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XXXVI Cycle

Innovative Wide-bandgap Multilevel Power Converters

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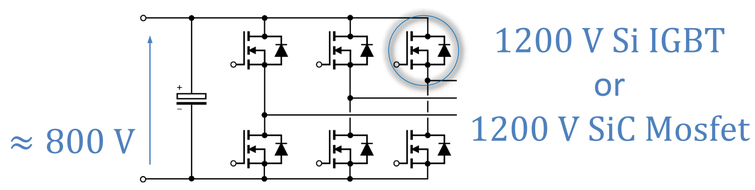
Supervisors: Prof. Radu Bojoi, Prof. Eric Armando

Research context and motivation

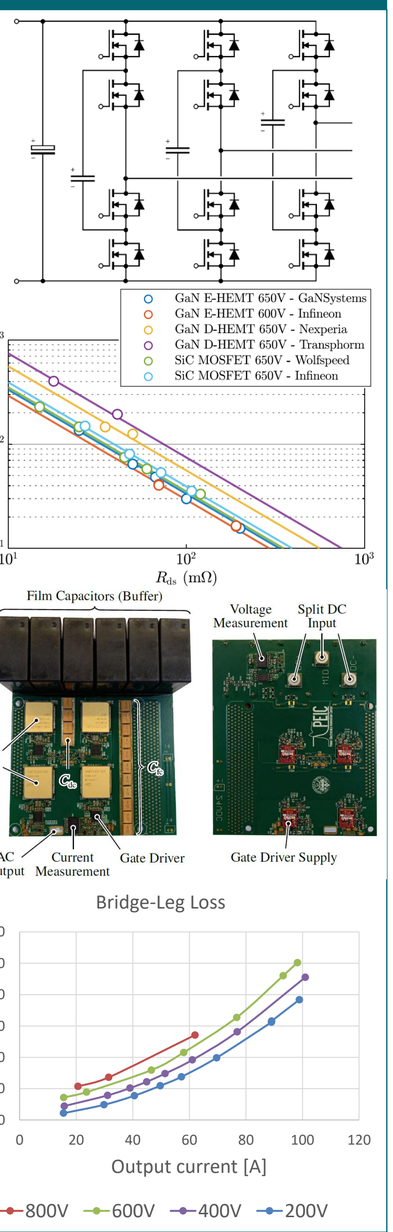
- The goal of the PhD activity is the design, optimization and realization of a three-phase three-level multilevel Flying Capacitor converter employing WBG devices
- Presently, the 800V two-level inverter employing 1200V Si IGBT or SiC Mosfet is the state-of-art structure for variable speed drive inverters and grid-connected rectifiers. It presents some margin of improvements:
  - Efficiency (i.e. low load)
  - Power density



- These goals can be achieved adopting the combination of wide bandgap (WBG) devices and novel inverter topologies (i.e. multilevel converter)
- The main challenges are a more complicated hardware structure and control

Addressed research questions/problems

- Three-level Flying Capacitor converter turned out to be best choice because of the following features:
  - Low dv/dt stress on the load and low output voltage distortion
  - It enables the use of lower voltage rate devices which feature a better Figure of Merit (FoM)
  - Challenges related to higher device number and structure complexity
- Comparison between the 650 V devices, GaN technology shows the highest future potential:
  - Lower conduction and switching losses
  - Challenges related to gate driving, higher dv/dt stress on the load and cooling system
- Evaluation of the ceramic capacitor to replace film capacitors for power density improvement :
  - Experimental evaluation of the effective capacitance and rms current capability of the $Ceralink^{®}$ TDK ceramic capacitor
- Experimental testing on a two-level half-bridge board:
  - Devices DPT tests
  - Gate driver circuit and commutation loop performance tests
- Experimental testing of a single-phase Flying Capacitor converter:
  - Thermal characterization
  - Converter loss measurements



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Novel contributions

- Comparison of different switch technologies by a new FOM to select the best power switch already in the preliminary converter design
- Replacement of State-of-the-art DC-Link Film capacitors with ceramic capacitor
- Optimization of the commutation loop to enable the elimination of the commutation capacitor
- High-efficiency, high power density converter design combining the advantages offered by:
  - GaN devices
  - multilevel topology
  - $Ceralink^{®}$ TDK capacitors

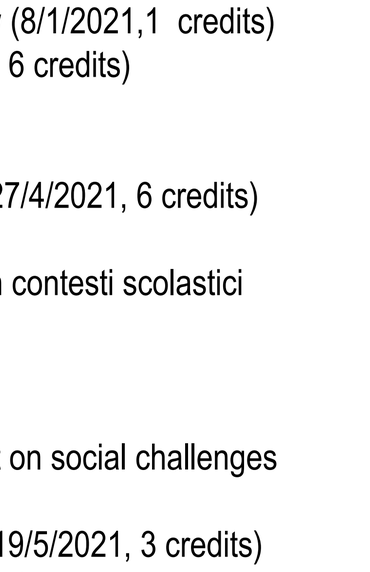
Adopted methodologies

- Simulation of the complete power converter (with closed loop control) using the software PLECS
- Matlab simulation to evaluate the converter component stresses and the impact of different control and modulation strategies
- Evaluation of the power switches commutation waveforms and simulation of the electronic conditioning circuity using the software LTspice
- PCB design with Altium
- Open loop control code implemented on Xilinx Zynq 7020 FPGA (i.e. C code and VHDL code)

plecs
LTspice
Altium Designer
VIVADO
ZYNQ
XILINX

Future work

- Test of the driving circuit for two devices in parallel in a single-phase two-level bridge leg configuration (the PCB board has been already designed and assembled)
- Evaluate MicrolabBox from dSpace as control unit
- Design and test a 50 kW three-phase three-level Flying Capacitor converter



