(i_X, T_j) + P_{con,FWD}(i_X, T_j) \tag{25}$$

Second order approximation increases the complexity of the conduction losses calculation with respect to the previous method. Therefore, this new method is suggested when the $v-i$ characteristic of the switch owns high non-linearity and/or the current ratio is low.

4.3. Final Consideration

The main problem in conduction losses evaluation is to formulate the $v-i$ characteristic of the switch with an analytical equation. This can be done in several ways and it is the only difference between these two methods.

To evaluate the total power conduction losses, it should be noted that, normally the current that flow through the switching device, has high intermittency. Hence, the method Con1 seems to be a good compromise between simplicity and accuracy. Only when the device has a non-linear $v-i$ characteristic and/or it is in low current conditions, new method Con2 is preferable.

5. Total Losses Evaluation and Implementation Approach into Continuous Time-Domain

With equations described in Sections 3 and 4, it is possible to calculate an IGBT with the anti-parallel FWD module power losses with good accuracy using the instantaneous value of the current i or its derivatives. As reported in Figure 7, for rms load current equal to 400 A, the instantaneous current i in semiconductor switch is varying between zero to around 150% of the rms load current.

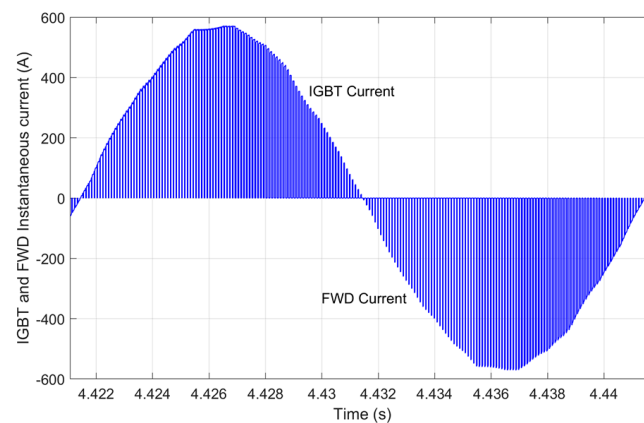


Figure 7. Instantaneous current of an IGBT module in a direct current/alternating current (DC/AC) application.

Equation (26) represents the total power losses (P_{loss}) as the sum of IGBT power losses ($P_{loss,IGBT}$) and FWD losses ($P_{loss,FWD}$) which consists of IGBT power switching losses ($P_{sw,IGBT}$), FWD switching losses ($P_{sw,FWD}$), IGBT power conduction losses ($P_{con,IGBT}$) and FWD conduction losses ($P_{con,FWD}$).

$$P_{loss} = P_{loss,IGBT} + P_{loss,FWD} = P_{sw,IGBT} + P_{sw,FWD} + P_{con,IGBT} + P_{con,FWD} \quad (26)$$

For switching losses evaluation, the required instantaneous measurements are: the collector-emitter current i , the module supply voltage (DC bus) v_{DC} and the junction temperature T_j .

For conduction losses evaluation, the required measurements are: the collector-emitter current I and i_{ave} (rms and average current) and the junction temperature T_j .

All the voltages and currents measurements can be available in any simulation tool such as Matlab Simulink, the only missing part is the correct value of the working junction temperature T_j of the device. It can be modelled inside the Matlab simulation with electro-thermal modelling [22] as well, but it needs detail info about the design and implementation of the power electronics converter.

To have a better accuracy in power losses estimation, the temperature behaviours of IGBT and FWD need to be considered. The working junction temperature T_j can be evaluated by the thermal junction to case ($j-c$) resistances, for IGBT $R_{th_IGBT(j-c)}$ and for FWD $R_{th_FWD(j-c)}$.

