

POWER SEMICONDUCTOR LOSSES SIMULATION CAPABILITIES IN MATLAB/SIMULINK

Daniel GORDAN, Marek PÁSTOR

Dept. of Electrical Engineering and Mechatronics, Faculty of Electrical Engineering and Informatics,
Technical University of Košice, Letná 9, 042 00 Košice, Slovak Republic, Tel. +421 55 602 4220, E-mail: marek.pastor@tuke.sk

ABSTRACT

The paper describes methods of simulation conduction and switching losses of power semiconductors in MATLAB/Simulink. The comparison of simulation results for Infineon's semiconductor with PLECS Standalone simulation is presented. The results show that the simple ideal switching model of the IGBT in Simulink gives similar results to the PLECS simulation with the Infineon PLECS library.

Keywords: MATLAB/Simulink, PLECS, converter, model, switching losses, conduction losses

1. INTRODUCTION

The design of a power converter is a complex task, which includes circuit theory, thermal management, electromagnetic compatibility, etc. Time-consuming analytical analysis by different subject experts was used in the past to overcome these complex challenges. Nowadays, the use of computer simulation in the design of electronic systems is a standard [1]-[3]. It is necessary to determine the functionality and efficiency of the converter during its development. Power losses in the converter are caused mainly by conduction and switching losses of semiconductors. Also, the real-time hardware-in-the-loop (HIL) simulators [4] or FPGA-based real-time simulation [5] can be used for rapid control prototyping or thermal behaviour simulation of semiconductor converters.

In the field of power electronics, many programs are available for the simulation of power converters. The standard in this sector is the OrCAD/PSpice program from Cadence, but it is not suitable for converters with advanced control algorithms. For the design of a converter with modern control, it is preferable to use programs such as MATLAB/Simulink, PLECS, PSpice, etc. In tandem with simulation, these programs also allow the application of advanced control methods [6] and thermal simulations [7].

Circuit-level simulators (e.g. PSpice) are useful for the prediction of the detailed switching transients in the power converter. This is useful for applications that require the simulation of slew rates, voltage edges, and high-dynamic transients such as electromagnetic compatibility analysis, switching losses analysis, Monte Carlo analysis, etc. This is thanks to the high complexity of used models. Unfortunately, this increased complexity of models causes slow simulation speed. The simulation speed is usually in the order of several milliseconds for one second of a simulation time. [8]. However, the precise simulation in PSpice can provide the dynamic performance of the semiconductor components only up to the specification in the datasheet. The information about the performance for conditions beyond the one specified in the datasheet (e.g. for a gate resistor selection) can be obtained only by measurements on an evaluation kit.

On the other hand, top-down concept simulators such as PLECS or MATLAB/Simulink are extremely useful for

control design, device selection, predicting system losses, predicting device junction temperature, and thermal system design [8]-[10]. The simulation in this software can include magnetic, thermal and mechanical aspects of systems which include the power semiconductor converter, such as electrical drives, battery charging stations, electric vehicles, HVDC transmissions, etc. They usually include simplified models of semiconductor devices based on datasheet values. However, this simplified approach can still simulate the low-frequency characteristics of the converter such as output voltage ripple, power losses, converter transfer function, etc. Although this information is not sufficient for high-dynamic analysis of the converter, it is more than enough to evaluate the performance of the control structure including modern control approaches based on fuzzy logic, predictive control or artificial intelligence.

The paper is focused on the comparison of two simulators with a top-down approach, PLECS and MATLAB/Simulink, for the prediction of total power losses of an integrated power module (IPM). The power module is intended to be used in a home appliance products. The IPM in MATLAB/Simulink is simulated by ideal switches from Simcspace library. The IPM in PLECS is simulated by using the PLECS library component created by Infineon.

2. POWER SEMICONDUCTOR MODULES

To simplify design and cooling, the power converters use power semiconductor modules, Fig. 1.



Fig. 1 Low power module (left) and medium power module (right) [11][12]

In addition to semiconductor elements such as MOSFETs or IGBTs, the power module may also include driver circuits, or overtemperature and overcurrent protection. This increases the reliability of the power converter and allows high power densities to be achieved.

