Electrothermal Modelling of Totem-Pole PFC Converter

by P. Górecki **, M. Strąkowska *, R. Olbrycht *, R. Kasikowski *

* *Łódź University of Technology, Institute of Electronics, 211/215 Wólczańska Str, 90-924 Łódź, Poland*
** *Gdynia Maritime University, Faculty of Electrical Engineering, 81-87 Morska Str, 81-225 Gdynia, Poland*

Abstract

In this paper, the electrothermal model dedicated to hybrid MATLAB/SPICE simulations of the Totem-Pole PFC Converter is presented. The accuracy of the model was validated experimentally to prove its accuracy and usability.

1. Introduction

Power electronic converters, due to nonlinear load characteristics, generate significant mains harmonics, requiring power factor correction (PFC) circuits to prevent power quality degradation. PFC, typically implemented as modular circuitry, adjusts the input current waveform to align with the input voltage, achieving a high power factor. This, along with conversion efficiency, remains a key performance parameter of modern designs.

In the literature, multiple PFC topologies are presented [1]. For single-phase grids, bridgeless topologies are increasingly popular, especially when input voltage is below 100 V. Under such conditions, conventional bridge boost PFC efficiency falls below 95%, which is considered unacceptable in industry applications. A suitable solution is the Totem-Pole topology, which combines advantages of traditional PFC circuits with elimination of the diode bridge rectifier using two pairs of power MOSFETs. One pair consists of MOSFETs with low RDS(on), while the second uses fast-switching devices such as GaN HEMTs. Conduction losses in MOSFETs are significantly lower than in diode rectifiers, while the switching frequency of the second pair largely determines power density of the PFC circuit.

Effective PFC circuit design requires dedicated integrated circuits (controllers and drivers) to control transistors [2]. To minimize PCB area, dedicated analogue circuits are typically used. However, circuit-level modelling is hindered by the lack of available data for accurate model generation, while manufacturer models exist only for a small number of ICs, usually older devices rather than newer ones. A simplified mathematical model of the controller can be formulated, but this is more easily implemented in dedicated tools such as MATLAB and cannot be directly used in SPICE simulations.

This extended abstract presents an electrothermal circuit-level model of a PFC circuit for SPICE simulations, using control voltage waveforms of power transistors calculated in MATLAB. Nonlinear thermal models for all components are included to ensure accuracy, and the simulation results obtained were validated experimentally.

2. Totem-pole PFC circuit

In the Totem-Pole topology (Fig. 1), two power transistors (MOSFET1 and MOSFET2) operate at a switching frequency equal to the input voltage frequency. Operating in the third quadrant, their conduction losses are lower than those of a conventional diode rectifier. The second pair of transistors (GaN1 and GaN2) operates at high switching frequency as part of a synchronous boost converter with a boost inductor and storage capacitor. Due to superior switching performance, GaN transistors easily support operation as high as 65 kHz. A variable duty cycle of the high-frequency transistors maintains constant output voltage and ensures low total harmonic distortion (THD).

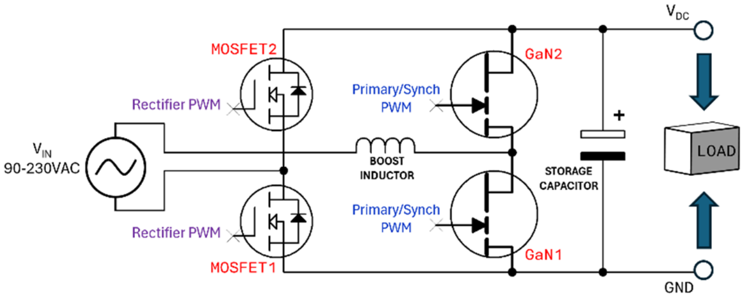

Figure 1. Totem pole evaluation board with marked heat sources (a) and daughter board with GaN transistors (b)

3. Electrothermal modelling framework

Circuit-level simulations of power converters are an effective tool for optimizing design. Accurate loss predictions across all components enable optimal selection of switching frequency and components. To verify component suitability, temperatures are calculated over planned operating conditions. A key challenge in electrothermal circuit-level transient simulations is the large disparity in time constants. The shortest time constant, which sets the maximum simulation step, corresponds to transistor switching rise and fall times on the order of tens of nanoseconds. The longest time constant, which determines simulation duration, represents thermal dynamics and can reach several kiloseconds in PCB assemblies with free convection. This wide range makes electrothermal simulation computationally demanding. Therefore, efficient simulation requires dedicated methods and the use of multiple simulation tools.

LTspice served as the primary simulation program. To address differences in time constants in the simulated converter, a segregated iteration method was employed: after every three input voltage periods, component temperatures were updated via the .IC command, with simulations repeated until results following three periods varied by no more than 1°C from the initial values Approximate steady-state temperatures were calculated in MATLAB using the average power dissipated across all components, computed in LTspice, and their thermal resistances R_{thj-a}.