These values are reported in the datasheet. Then knowing the ambient temperature (T_a) it is possible to estimate IGBT and FWD working junction temperature by the following equation [30].

$$T_j = P_{loss} \cdot \left(R_{th_IGBT(j-c)} + R_{th_FWD(j-c)} \right) + T_a \quad (27)$$

This equation does not consider the heatsink or cooling system where power electronic switches are installed. The heatsink design and characteristics can be modelled and included in the temperature evaluation process. The cooling system, can be natural air cooling, forced air cooling (fans) or a liquid cooling system, also it can be modelled as a thermal resistance and included in Equation (27), depending on configuration in series or parallel to the junction to case resistances. The temperature estimation depends on several design factors and it is out of the focus of this paper. However, upon availability of all data, the implementation in this model, to include temperature variation, can be undertaken as depicted in Figure 8.

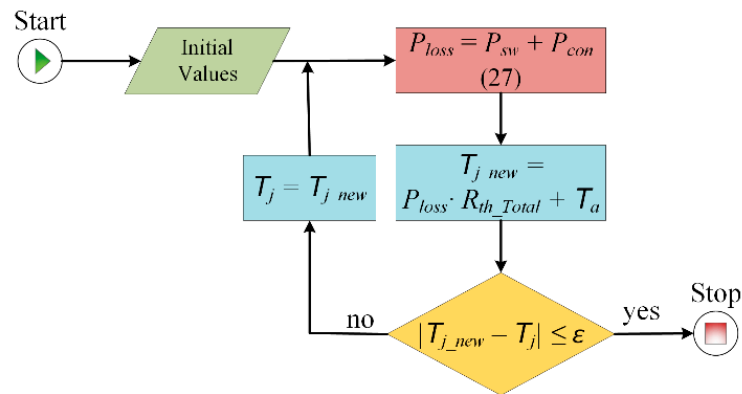


Figure 8. Junction temperature evaluation flowchart.

Initially T_j is considered equal to ambient temperature, T_a . P_{loss} is calculated and then based on the P_{loss} , the new junction temperature can be estimated. Then the absolute value of the temperature variation is checked, when it is within acceptable error (e.g., $\epsilon = 1\text{ }^\circ\text{C}$) the losses calculation can be terminated, otherwise the new junction temperature T_{j_new} is considered as T_j and a new P_{loss} is calculated again.

All presented loss calculation methods can be implemented in any simulation environment following the implementation approach explained here.

In a simulation environment, all the instantaneous current and voltage signals, of any power electronic module, can be measured. In particular, as it is depicted in Figure 9, it is possible to separate IGBT and FWD instantaneous currents in a simple manner, because the positive current flows through IGBT, while the negative current flows through FWD.

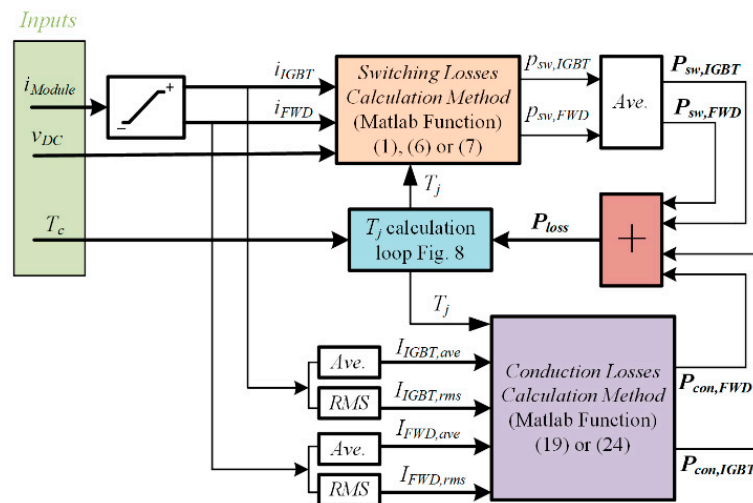


Figure 9. Implementation of losses calculation methods in Matlab Simulink.

Switching losses calculation methods, need instantaneous values, so current, voltage and temperature values are used to evaluate instantaneous switching losses ($p_{sw,IGBT}$ and $p_{sw,FWD}$) for IGBT and FWD. Considering that datasheet reports averaged values (energy losses curves), these values are averaged over one switching cycle to obtain the switching losses, $P_{sw,IGBT}$ and $P_{sw,FWD}$.