Integrating the power and driver components of the converter into a single module greatly simplifies the design of the most common power semiconductor converter topologies. On the other hand, it complicates the measurement of the converter. Fig. 2 shows a module where, for example, collector currents cannot be measured. To determine the conduction and switching losses of the converter, it is thus advisable to use simulation and verify the total losses only by thermal measurements.

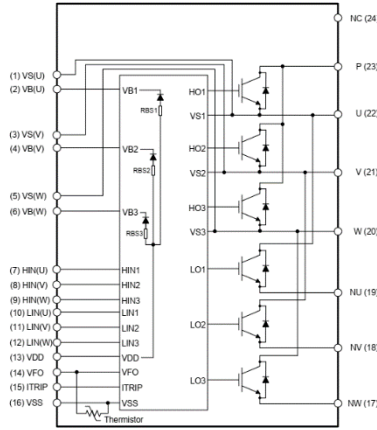


Fig. 2 Typical structure of power semiconductor module with integrated driver [12]

Power component losses are categorised into conduction and switching losses. The conduction losses depend on the RMS value of the current flowing through the component, and the switching losses depend on the magnitude of the current, voltage and switching frequency. Of course, losses also depend on power component parameters such as saturation voltage, channel resistance in the open state, switching times and temperature. The IKCM15H60GA power module, Fig. 2, will be used for modelling and simulation. The internal structure consists of IGBTs with antiparallel diodes. The module was chosen for application in home appliances such as washing machines or dishwashers. Its parameters are shown in Table 1.

Table 1 IKCM15H60GA parameters [11]

Symbol	Description	Value
V_{DC}	Maximum DC link supply voltage	450 V
I_C	Output current	15 A
P_{tot}	Power dissipation per IGBT	25,2W
f_{PWM}	Switching frequency	20 kHz
V_{IN}	Logic input voltage	5 V

Majority and minority charge carriers participate in the conductivity of bipolar components. For this reason, their output characteristic has a threshold voltage. After passing this voltage, the characteristic is approximated by a straight line whose slope is the on-state resistance. The output characteristics of an IGBT transistor are described by the equation of a straight line [13]:

$$u_{CE} = U_{CE0} + r_T i_C \quad (1)$$

U_{CE0} = threshold voltage (collector voltage at zero current),

r_T = on-state resistance,

i_C = collector current.

The conduction losses of an IGBT P_{VT} can be defined based on the average (AV) and effective (RMS) value of the collector current [13]:

$$P_{VT} = U_{CE0} I_{AV} + r_T I_{RMS}^2 \quad (2)$$

The static characteristic of the diode is represented by the equation of a straight line [13]:

$$u_D = U_{D0} + r_D i_D \quad (3)$$

U_{D0} = threshold voltage (voltage in the forward direction at zero anode current),

r_D = differential resistance in the on-state,

i_D = diode current.

The conduction losses of a diode can be defined based on the average (AV) and effective (RMS) value of the anode current:

$$P_{VD} = U_{D0} I_{AV} + r_D I_{RMS}^2 \quad (4)$$

The switching losses of an IGBT transistor are composed of turn-on and turn-off losses. When ignoring the diode reverse recovery, the turn-on losses of the IGBT transistor can be determined based on the datasheet value of the transistor turn-on time t_{on} [13]:

$$P_{on} = f_s \frac{U_{IC}}{2} (t_{ri} + t_{fv}) = f_s \frac{U_{IC}}{2} t_{on} \quad (5)$$

Similarly, the turn-off loss of an IGBT transistor can be determined based on the datasheet value of the transistor's turn-off time t_{off} [13]:

$$P_{off} = f_s \frac{U_{IC}}{2} (t_{rv} + t_{fi}) = f_s \frac{U_{IC}}{2} t_{off} \quad (6)$$

The switching losses of a diode are formed by the switching losses caused by the reverse recovery charge Q_{rr} of the diode when it is turned off [13]:

$$P_{offD} = f_s \frac{1}{4} Q_{rr} U_D \quad (7)$$

3. PERMANENT MAGNET SYNCHRONOUS MOTOR

The power semiconductor module was simulated in a converter for a small permanent magnet synchronous motor (PMSM) to provide realistic working conditions. The speed was controlled by vector control, the schematic is shown in Fig. 3.