Fig. 2 shows the developed electrothermal model network of the PFC power stage.

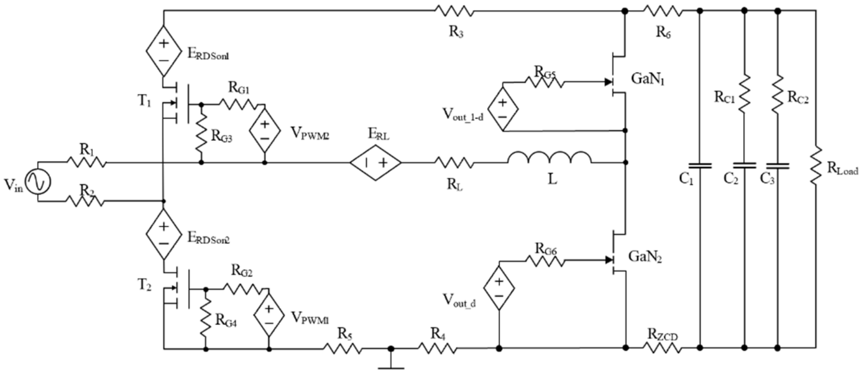

Figure 2. Network representation of the developed model of the PFC circuit power stage

4. Experimental verification

The developed model was experimentally verified using a totem-pole PFC converter. In Fig. 3, the temperatures of the tested PFC circuit components measured using a thermal camera are compared with the simulation results at output powers of 400W (a) and 200 W (b).

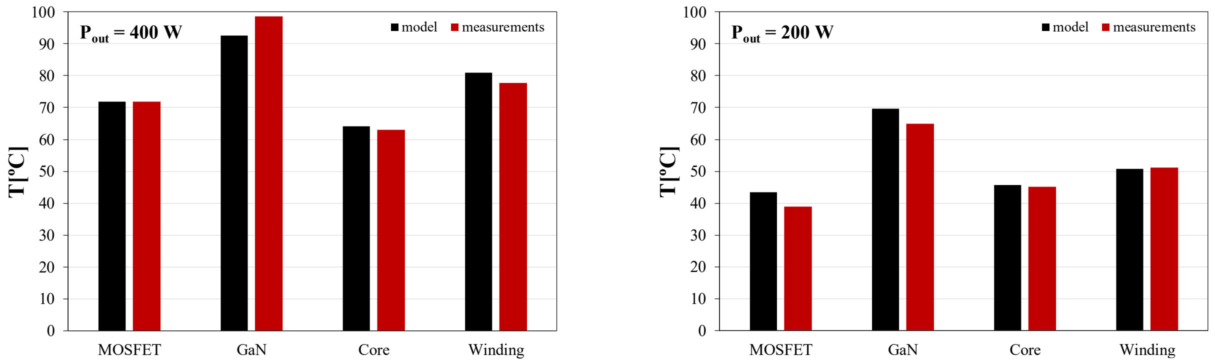

Figure 3 The simulation results obtained using the developed model compared with the measurement results

Fig. 3 shows that the developed model is an effective tool for simulating temperature distribution in the PFC circuit. The computed component temperature increase errors do not exceed 10% and are highest for the GaN HEMTs due to limited data on switching energies, which affects the accuracy of simulated power dissipation in the devices.

The model also effectively verifies proper electrical operation. The computed average output voltage differs from the measured value by no more than 1%, and the absolute error in the output voltage amplitude does not exceed 1 V.

5. Conclusions

The extended abstract presents an electrothermal model of a PFC circuit for single-phase grid operation. The model enables computation of electrical characteristics and temperatures of key components. A multipath nonlinear thermal model ensures high accuracy, validated by high-resolution thermal imaging. Correct implementation of the control part is achieved by coupling MATLAB simulations with an LTspice model of the power stage.

In the full-text article, the datasheet-based parameter estimation procedure together with a detailed description of the thermal modelling will be presented. Additionally, the experimental verification will be extended with the results presenting watt-hour efficiency and temperatures of components in a wide range of operating conditions.

Acknowledgments

This research was carried out as part of a project funded by the National Centre for Research and Development (Polish: NCBR—Narodowe Centrum Badań i Rozwoju) under the LIDER XV program, in accordance with the contract for the execution and financing of project No. LIDER15/0205/2024.

References

[1] C. Adragna, A. Bianco, G. Gritti, M. Sucameli, State-of-the-Art Power Factor Correction: An Industry Perspective, Encyclopedia, vol. 4, no. 3, pp. 1324-1354, 2025.

[2] P. Górecki, D. Wojciechowski, Accurate Computation of IGBT Junction Temperature in PLECS, IEEE Transactions on Electron Devices, Vol. 67, No. 7, pp. 2865-2871, 2020.