Indeed, conduction losses methods calculation need rms current, average current, and temperature values. Therefore, IGBT and FWD currents rms and average values and temperature are used to obtain $P_{con,IGBT}$ and $P_{con,FWD}$.

6. Results Comparison—Models Versus Semisel

To compare different losses evaluation methods, it is mandatory to define a reference point. Data coming from manufactures, such as datasheet information (utilized so far), is the most reliable one because manufacturers have done series of experimental tests on their products and collected all the required information.

Laboratory experimental test results are affected by additional parameters such as parasitic components. Moreover, it would be very difficult to separate switching and conduction losses for IGBT and FWD in a single module (usually only total losses can be evaluated). Therefore, instead of laboratory experimental test results, the Semikron SemiSel online tool has been used as benchmark in this study.

Semikron has the SemiSel v4 online simulation tool for different purposes [31]. After selecting one of the few predefined hardware configurations and inserting the device parameters, it is possible to select the semiconductor switching module (among available Semikron products). Then the tool gives operational information including the power losses. SemiSel v4 gives power losses in separated form, reporting for any single device switching and conduction losses ($P_{sw,IGBT}$ and $P_{con,IGBT}$ for IGBT and $P_{sw,FWD}$ and $P_{con,FWD}$ for FWD) and the total losses of the converter under analysis (P_{losses}).

To compare each losses calculation method of this study to the reference one, a single-phase DC to AC inverter model is used to evaluate and compare the results. The test circuit is shown in Figure 10. The inverter is controlled, at switching frequency of 5 kHz, as AC voltage generator (V_s) to supply at 230 V/50 Hz, four different loads, with a load power factor of 0.9.

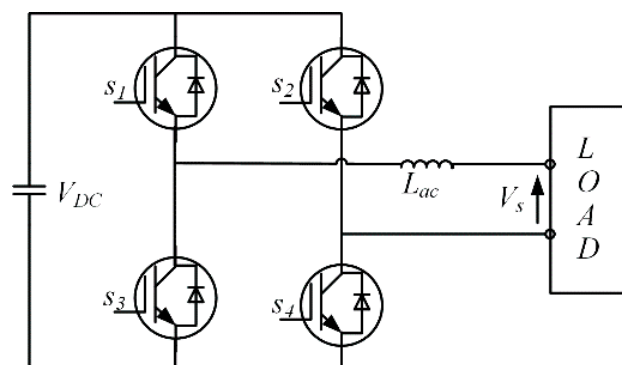


Figure 10. Single-phase H-bridge DC to AC inverter test circuit.

The losses are evaluated with three different DC bus voltages.

Following the implementation approach into the simulation tool described, it is possible to observe that in this test circuit, there is not a variation of the DC voltage ($v_{DC} = V_{DC}$), therefore, in the losses calculation it has been treated as constant value. Moreover, the junction temperature can be obtained depending on working condition following the new procedure described in Figure 8 or fixing it at the beginning of the simulation process to the estimated value given by the Semisel tool. To simplify the simulation process in this paper, the junction temperature was considered as a known parameter.

Table 7 reports the four test conditions (A–D) and the working junction temperature T_j used.

Table 7. Test conditions, $V_{DC} = 500\text{--}700$ V.

Test	A	B	C	D
I_L (Load rms current)	50 A	100 A	300 A	500 A
T_j	23 °C	27 °C	50 °C	87 °C

The same IGBT module “SKM400GB12T4” is always used as switching component to realize the single-phase DC to AC inverter. Then, it was used in a wide range (low current and over current) of working conditions.

6.1. Switching Losses

In this section IGBT switching losses ($P_{sw,IGBT}$) and the FWD switching losses ($P_{sw,FWD}$) have been reported and compared versus Semisel results.

Table 8 reports the results for the four different loading conditions described in Table 7 when the DC bus voltage fixed to 500 V. Tables 9 and 10 repeat the same loading steps with DC bus voltage fixed to 600 V and 700 V, respectively.

Table 8. Switching losses comparison, $V_{DC} = 500$ V.