Basic parameters of the PMSM drive are shown in Table 2. The PMSM drive is supplied from a single-phase grid. The motor speed is measured by a sensor. Mechanical

load parameters are based on the general washing machine drum. The current in the steady state was set by the friction coefficient.

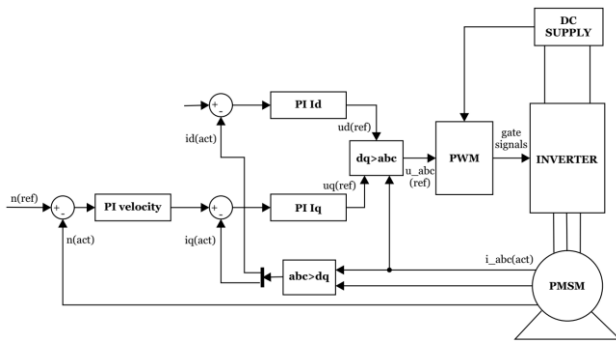


Fig. 3 PMSM control block diagram

Table 2 PMSM Field Oriented Control Parameters

Symbol	Description	Value
V_{DC}	DC voltage	325 V
P_N	nominal motor power	850 W
V_{ab_rms}	motor monimal line voltage	93 V
M_N	nominal motor torque	2,1 Nm
$2p$	number of pairs of poles	4
L_d	inductance of the motor in the d-axis	15,5 mH
L_q	inductance of the motor in the q-axis	21,5 mH
f_s	switching frequency	14 kHz

4. SIMULATION IN MATLAB/SIMULINK

Fig. 4 shows the program scheme for MATLAB/Simulink. It consists of a permanent magnet synchronous motor vector control block (PMSM Field-Oriented Control) whose output is a vector of gate pulses (G) led to a voltage source inverter block (VSI1). The inverter output is connected to a motor whose speed is measured by an encoder. The voltage inverter subsystem is shown in Fig. 5. It consists of three legs formed by upper and lower IGBT transistors with an antiparallel diode. During steady-state operation of the motor, the waveforms of all upper and lower components are identical, thus the losses are measured on only one upper (HS) and one lower (LS) transistor.

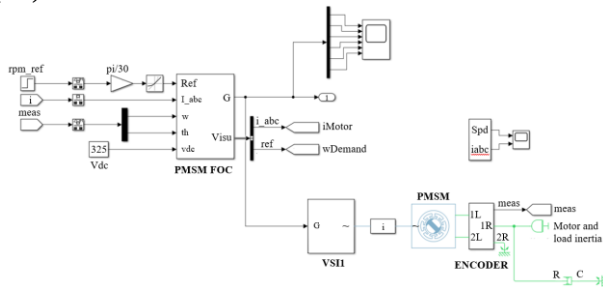


Fig. 4 Program control scheme of a PMSM in MATLAB/Simulink

The look-up table method was chosen to determine the transistor and diode losses. Parameters from the integrated power module datasheet were entered into it.

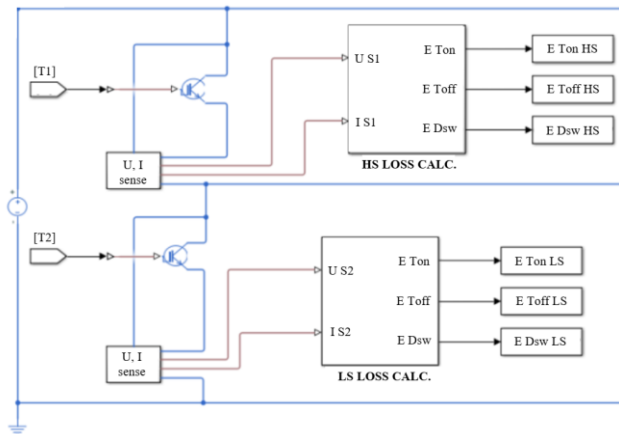


Fig. 5 Schematic of the inverter (one of three legs)

For the switching losses of the IGBT transistors, based on (5) and (6), two-dimensional lookup tables were selected whose inputs were the collector voltage and collector current of the transistors. The conduction losses were determined based on (2) from a one-dimensional table whose input was the collector current of the IGBT transistors. For diodes, the turn-off losses were simulated based on (7) and conduction losses based on (4).

