PMEC BIL RELIABILITY RESEARCH JOURNAL

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# Multiphysics Modeling of Power Electronic Devices

This work will model the power electronic devices in two steps: loss modeling and thermal modeling for IGBTs, MOSFETs, and power diodes. There will be no specific devices used; just general device parameters found from a market survey at different voltage/current ratings. This section covers how these modeling methods are designed for each respective device.

### Relevant Converter Topologies in WEC Applications

***Updated:*** *12/16/2024*

H-Bridge voltage source converters are the most common in WEC systems, especially when arranged in an AC-DC-AC or BTB topology. The rectification stage can be of active or passive rectification, and the rectification/inversion stages can be controlled independently with the presence of a DC link capacitor. The downsides of these topologies include: switching losses, low reliability of the DC link capacitor, and EMI issues [1]. Authors in [2] present a traditional 3-phase active rectifier for the front-end converter (connected to the generator) with a DC-link capacitor, followed by a DC-DC buck converter to step down the DC link voltage.

Multi-level converters (MLCs) have become more prevalent. MLCs are often used in a BTB configuration, with MLCs replacing both the rectification and inversion stages in the conventional H-bridge topologies. The three key topologies include diode-clamped converters (DCC), flying-capacitor converters (FCC), and cascaded H-bridge (CHB) converters [1]. The advantages of these topologies include lower switching losses and EMI [1] as well as higher allowable DC bus voltages which leads to reduced phase currents and lower I2R losses. Some of the disadvantages include voltage imbalances between submodules/levels [1], more complex control, and higher component counts which may have a negative impact on converter reliability.

Matrix converters are a single-stage AC-AC converter topology, where any generator input phase can be connected directly to one or more output phases, allowing for flexible switching configurations and accurate control of voltages/currents [1]. These systems are more compact than H-bridge or MLC-based BTB converters as there is no DC link and a low number of switching components [1]. Without a DC link, the reliability of the matrix converter is also improved compared to H-bridge and MLC topologies. One of the primary limitations of matrix converters is that they should not be used systems with linear generators as phase voltages in linear generator-based systems drop to 0 as the velocity decreases [1].

As presented by [3], many applications use SVPWM to generate switching signals to activate the semiconductor devices. We should, therefore, consider both an SPWM and SVPWM method for each module developed (if applicable).

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[1] J. K. H. Shek, D. E. Macpherson and M. A. Mueller, "Power conversion for wave energy applications," *5th IET International Conference on Power Electronics, Machines and Drives (PEMD 2010)*, Brighton, UK, 2010, pp. 1-6, doi: 10.1049/cp.2010.0019.

[2] E. A. Amon, A. A. Schacher and T. K. A. Brekken, "A novel maximum power point tracking algorithm for ocean wave energy devices," *2009 IEEE Energy Conversion Congress and Exposition*, San Jose, CA, USA, 2009, pp. 2635-2641, doi: 10.1109/ECCE.2009.5316277.

[3] J. Burhanudin, A. S. A. Hasim, A. M. Ishak, J. Burhanudin and S. M. F. B. S. M. Dardin, "A Review of Power Electronics for Nearshore Wave Energy Converter Applications," in *IEEE Access*, vol. 10, pp. 16670-16680, 2022, doi: 10.1109/ACCESS.2022.3148319.

### Accounting for Device Sensitivity to Junction Temperature

***Updated:*** *12/31/2024*

All power semiconductor devices are sensitive to the operating temperature at the junction of the device. For the multiphysics modeling method, these impacts are seen in switching and conduction losses. Intuitively, the thermal sensitivity is dependent on several factors and should be analyzed for each device in the system. However, to simplify the modeling of the device, approximation methods can be used for each respective category.

#### Impacts on Conduction Losses

Conduction losses of IGBTs and MOSFETs are largely driven by losses where the on-resistance is dependent on the applied gate voltage, drain/collector current, and junction temperature. For diodes, both the forward voltage and the on-resistance is dependent on junction temperature. For all device technologies, the on-resistance (and forward voltage) has a positive relationship with junction temperature (i.e., as junction temperature increases, the respective parameters also increase). We can model this relationship either in a linear or nonlinear fashion, and the modeling method should be selected based off of device technology.

[1] presents a non-linear method for estimating junction temperature impacts on MOSFETs using the below equation, where is the resistance value given at 25C, and can be derived by selecting another resistance value at some junction temperature other than 25C and solving the below equation. After a survey of common MOSFET technologies on the market, this approach most closely models the relationship found in the device datasheets.

For most IGBTs and diodes, there are not explicit definitions of the device on resistance and must be derived from the output characteristics of the device. It is then more appropriate to use a simple linear approximation of junction temperature effects using the data provided by the manufacturer, considering the lack of data. This can be done by solving the following equation, where and are the typical resistance and typical temperatures, respectively (normally 25C) [2].

#### Impacts on switching losses

For MOSFETs, most major manufacturers provide data for estimating the effects of junction temperature on switching energy. This data can be collected and turned into an LUT but should likely be normalized by the switching energy realized at nominal operating conditions. The same is true for IGBT manufacturers.

For diodes, it has been shown that there is interplay between junction temperature and reverse recovery charge in the diode [3] (the main driver in determining switching losses), but most manufacturers do not provide this data in their datasheets. For now, these impacts will be neglected. Note that there will be no switching loss in passive rectification.

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[1] D. D. Graovac, M. Pürschel, and A. Kiep, “MOSFET Power Losses Calculation Using the Data- Sheet Parameters,” *Infineon Application Note*, pp. 1–23, 2006.

