High-Efficiency Converter Modulation Techniques for Reduced Switching Losses

Research Focus

- **AC–AC Voltage Source Back-to-Back Converter (V-BBC)** for grid-to-machine applications
- **AC–DC Converters** for automotive applications
- **Soft-switching and soft-switched converter concepts**

Contact: Christos Leontaris, christos.leontaris@tum.de, Gean Sousa, gean@sousa@tum.de

Short Description

AC–AC Converters (Voltage Source Back-to-Back Converter)

Bidirectional **Integrated Motor Drive (IMD)** systems require compact power converters that fit inside the electric machine housing. This drives the need for **high switching frequencies**, which improve power density but increase switching losses and heat generation—making thermal management and cooling more challenging.

While **wide-bandgap (WBG)** semiconductors significantly reduce switching losses, further improvements are possible by **reducing the total number of switching transitions**. Our research introduces a **Voltage Source Back-to-Back Converter (V-BBC)** operated in a holistic manner through **synergetic control of both converter stages**. The key idea is that **only three out of six legs switch in any given switching cycle**, reducing switching events and overall switching losses.

An **11 kW laboratory prototype** has been built and tested, achieving:

- **Power density:** 4.7 kW/L
- **Efficiency > 98.2% at 100 kHz** switching frequency
- **Efficiency > 98.5% at 50 kHz** switching frequency
- **Peak efficiency:** 98.68% (100 kHz) and 98.87% (50 kHz)

AC–DC Current Source Converter (CSC)

Recently introduced bidirectional **GaN switch technologies** can revive **Current Source Converters (CSCs)**, as conduction losses for a given chip area can be **approximately**

halved. Beyond efficiency, our broader objective is to unlock the potential of CSCs for **reduced material usage** and **lower overall environmental impact**.

To reduce the size of passive components (**L, Cs, and EMC filter components**), the converter is operated at **higher switching frequencies**. Although GaN devices reduce switching losses, switching losses remain a key limitation at high frequency. Therefore, the approach pursued here is the development of **novel modulation strategies that achieve Zero Voltage Switching (ZVS) for all devices**.

The central challenge is achieving ZVS **without significantly increasing circulating currents**. This requires accurate prediction of current waveforms during switching transitions. To enable this, **mathematical models** are derived and used to define advanced modulation strategies.

Two modulation schemes are proposed:

- **Trapezoidal Current Modulation (TrCM)**
- **Advanced Trapezoidal Current Modulation (A-TrCM)**

Preliminary results predict a semiconductor efficiency of **$\eta \approx 99.55\%$** at the nominal operating point of **6.75 kW**. The required DC-link inductance is only **$L = 8\ \mu H$**, which is **at least one order of magnitude lower** than that of traditional continuous-conduction-mode CSC modulation—supporting substantial reductions in overall converter volume.

A hardware prototype is currently under development.

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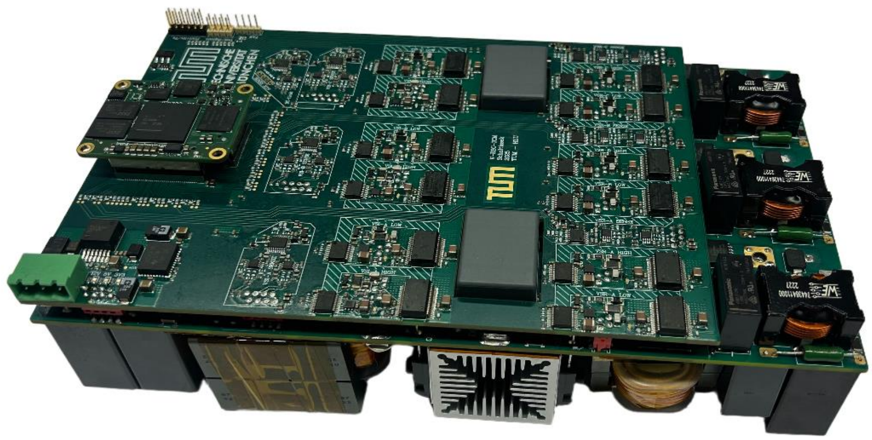
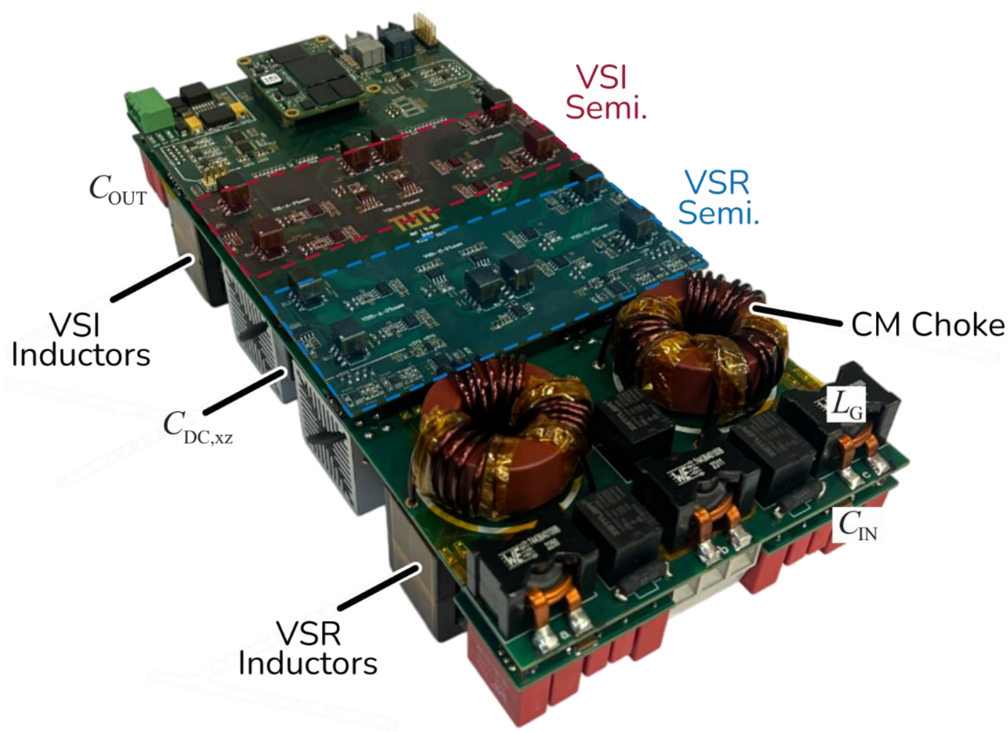
Picture(s)





VSI
Semi.
VSR
Semi.
C_{OUT}
VSI
Inductors
CM Choke
L_G
$C_{DC,xz}$
C_{IN}
VSR
Inductors

Publications:

- C. Leontaris, G. J. M. de Sousa and M. L. Heldwein, "Three-Leg Operation of Back-to-Back Converters," in *IEEE Transactions on Power Electronics*, doi: 10.1109/TPEL.2025.3624327.
- C. Leontaris, G. J. M. de Sousa and M. L. Heldwein, "Three-Stage/-Phase Voltage/Current DC-link AC-AC Converter with Synergetic Control," *PCIM Conference 2025; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management*, Nürnberg, Germany, 2025, pp. 1321-1330, doi: 10.30420/566541172.
- C. Leontaris, G. J. M. de Sousa and M. L. Heldwein, "Soft-Switched GaN-based Current Source Converter," *2025 Brazilian Power Electronics Conference (COBEP), Vitoria, Brazil, 2025*.