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Grid Connected Inverters Emulating Synchronous Generators

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Research context and motivation

Aim of this research project is to investigate the **Virtual Synchronous Generator (VSG) concept** applied to the control of grid connected inverters.

This concept consists in **controlling** grid-tied **inverters**, so that they **behave as** traditional **Synchronous Generators (SGs)**.

The **benefits** and possibilities guaranteed by this solution are:

- Higher integration of **renewable energy sources** is the electric grid;
- **Virtual inertia** to support the grid frequency;
- **Reactive support** during grid faults;
- Power quality improvement, thanks to current **harmonic compensation**.

Novel contributions

- Analisys and **comparison** of the existing **VSG models**;
- **Improvement** of the **damping** of the electromechanical part of the VSG using a **virtual damper winding** on the *q*-axis of the VSG;
- **Decoupling** of the **damping** of the VSG from the primary regulation of the frequency;
- Higher **immunity** to phase jumps in the grid voltage during faults→ better grid **frequency estimation** during faults;
- Optimal **tuning** of the VSG parameters to provide the desired behavior (e.g. virtual inertia);
- **Flexible and modular state-space modelling** of the inverter digital control to allow an easier integration of the VSG models into power system level simulations.

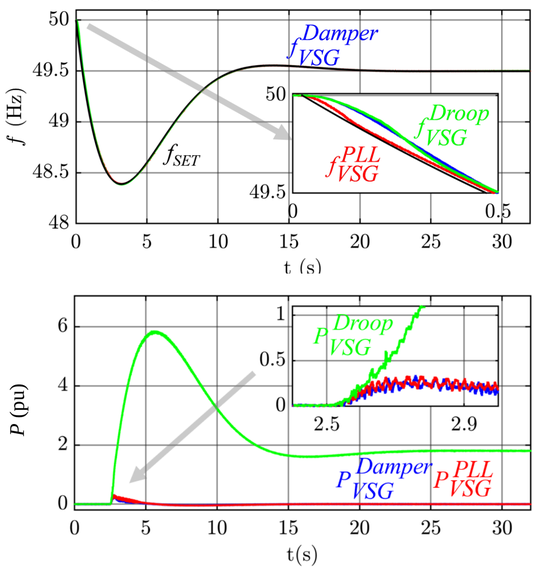

Fig 1. Comparison of damping techniques. A grid frequency drop is applied (top) and the active power injected by three VSGs using different damping methods is compared (bottom):

- Droop-based damping: abnormal power injection due to modified droop coefficient.
- PLL based damping: Power injection only during frequency change
- Proposed damper-based damping: Power injection only during frequency change

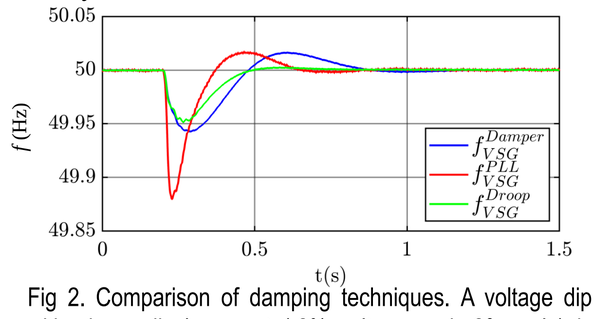

Fig 2. Comparison of damping techniques. A voltage dip with phase displacement (-2% voltage and -2° angle) is applied. The frequency estimation of the VSG is compared:

- Droop-based damping: Damped response and small frequency error.
- PLL based damping: Damped response but large frequency error
- Proposed damper-based damping: Damped response and small frequency error

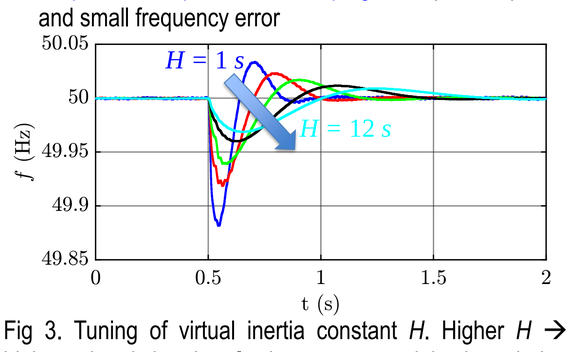

Fig 3. Tuning of virtual inertia constant *H*. Higher *H* → higher virtual inertia → larger power injection during frequency variations.

