FINAL REPORT

Student name: Davide Biadene

Cycle: XXX

Curriculum: *ICT*

Supervisor name: Prof. Giorgio Spiazzi

Thesis title (final): High Efficiency Interfacing Converters for Distributed Energy Systems.

PART 1 - COURSES, CONFERENCES AND MOBILITY

Courses for Ph.D. students

- Applied Linear Algebra;
- Statistical Methods;
- Resonant Converter and Inverters: Topologies and Modeling;
- Digital Processing of Measurement Information.

Summer schools, short courses, tutorials

- GE Annual Meeting 2015, June 24-26, 2015, Siena (Italy);
- 18th European PhD School: Power Electronics, Electrical Machines, Energy Control and Power System, May 22-26, 2017, Gaeta (Italy).

Seminars

- Interdepartmental Centre Giorgio Levi Cases, *Smart Grid*
- Interdepartmental Centre Giorgio Levi Cases, *Energy Storage for the Future*
- Rodolphe Sepulchre, Dept. of Engineering, University of Cambridge, *Do brains compute?*
- Walter Snoeys, PH department, CERN, Geneva, Switzerland, *How chips helped discover the Higgs boson at CERN*
- Analog Devices – EBV, *Transform your project into a Success with Analog Devices*
- Luigi Colangeli, Directorate of Science and Robotic Exploration European Space Agency, *Rosetta rendez-vous with the 67P/Churyumov-Gerasimenko comet*
- Josè A. Cobos, Technical University of Madrid (UPM), *Power Supply Systems for Energy Efficiency*
- Umberto Vincenti, University of Padova, *Il principio di responsabilità*
- Umberto Vincenti, University of Padova, *Etica per una repubblica*

- Elisabetta Collini, Dipartimento di Scienze Chimiche, University of Padova, *Quantum mechanics in energy and signal transfer processes*
- Daisuke Ueda, Advanced Technology Research Laboratories & Device Solution Center, Panasonic Corp., Japan, *Present and Future of GaN Power Devices*

Other learning activities

- LabView *Core 1* Course, National Instruments;
- LabView *Core 2* Course, National Instruments;
- LabView *Embedded Control and Monitoring* Course, National Instruments.

Mobility periods

The student has performed his research at Swiss Federal Institute of Technology (ETH) - Zürich (Switzerland) in the Power Electronic System Laboratory (PES) under the supervision of prof. J.W. Kolar from 15 February 2016 to 15 August 2016. His research activity focused on Multi-Objective Optimization applied on Power Converters.

PART 2 - RESEARCH ACTIVITY

Contents: In the last years, the development of low-carbon energy technologies is increasingly becoming a major challenge in order to address energy security and climate change. The smart grids are being considered as possible solution as they provide several opportunities to increase the efficiency, reliability and stability of the whole system, while minimize the costs and environmental impacts. The main difference between the traditional distribution network and the smart grid is the energy generation and storage arrangement: from the large and centralized power plants present in the traditional system to a growing array of customer-sited distributed energy resources (DERs), including renewable energy sources (RES) and energy storage system (ESS), in the future smart network. A large usage of Electronic Power Processors (EPPs) will be mandatory to interface, control and manage the huge amount of DERs and to connect the micro grid to the distribution infrastructure.
Typical examples of RES and ESS used in the described scenario are photovoltaic panel and fuel cells for the first, battery and supercapacitor stacks for the second. They are both characterized to be low voltage, high current DC devices. Usually, they are connected to a common high voltage DC bus (typically 400V) via high step-up DC/DC converters to transfer power to the grid through an AC/DC converter (inverter) or to a DC micro grid.
The aim of the research consists to investigate the EPP design procedure to maximize efficiency and power density in order to achieve a deep integration of DERs in the future smart grid.

Activity Synoptic:

- Multi-Objective Optimization (MOO) concerns with optimization problems involving more than one objective function to be optimized simultaneously. MOO represents the mathematical framework to solve the trade-off between efficiency and power density in EPP design.
  According with the converter specifications, the design space is the feasible set of decision vectors. Each vector represents a feasible solution or decision in EPP design procedure. Some examples of degrees of freedom (vector components/directions) are:
  - switching frequency;

- passive component values (inductor, capacitor, transformer turn ratio,…);
- switching device arrangement (parallel and series connection);
- converter topology;
- etc.