[2] <https://assets.danfoss.com/documents/latest/444047/AB501641682475en-000201.pdf>

[3] D. P. Nayak, R. K. Yakala, M. Kumar and S. K. Pramanick, "Temperature-Dependent Reverse Recovery Characterization of SiC MOSFETs Body Diode for Switching Loss Estimation in a Half-Bridge," in *IEEE Transactions on Power Electronics*, vol. 37, no. 5, pp. 5574-5582, May 2022, doi: 10.1109/TPEL.2021.3128947.

### Estimating Power Semiconductor Device Losses

***Updated:*** *01/02/2025*

The losses that a device experiences are highly dependent on the application environment for the given device. In the case of WEC systems, the pertinent information includes the power electronic converter topology, the type of semiconductor device, energy storage elements, switching methods, and overall control methods. In this section, we will look at three common types of generator-side converters: MOSFET-based 2L VSI with SPWM, IGBT-based 2L VSI with SPWM, and three-phase diode rectifier with fixed DC bus.

#### MOSFET-Based Two-Level Voltage Source Converter with Sinusoidal Pulse-Width Modulation

***Updated:*** *01/02/2025*

This is the most common topology used in the renewable energy sector, especially in low-power PMSG-based systems. SPWM is the simplest type of PWM method, with space vector modulation (SVM) being the most common and most efficient. Future work will consider SVM as well, but for the first version we will solely consider SPWM.

[1] presents an averaged-method to estimate MOSFET losses assuming SPWM switching which is suitable for PMSM, BLDC, and induction motor systems. There are a number of key parameters that must be known for this modeling scheme: peak phase current value, modulation index, and power factor. The application note presents the following equations to estimate MOSFET conduction losses (), diode conduction losses (), and average/DC device currents () which are used to estimate the combined MOSFET/diode switching energies.

Where is used to find switching loss estimates for the MOSFET and Diode from an LUT derived from datasheet parameters.

#### IGBT-Based Two-Level Voltage Source Converter with Sinusoidal Pulse-Width Modulation

#### Three-Phase Diode-Based Passive Rectification with a Fixed DC Bus

#### Other Topologies (TO BE EXPLORED LATER)

The paper by Zhang et al., 2019 [n] presents a new loss modeling method that is more suitable for MMC topologies considering the DC arm current bias.

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[1] D. D. Graovac, M. Pürschel, and A. Kiep, “MOSFET Power Losses Calculation Using the Data- Sheet Parameters,” *Infineon Application Note*, pp. 1–23, 2006.

[n] Y. Zhang, H. Wang, Z. Wang, Y. Yang, and F. Blaabjerg, “Simplified Thermal Modeling for IGBT Modules With Periodic Power Loss Profiles in Modular Multilevel Converters,” *IEEE Transactions on Industrial Electronics*, vol. 66, no. 3, pp. 2323–2332, Mar. 2019, doi: [10.1109/TIE.2018.2823664](https://doi.org/10.1109/TIE.2018.2823664).

### Real-Time Power Loss Modeling

***Updated:*** *01/02/2025*

After the average device losses have been calculated, we need to turn this into a continuous-time signal to model the thermal response for the given application. This is most often done either through rectangular pulses or sinusoidal pulses. In both cases, it is assumed that the device is engaged for one half of the fundamental period of the phase current. In the square-wave case, we then apply a square wave when the device should be engaged (in an average sense) with an amplitude equal to the average losses calculated before. In the sinusoidal case, the timing of the pulse is the same, but instead the pulse is of the shape of a half of a sine wave, with an amplitude of , where is the average device losses over the fundamental period. At high frequencies, there is little difference between the responses of the two methods. At low frequencies, the rectangular pulse method does not accurately track the true shape of the loss curve, and makes it difficult to realize a meaningful junction temperature response [1]. Therefore, in this work, we will adopt the half-sine approach despite the additional complexity.

We do this

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[1] Infineon Technologies AG, “Dimensioning program IPOSIM for loss and thermal calculation of Infineon IGBT modules.” Infineon.

### MOSFET Loss Modeling

#### Loss Modeling in Two-Level Voltage Source Converter Topologies:

***Updated:*** *11/26/2024*

Modeling of the MOSFETs will be done largely using the examples in the application note by Graovac et al., 2006. This method also considers the losses of the body diode, so for MOSFET applications, no extra parallel diode will be included. Table 1 lists all input/output information for the MOSFET loss block. For inputs, , , , and are used to calculate the amplitude of . The switch location information is required for timing of the power pulse relative to the instantaneous phase current value.

Table 1: Inputs and outputs used for device modeling.

|  |  |
| --- | --- |
| **Input** | **Output** |
| RMS Phase Current () | Sine Wave Pulsed Power Output () |
| Electrical Frequency () |
| Modulation Index () |
| Power Factor () |
| Switch Location |

From Graovac et al., the average device losses over a fundamental period in three-phase motor drive applications can be defined as follows:

Where is used to find switching loss estimates for the MOSFET and Diode from an LUT derived from datasheet parameters.

In total, these losses are summed together to determine the periodic average losses of the device with respect to the fundamental frequency,

As presented in the IPOSIM documentation from Infineon, the periodic average is then used to create a half-sine wave pulsed power waveform with amplitude

This half-sine pulse should be applied in-phase with the RMS phase current through the MOSFET. For example, for a high-side MOSFET, this pulse should be applied in-phase with the positive half-cycle of the phase current. For a low-side MOSFET, the pulse should be applied in the negative half-cycle.

**NOTE:** This method is limited in that it is only valid for SPWM switching methods. Other loss calculations will need to be done for other switching methods such as SVM.

#### Loss Modeling in Modular Multilevel Converter (MMC) Topologies

The paper by Zhang et al., 2019 presents a new loss modeling method that is more suitable for MMC topologies considering the DC arm current bias.