	Semisel	IGBT— P_{sw} (W)			Semisel	FWD— P_{sw} (W)		
		SW1	SW2	SW3		SW1	SW2	SW3
A	9.60	7.50	13.55	11.9	3.30	8.34	6.84	3.89
B	20.00	15.36	24.23	22.30	5.96	12.68	10.86	7.81
C	71.00	50.93	65.30	63.28	22.00	29.89	27.41	26.76
D	155.0	99.46	111.4	111.5	56.00	57.52	59.00	57.07
Ave. error%	-	27.29	24.61	18.59	-	76.01	54.85	18.11

Table 9. Switching losses comparison, $V_{DC} = 600$ V.

	Semisel	IGBT— P_{sw} (W)			Semisel	FWD— P_{sw} (W)		
		SW1	SW2	SW3		SW1	SW2	SW3
A	12.00	9.01	16.45	14.40	3.75	9.05	7.40	4.13
B	26.00	18.44	29.39	26.95	6.88	13.77	11.76	8.303
C	94.00	61.66	79.85	77.36	27.00	33.26	30.40	29.36
D	205.0	121.6	137.2	137.9	68.00	65.06	66.85	64.07
Ave. error%	-	32.27	24.56	18.52	-	67.24	45.63	11.33

Table 10. Switching losses comparison, $V_{DC} = 700$ V.

	Semisel	IGBT— P_{sw} (W)			Semisel	FWD— P_{sw} (W)		
		SW1	SW2	SW3		SW1	SW2	SW3
A	15.00	10.62	19.55	17.08	4.19	9.91	8.08	4.45
B	32.00	21.74	34.92	31.93	7.76	15.05	12.82	8.93
C	118.0	73.25	95.59	92.55	31.00	37.05	33.79	32.34
D	251.0	138.9	157.6	159.0	73.00	65.96	67.86	64.55
Ave. error%	-	35.96	23.91	18.07	-	64.90	43.52	9.29

It can be noticed that method SW1, originally suggested by manufacturer, is associated with high error sometimes even more than 50% specially calculating FWD switching losses.

It should be noted that the value in the last row in Tables 8–10 (same for Tables 11–13) is the average error of all four selected working conditions which is meant to show the overall improvement of the losses evaluation accuracy. A deeper look into reported results reveals that the error falls below 5% in some cases specially when the current is close to the nominal one. Instead, the associated error is quite high in other working conditions (sometime more than 100%), especially when the current is quite low or rather high.

Table 11. Conduction losses comparison, $V_{DC} = 500$ V.

	IGBT— P_{con} (W)			FWD— P_{con} (W)		
	Semisel	Con1	Con2	Semisel	Con1	Con2
A	17.00	18.57	16.99	9.91	9.36	7.94
B	40.00	41.66	38.89	21.00	20.27	18.02
C	193.0	185.6	179.9	82.00	78.04	74.42
D	496.0	447.7	439.3	170.0	162.6	151.3
Ave. error%	-	6.73	5.26	-	4.55	13.57

Table 12. Conduction losses comparison, $V_{DC} = 600$ V.

	IGBT— P_{con} (W)			FWD— P_{con} (W)		
	Semisel	Con1	Con2	Semisel	Con1	Con2
A	16.00	17.58	16.09	11.00	10.74	9.12
B	38.00	39.45	36.81	24.00	23.28	20.74
C	183.0	176.1	170.6	94.00	90.15	86.03
D	474.0	427.8	419.9	197.0	189.5	176.1
Ave. error%	-	6.80	5.47	-	3.31	12.44

Table 13. Conduction losses comparison, $V_{DC} = 700$ V.

	IGBT— P_{con} (W)			FWD— P_{con} (W)		
	Semisel	Con1	Con2	Semisel	Con1	Con2
A	16.00	16.87	15.44	12.00	11.71	9.95
B	36.00	37.87	35.34	26.00	25.39	22.64
C	177.0	169.7	164.4	102.0	98.75	94.25
D	451.0	403.7	396.0	216.0	207.9	193.3
Ave. error%	-	6.31	6.16	-	2.92	12.02

In general, it is a challenging task to calculate or estimate switching losses, and results reveal that it is much more difficult in the case of FWD rather than IGBT. Method SW2 has better accuracy even if the accuracy has been improved further utilizing method SW3 which proposes a second order polynomial approximation. In these cases, method SW3 has losses evaluation error less than 20% and in some cases around 10%.