Given the design space parameters, the MOO tool sweeps the design space for optimum designs, i.e. the Pareto Front, mapping it to the objective space through the identified objective functions follow reported:

- switching loss model;
- magnetic loss model;
- modulation converter model;
- volume estimator.

The investigated methods to find the Pareto Front have been

- brute-force search;
- weighting method;
- genetic algorithms.

In EPP design scenario, brute-force search has been identified as the most easy-to-use for rapid evaluation.

– Magnetic Theory have been widely studied in order to understand the origin of losses in magnetic devices. Several methods for core loss estimation are present in literature, among which have been considered:
  - Steinmetz Equations (SE);
  - Improved Generalized Steinmetz Equation (iGSE);
  - Improved iGSE (i^2GSE);
  - Loss Separation (hysteresis, eddy current, residual);
  - Empirical Hysteresis Model.

  The iGSE method has been identified as the suitable trade-off between precision and complexity in EPP design.

– Modulation Converter Model is mandatory to quantify the losses of the converter in steady-state operation. The focus has been put on the resonant converter, series- (SRC) in particular, because they permit to reduce the switching losses achieving Zero-Current Switching (ZCS) or Zero-Voltage Switching (ZVS) transitions and to reach high switching frequency reducing the magnetic components size. However, there are some disadvantages: they can be only optimized in a limited operating range, they present high RMS circulating currents compared to the non-resonant counterpart and the complexity of analysis is not negligible.
  In order to overcome the complexity of the analysis in steady state condition, a Closed-Form State-Space Model for SR converters has been developed [J1]. It provides a matrix formulation of the well-known State Plane Analysis.
  The presented framework has been verified using, as test case, the Interleaved Boost with Coupled Inductors (IBCI) converter [C1].

– MOO study of an Isolated Back End Based Solid-State Transformer (IBE SST) Cell has been performed. Each IBE cell is a two stage AC/DC converter composed by an Active Rectification Unit (ARU) and an Isolated Voltage Regulator Unit (I-VR). The ARU has been implemented with a Power Factor Corrector (PFC) Boost, and the I-VR stage has been realized with an isolated Dual Active Bridge (DAB) with Phase Shift Modulation (PSM) control.
  The analysis carried out on the DAB stage was oriented to find the optimum transformer design to minimize the conduction and switching losses. The design space is given by

leakage inductance, magnetizing inductance and turn ratio values. This approach permits to define the locus of points corresponding to the minimum RMS current for both side and the region where soft switching conditions are achieved.
Concerning the PFC Boost stage, the internal Triangular Current Modulation (iTCM) has been developed to reduce the switching losses in continuous conduction mode operation. The analysis has also provided a simplified boost inductor estimation for the IBE-based multi-cell SST [C2].

- Other EPP has been taken into account in the DER scenario: hybrid converters where conventional topologies are integrated with charge pump cell to reduce the energy stored in the magnetic device and hence their size [C3], or high step-up bidirectional converter for energy storage application in DC micro grid [C4].

PART 3 - PUBLICATIONS

List of publications on international journals

J1. D. Biadene, and G. Spiazzi, "Closed-Form State-Space Model-Based Solution for Series-Resonant DC-DC Converters," IEEE Transactions on Power Electronics (undergoing 2nd revision process)

List of publications on conference proceedings

C1. G. Spiazzi; S. Buso; D. Biadene, "Efficient high step-up topology for renewable energy source interfacing," Applied Power Electronics Conference and Exposition (APEC), March 15-19, 2015.

C2. D. Rothmund; D. Bortis; J. Huber; D. Biadene; J.W. Kolar, "10kV SiC-Based Bidirectional Soft-Switching Single-Phase AC/DC Converter for Medium-Voltage Solid-State Transformers," 8th International Symposium on Power Electronics for Distributed Generation Systems (PEDG 2017), April 17-20, 2017.

C3. G. Spiazzi, D. Biadene, S. Marconi, A. Bevilacqua "Non-isolated High Step-up DC-DC Converter with Minimum Switch Voltage Stress," 3rd Annual Southern Hemisphere Power Electronics Conference (SPEC 2017), December 4-7, 2017 (accepted)

C4. G. Spiazzi; S. Buso; D. Biadene, G. Rossetto, F. Mela, "High Efficiency Battery Charger for Photovoltaic Inverters," 3rd Annual Southern Hemisphere Power Electronics Conference (SPEC 2017), December 4-7, 2017 (accepted)

Padova, 27/09/2017

Student signature

Supervisor signature