5. SIMULATION IN PLECS

The simulation in MATLAB/Simulink was compared to the simulation in PLECS. Both programs are similar in the model complexity and simulation approach. The simulation model of the inverter with its control is shown in Fig. 6. The main part of the model is the Infineon IPM model. The switching and conduction losses are calculated for one high-side and one low-side transistor with its antiparallel diode. The calculation is based on 2-D look-up tables with model shown in Fig. 7.

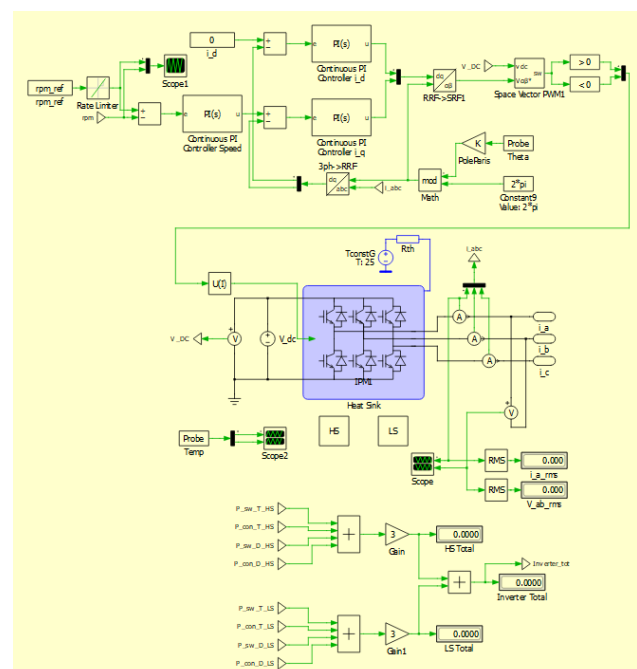


Fig. 6 Simulation scheme of the inverter in PLECS

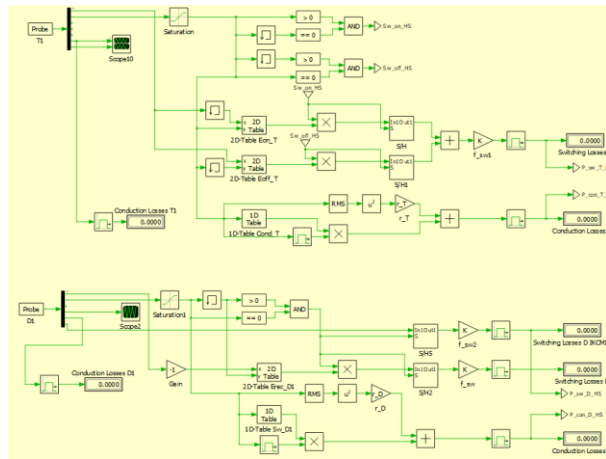


Fig. 7 Simulation scheme of the high-side switch conduction and switching losses calculation in PLECS

6. RESULTS OF THE SIMULATION

The simulation of the motor powered by the IKCM15H60GA integrated module was performed for different motor rotational speeds in the range of 450 to 650 rpm. The simulation was run with the variable step size and relative tolerance set to $1e-6$. The results of the MATLAB/Simulink simulation were compared with the PLECS Standalone simulation for the same simulated system configuration.

Fig. 8 shows the simulated motor start-up at 500 rpm and the sensed motor currents used to estimate the steady-state motor speed losses of the IKCM15H60GA integrated power module.