It should be noticed that proposed losses calculation methods are evaluated in wide range current.

6.2. Conduction Losses

In this section IGBT conduction losses ($P_{con,IGBT}$) and FWD conduction losses ($P_{con,FWD}$) have been reported and compared versus Semisel results.

Tables 11–13 report the results for the same four different loading conditions when the DC bus voltage is fixed to 500 V, 600 V and 700 V respectively.

Conduction losses estimation both for IGBT and FWD has good accuracy with both Con1 and Con2 methods even if, in the analyzed cases, method Con1 has better accuracy with respect to method Con2. Only in some cases, method Con2 leads to a better accuracy with respect to the other one.

Considering the linear $v-i$ characteristic, it is easy to understand the reasons why method Con1 outperforms method Con2. Method Con2 uses the cubed of switch current as it is reported in Equation (23), therefore it cannot perfectly fit the linear behavior of this device at high current values as method Con1 can do.

In general, it can be noticed that in this case the associated error is lower compared to the switching losses calculation errors, this is due because the current variation during the conduction period is very low.

Therefore, the best practice could be to use the linear (first order) approximation method and avoid complexity which may increase the calculation error somehow. This might not be the case for all other switches.

7. Conclusions

To increase the losses calculation accuracy, the paper describes a new approach introducing some new methods for switching and conduction losses calculation of IGBT with FWD module that can be used during simulations. Moreover, unlike the common methods in the literature, this paper evaluates and compares the switching and conduction losses separately for both IGBT and FWD.

For switching losses calculation, considering reported tests in the paper, new completed method SW3 showed a very good compromise between complexity, computation burden and accuracy with respect to other described methods. However, it is important to underline that only the new method SW2 can fit very well the energy losses curves reported in the datasheet. Therefore, only method SW2 should be used to cover a very extended range of currents.

For conduction losses calculation, method Con1 is associated with lower error to estimate IGBT and FWD conduction losses. Method Con2 led to better accuracy in some cases but worsens the losses calculation accuracy in some other cases. Therefore, for conduction losses calculation, method Con1 can be considered the better method to be adopted unless the v - i characteristic of the device possesses high non-linearity and/or the current is low.

Therefore, combination of method SW3 for switching losses and method Con1 for conduction losses performs better to calculate the overall losses of the device and it is easily applicable in all the simulation processes.

The new proposed approach is discussed in a more generic way, so it can be easily used in simulation tools with other switching devices. Moreover, considering that it can be used for any current, voltage, temperature, control strategy, switching frequency and hardware configuration, it can be considered more useful with respect to the Semisel online tool v4. Since Semisel has only some popular configurations, such as a single-phase DC-AC inverter, three-phase DC-AC inverter, direct converter and two types of three level inverters.

To increase the accuracy of the models, manufacturers should provide more numerical information on switching energy losses (E_{on} , E_{off} and E_{rr}) and also on-state resistance R_X and voltage drop V_X at different temperatures T_j beside energy losses graphs and components v - i characteristic curves.

For future studies, the presented methods can be further developed to consider parasitic components' effects in switching losses evaluation. Moreover, with detail thermal modelling, the junction temperature evaluation can be improved, and it will increase the accuracy of the results. As another direction for future study, the converter heatsink or cooling system can be considered in thermal modelling for temperature evaluation, which can be useful for final converter design.