Submitted and published papers

- Cittanti, D., Vico, E., Gregorio, M., Mandrile, F., & Bojoi, R. (2020, November). Iterative design of a 60 kW all-Si modular LLC converter for electric vehicle ultra-fast charging. In 2020 AEIT International Conference of Electrical and Electronic Technologies for Automotive (AEIT AUTOMOTIVE) (pp. 1-6). IEEE.
- Cittanti, D., Vico, E., Gregorio, M., & Bojoi, R. (2021, October). Design and Experimental Assessment of a 60 kW All-Si Three-Phase Six-Leg T-Type Rectifier for Electric Vehicle Ultra-Fast Charging. In 2021 International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME) (pp. 01-08). IEEE.
- Cittanti, D., Gregorio, M., Vico, E., Mandrile, F., Armando, E., & Bojoi, R. (2022). High Performance Digital Multi-Loop Control of LLC Resonant Converters for EV Fast Charging with LUT-Based Feedforward and Adaptive Gain. IEEE Transactions on Industry Applications.
- Cittanti, D., Vico, E., & Bojoi, I. R. (2022). New FOM-based performance evaluation of 600/650 V SiC and GaN semiconductors for next-generation EV drives. IEEE Access, 10, 51693-51707.
- Cittanti, D., Stella, F., Vico, E., Liu, C., Shen, J., Xiu, G., & Bojoi, R. (2022, May). Analysis and Design of a High Power Density Full-Ceramic 900 V DC-Link Capacitor for a 550 kVA Electric Vehicle Drive Inverter. In 2022 International Power Electronics Conference (IPEC-Himeji 2022-ECCE Asia) (pp. 1144-1151). IEEE.
- Cittanti, D., Vico, E., Armando, E., & Bojoi, R. (2022, May). Analysis and Conceptualization of a 800 V 100 kVA Full-GaN Three-Level Flying Capacitor Inverter for Next-Generation Electric Vehicle Drives. In 2022 International Power Electronics Conference (IPEC-Himeji 2022-ECCE Asia) (pp. 2320-2327). IEEE.
- Cittanti, D., Vico, E., Armando, E., & Bojoi, R. (2022, June). Analysis and Conceptualization of a 400V 100 kVA Full-GaN Double Bridge Inverter for Next-Generation Electric Vehicle Drives. In 2022 IEEE Transportation Electrification Conference & Expo (ITEC) (pp. 740-747). IEEE.
- **In press**, "Design and Testing of an Automotive Compliant 800V 550 kVA SiC Traction Inverter with Full-Ceramic DC-Link and EMI Filter" (ECCE USA 2022)
- **In press**: "Analysis and Conceptualization of a Single-Phase Buck-Boost Integrated EV On-Board Charger Based on a Double Bridge Inverter Drive System" (ECCE USA 2022)

List of attended classes

- 01DPIRO – Advanced Topics in Energy Storage System and Electric Vehicle Drivetrain Design (didattica di eccellenza) (7/9/2022, 4 credits)
- 01SINPG – Antropologia dei contesti scolastici ed educativi (16/6/2021, 6 credits)
- 02LWHRV – Communication (23/12/2020, 1 credits)
- 01SIOPG – Didattica, tecnologie e ricerca educativa (14/6/2021, 6 credits)
- 01SHMRV – Entrepreneurial Finance (6/1/2021, 1 credits)
- 02LCPRV – Experimental modeling: costruzione di modelli da dati sperimentali (9/2/2021, 7 credits)
- 01QSFIV – Global energy trends and outlook (13/2/2021, 2 credits)
- 01LDVRU – Magnetismo nei materiali e misure magnetiche (8/6/2021, 4 credits)
- 01UNVRV – Navigating the hiring process: CV, tests, interview (8/1/2021,1 credits)
- 01SILPG – Pedagogia della scuola e dell'inclusione (9/6/2021, 6 credits)
- 01UNYRV – Personal branding (11/1/2021, 1 credits)
- 01LEVRV – Power system economics (14/7/2021, 3 credits)
- 02SFURV – Programmazione scientifica avanzata in matlab (27/4/2021, 6 credits)
- 08IXTRV – Project management (7/12/2020, 1 credits)
- 01UHIPG – Psicologia dell'educazione e dell'apprendimento in contesti scolastici (11/6/2021, 6 credits)
- 01RISRV – Public speaking (15/12/2020, 1 credits)
- 01SYBRV – Research integrity (10/1/2021, 1 credits)
- 01SWQRV – Responsible research and innovation, the impact on social challenges (29/12/2020, 1 credits)
- 01TSLRO – Soluzioni innovative per veicoli elettrici e/o ibridi (19/5/2021, 3 credits)
- 02RHORV – The new Internet Society: entering the black-box of digital innovations (2/1/2021, 1 credits)
- 01UNXRV – Thinking out of the box (11/1/2021, 1 credits)
- 01SWPRV – Time management (25/11/2020, 1 credits)
- 01QORRV – Writing Scientific Papers in English (11/1/2021, 3 credits)
- European Ph.D. school of power electronics (23-27/1/2021, 40h)
- ECPE "Advanced Drivers for Si, SiC and GaN Power Semiconductor Devices" (15/5/2022, 16h)

Politecnico di Torino

PhD program in
Electrical, Electronics and Communications Engineering