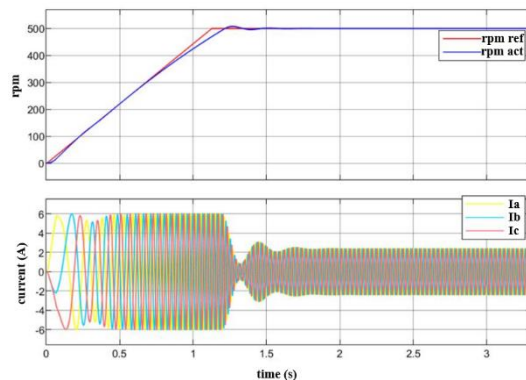


Fig. 8 Speed and current waveform of a PMSM driven by the IKCM15H60GA module for a reference speed of 500 rpm, phase rms voltage 93 V, output power $P_{\text{mech}} = 62$ W

A comparison of the total power losses of the integrated module shown in Fig. 9 shows that the two programs predict approximately the same total losses. The motor was not under load during the simulation, so the total losses of the module depend only minimally on the rpm. The rpm are chosen within the range of typical speed for washing cycle. The gear ratio between PMSM drive and washing drum was set to 10. The simulation allows the estimation of switching and conduction losses separately for the upper and lower transistors as well as for their antiparallel diodes (a total of 8 values of losses).

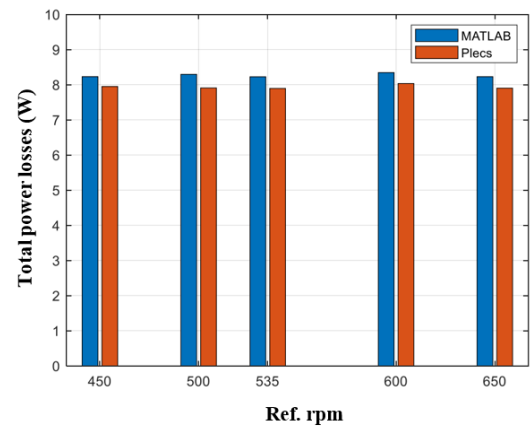


Fig. 9 Comparison of total module losses simulated in MATLAB/Simulink and PLECS Standalone for different motor speed

The comparison of conduction and switching losses is shown in Fig. 10. There is no significant difference in total power losses for various motor speed. The motor speed of 535 rpm was chosen as a reference for detailed losses analysis. Each leg of the inverter consists of the upper transistor (T_HS) with its antiparallel diode (D_HS) and the lower transistors (T_LS) with its antiparallel diode (D_LS). The conduction and switching losses for each component of one leg are shown in Fig. 10.

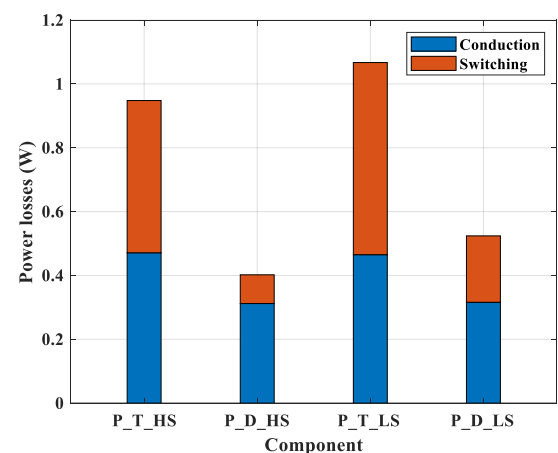


Fig. 10 Comparison of switching and conduction losses for motor speed of 535 rpm

7. CONCLUSIONS

The paper deals with the possibilities of simulation of the total power losses of an integrated power module when powering a permanent magnet synchronous motor in the MATLAB/Simulink environment. This simulation environment is often chosen for the simulation of control structures of electric drives. Including the calculation of the losses of the power part of the inverter makes it possible to predict the efficiency of the system. This can be beneficial e.g. in the development of white goods, where the energy class classification of an appliance can be predicted based on such a simulation. The simulation results still need to be verified by measurement or simulation in a program that uses PSice models of transistors and diodes. This may be

more accurate because the simulation includes the entire model and not just data from the datasheet.

ACKNOWLEDGMENTS

This paper was supported by the Scientific Grant Agency of the Ministry of Education, Science, Research and Sport of the Slovak Republic and the Slovak Academy of Sciences within the project VEGA 1/0363/23.