Author Contributions: Conceptualization, H.H. and R.F.; formal analysis, H.H. and R.F.; investigation, H.H. and R.F.; methodology, H.H. and R.F.; validation, H.H.; writing—original draft preparation, H.H. and R.F.; writing—review and editing, H.H. and R.F. Both authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Parthasarathy, C.; Hafezi, H.; Laaksonen, H.; Kauhaniemi, K. Modelling and Simulation of Hybrid PV & BES Systems as Flexible Resources in Smartgrids—Sundom Smart Grid Case. In Proceedings of the IEEE PES PowerTech Conference, Milano, Italy, 23–27 June 2019.
2. Blaabjerg, F.; Chen, Z.; Kjaer, S.B. Power Electronics as Efficient interface in Dispersed Power Generation Systems in Dispersed Power Generation Systems. *IEEE Trans. Power Electron.* **2004**, *19*, 1184–1194. [CrossRef]
3. Emadi, A.; Lee, Y.J.; Rajashekara, K. Power electronics and motor drives in electric, hybrid electric, and plug-in hybrid electric vehicles. *IEEE Trans. Ind. Electron.* **2008**, *55*, 2237–2245. [CrossRef]
4. Kaleybar, H.J.; Kojabadi, H.M.; Fazel, S.S.; Foiadelli, F. An intelligent control method for capacity reduction of power flow controller in electrical railway grids. *Electron. Power Syst. Res.* **2018**, *165*, 157–166. [CrossRef]
5. Hafezi, H.; Faranda, R. Power quality and custom power: Seeking for a common solution in LV distribution network. In Proceedings of the 2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe), Milan, Italy, 6–9 June 2017; pp. 1–6.
6. Hafezi, H.; Laaksonen, H. Autonomous Soft Open Point Control for Active Distribution Network Voltage Level Management. In Proceedings of the 2019 IEEE Milan PowerTech, Milan, Italy, 23–27 June 2019.
7. Hafezi, H.; Faranda, R. Dynamic Voltage Conditioner: A New Concept for Smart Low-Voltage Distribution Systems. *IEEE Trans. Power Electron.* **2018**, *33*, 7582–7590. [CrossRef]
8. Faranda, R.; Hafezi, H. Reassessment of voltage variation for load power and energy demand management. *Int. J. Electr. Power Energy Syst.* **2019**, *106*, 320–326. [CrossRef]
9. Xia, Y.; Ayyanar, R. Naturally Adaptive, Low-Loss Zero-Voltage-Transition Circuit for High-Frequency Full-Bridge Inverters with Hybrid PWM. *IEEE Trans. Power Electron.* **2018**, *33*, 4916–4933. [CrossRef]
10. Li, Z.; Qian, W.; Zhang, X. An Optimized Zero-Voltage Zero-Current Transition Boost Converter Realized by Coupled Inductor. *IEEE Trans. Power Electron.* **2019**, *34*, 8882–8893. [CrossRef]
11. Sepahvand, H.; Khazraei, M.; Corzine, K.A.; Ferdowsi, M. Start-up Procedure and Switching Loss Reduction for a Single-Phase Flying Capacitor Active Rectifier. *IEEE Trans. Ind. Electron.* **2013**, *60*, 3699–3710. [CrossRef]
12. Krismer, F.; Kolar, J.W. Closed Form Solution for Minimum Conduction Loss Modulation of DAB Converters. *IEEE Trans. Power Electron.* **2012**, *27*, 174–188. [CrossRef]
13. Asiminoaei, L.; Rodriguez, P.; Blaabjerg, F.; Malinowski, M. Reduction of Switching Losses in Active Power Filters with a New Generalized Discontinuous-PWM Strategy. *IEEE Trans. Ind. Electron.* **2008**, *55*, 467–471. [CrossRef]
14. Faranda, R.; Valade, I. UPQC compensation strategy and design aimed at reducing losses. In Proceedings of the 2002 IEEE International Symposium on Industrial Electronics, ISIE 2002, L'Aquila, Italy, 8–11 July 2002; Volume 4, pp. 1264–1270.
15. Schweizer, M.; Kolar, J.W. Design and Implementation of a Highly Efficient Three-Level T-Type Converter for Low-Voltage Applications. *IEEE Trans. Power Electron.* **2013**, *28*, 899–907. [CrossRef]
16. Sadigh, A.K.; Dargahi, V.; Corzine, K.A. Analytical Determination of Conduction and Switching Power Losses in Flying-Capacitor-Based Active Neutral-Point-Clamped Multilevel Converter. *IEEE Trans. Power Electron.* **2016**, *31*, 5473–5494. [CrossRef]
17. Baliga, B.J. *Fundamentals of Power Semiconductor Devices*; Springer: Cham, Switzerland, 2008.
18. IEC-62751-2. *Determination of Power Losses in Voltage Sourced Converter (VSC) Valves for HVDC Systems—Part 2: Modular Multilevel Converters*; International Electrotechnical Commission: Geneva, Switzerland, 2014.
19. Ren, Y.; Xu, M.; Zhou, J.; Lee, F.C. Analytical loss model of power MOSFET. *IEEE Trans. Power Electron.* **2006**, *21*, 310–319.
20. Munk-Nielsen, S.; Tutelea, L.N.; Jæger, U. Simulation with Ideal Switch Models Combined with Measured Loss Data Provides a Good Estimate of Power Loss. In Proceedings of the onference Record of the 2000 IEEE Industry Applications Conference, Thirty-Fifth IAS Annual Meeting and World Conference on Industrial Applications of Electrical Energy (Cat. No.00CH37129), Rome, Italy, 8–12 October 2000.
21. Feix, G.; Dieckerhoff, S.; Allmeling, J.; Schönberger, J. Simple methods to calculate IGBT and diode conduction and switching losses. In Proceedings of the 13th European Conference on Power Electronics and Applications, Barcelona, Spain, 8–10 September 2009.
22. Matlab Example “Loss Calculation in a Three-Phase 3-Level Inverter”. Available online: <https://mathworks.com/help/physmod/sps/ug/loss-calculation-in-a-three-phase-3-level-inverter.html> (accessed on 20 December 2020).
23. Ivakhno, V.; Zamaruiev, V.V.; Ilina, O. Estimation of Semiconductor Switching Losses under Hard Switching using Matlab/Simulink Subsystem. *Electron. Control Commun. Eng.* **2013**, *2*, 20–26. [CrossRef]
24. Graovac, D.; Pürschel, M. *IGBT Power Losses Calculation Using the Data-Sheet Parameters*. Infineon Application Note; Infineon Technologies AG: Neubiberg, Germany, 2009; pp. 1–12.
25. Fakharmanesh, M.; Hackl, C.M.; Perini, R. Instantaneous Conduction and Switching Losses in Two-level Voltage Source Inverters. In Proceedings of the 2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe), Milan, Italy, 6–9 June 2017; pp. 7–12.
26. Zhang, Y.; Wang, H.; Wang, Z.; Blaabjerg, F.; Saeedifard, M. System-Level Power Loss Evaluation of Modular Multilevel Converters. In Proceedings of the 2019 IEEE Energy Conversion Congress and Exposition (ECCE), Baltimore, MD, USA, 29 September–3 October 2019; pp. 6797–6804.

27. Nicolai, U.; Wintrich, A. Application Note AN 1403, Determining Switching Losses of SEMIKRON IGBT Modules. SEMIKRON International GmbH, 2014. Available online: <https://www.semikron.com/service-support/downloads/detail/semikron-application-note-determining-switching-losses-of-semikron-igbt-modules-en-2014-08-19-rev-00.html> (accessed on 23 January 2021).
28. STMicroelectronics Application Note (AN604)—Calculation of Conduction Losses in a Power Rectifier. 2011. Available online: https://www.st.com/resource/en/application_note/cd00003894-calculation-of-conduction-losses-in-a-power-rectifier-stmicroelectronics.pdf (accessed on 23 January 2021).
29. Xiong, Y.; Sun, S.; Jia, H.; Shea, P.; Shen, Z.J. New physical insights on power MOSFET switching losses. *IEEE Trans. Power Electron.* **2009**, *24*, 525–531. [[CrossRef](#)]
30. Mohan, N.; Robbins, W.P.; Undeland, T.M. *Power Electronics: Converters, Applications and Design*, 3rd ed.; John Wiley & Sons: Hoboken, NJ, USA, 2002.
31. Semikron Online Tool. (Version 4.3.1). Available online: <http://semiselv4.semikron.com/Circuit.asp> (accessed on 20 January 2021).