REFERENCES

- [1] DE PAULA, W. J. – TAVARES, G. H. M. – SOARES, G. M. – ALMEIDA, P. S. – BRAGA, H. A. C. (2020): Switching losses prediction methods oriented to power MOSFETs – a review. *IET Power Electronics*, 13: 2960-2970. <https://doi.org/10.1049/iet-pel.2019.1003>
- [2] SYED, S. A. – KHALID, H. A. – FAROOQ, H.: Analytical and Simulation Comparison of Losses in Non-Isolated DC/DC Converter Using Si and SiC Switches for PV Application. *Eng. Proc.* 2022, 20, 11. <https://doi.org/10.3390/engproc2022020011>
- [3] 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>
- [4] OSÓRIO, C. R. D. – MILETIC, M. – ZELIC, J. – MAJSTOROVIC, D. – GAGRICA, O.: "Advancements on Real-Time Simulation for High Switching Frequency Power Electronics Applications (Invited Paper)," 2021 21st International Symposium on Power Electronics (Ee), Novi Sad, Serbia, 2021, pp. 1-6, DOI: 10.1109/Ee53374.2021.9628306.
- [5] TANG, J. – BAI, H. – MA, R. – ZHAO, D. – WANG, N. – HUANG, G.: "Datasheet Driven Electro-Thermal Real-Time Simulation of Power Electronics Converter," 2022 4th International Conference on Smart Power & Internet Energy Systems (SPIES), Beijing, China, 2022, pp. 208-213, DOI: 10.1109/SPIES55999.2022.10082696.
- [6] LESO, M. – ZILKOVA, J. – GIROVSKY, P.: "Development of Simple Fuzzy Logic Controller for DC-DC Converter", *Proc. IEEE 18th International Power Electronics and Motion Control Conference (PEMC)*, 2018, pp. 86–93
- [7] WANG, W. – WICKRAMASINGHE, H. R. – MA, K. – KONSTANTINOU, G.: "Real-time Co-Simulation for Electrical and Thermal Analysis of Power Electronics," 2019 9th International Conference on Power and Energy Systems (ICPES), Perth, WA, Australia, 2019, pp. 1-5, DOI: 10.1109/ICPES47639.2019.9105352.
- [8] Wolfspeed; Selecting Between Wolfspeed's Design Tools, 2022, [online] <https://www.wolfspeed.com/knowledge-center/article/selecting-between-wolfspeeds-design-tools>
- [9] RESUTÍK, P. – KAŠČÁK, S.: "Power Losses Analysis of 3×5 Matrix Converter Based on SiC Semiconductors in MATLAB Simulink," 2022 *International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM)*, Sorrento, Italy, 2022, pp. 348-353, DOI: 10.1109/SPEEDAM53979.2022.9842216.
- [10] FRIVALDSKY, M. – SEDO, J. – RESUTIK, P. – HANKO, B.: "Evaluation of the loss model accuracy of 3-phase NPC converter," 2022 *ELEKTRO (ELEKTRO)*, Krakow, Poland, 2022, pp. 1-5, DOI: 10.1109/ELEKTRO53996.2022.9803481.
- [11] Infineon, datasheet IKCM15H60GA, [online] <https://www.infineon.com/cms/en/product/power/intelligent-power-modules-ipm/ikcm15h60ga>
- [12] Infineon, datasheet F3I400R10W3S7F, [online] https://www.infineon.com/cms/en/product/power/igbt/igbt-modules/f3i400r10w3s7f_b11/
- [13] GRAOVAC, D. – PURSCHEL, M.: *IGBT Power Losses Calculation Using the Data-Sheet Parameters*, Infineon, p. 17, 2009

Received January 5, 2024, accepted February 15, 2024

BIOGRAPHIES

Daniel Gordan graduated (MSc) in 2023 with distinction at the Dept. of Electrical Engineering and Mechatronics, Technical University of Košice, Slovakia. He started his PhD. in 2023 in the area of power electronics. His research is focused on DC/DC converters with high efficiency.

Marek Pástor defended his PhD in the field of power electronics in 2014. Since 2021 he is working as an associate professor with the Dept. of Electrical Engineering and Mechatronics, Technical University of Košice, Slovakia. His scientific research is focused on isolated DC/DC converters.