Addressed research questions/problems

The key topics addressed in this research can be summarized in the following points:

- Necessary/useful **features** to include into the **VSG model** (full order model, simplified models…);
- **Current control** vs **Voltage control**: the inverter can work as a grid feeding, grid forming or grid sustaining inverter, grid-tied or in microgrid mode;
- **Behavior in fault conditions**: the inverter should not disconnect from the grid during faults and must comply to the grid code (Low Voltage Ride Through, **LVRT**);
- **Harmonic compensation**: the VSG should counteract the presence of current harmonics in the grid → Active filter behavior;
- **Islanding condition**: how the inverter must behave in case of disconnection of a portion (island) of the grid;
- **Power electronics-based power system**: the power system stability must be preserved even with a high penetration of power electronics-based converters (i.e. solar panels, wind turbines…);
- **Modelling of a multi-inverter power system** to analyze its **stability**.

Adopted methodologies

- **Analytical modelling** of the VSG and study of its dynamic behavior;
- **Simulation** of the complete power converter, equipped with digital control using the software **PLECS**;
- Control code and VSG model implementation in C language, ready for a real microcontroller or a prototyping environment, such as dSPACE;
- **Validation** of the designed control on a real grid-tied inverter interfaced to a grid emulator.

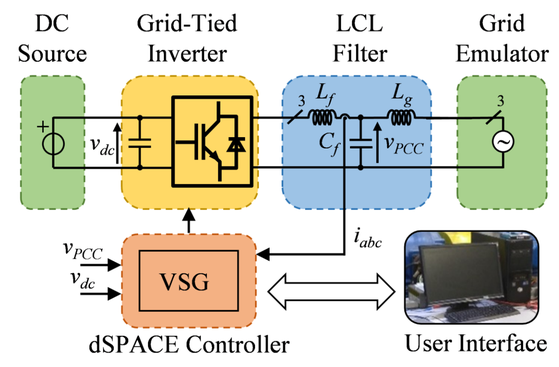

Fig 4. Diagram of the experimental setup. This setup represents an effective case study of an inverter-interfaced energy source (e.g. solar panels).

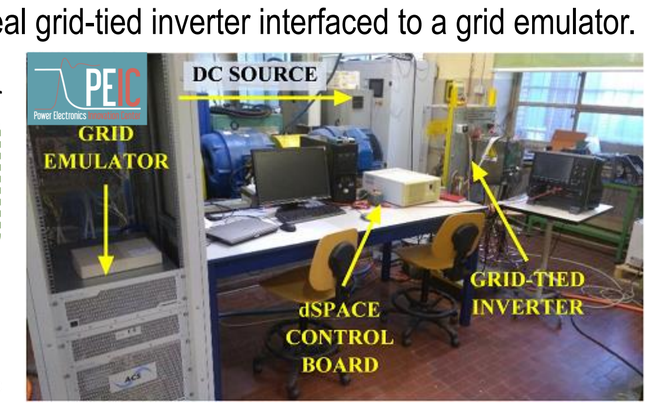

Fig 5. View of the experimental setup. The grid emulator is used to perform tests under emulated grid fault conditions.

Future work

- Analysis of the VSG reactive control in under and over excitation conditions;
- Test of the proposed VSG solution on multiple inverters connected to the same grid;
- Grid forming capability for the proposed VSG;
- Test of the grid forming VSG into a microgrid composed of multiple inverters and local loads.

Submitted and published works

- F. Mandrile, E. Carpaneto and R. Bojoi, "*Virtual Synchronous Generator with Simplified Single-Axis Damper Winding*," 2019 IEEE 28th International Symposium on Industrial Electronics (ISIE), Vancouver, BC, Canada, 2019, pp. 2123-2128.
- F. Mandrile, E. Carpaneto and R. Bojoi, "*Grid-Tied Inverter with Simplified Virtual Synchronous Compensator for Grid Services and Grid Support*," 2019 IEEE Energy Conversion Congress and Exposition (ECCE), Baltimore, MD, 2019, In press.
- F. Mandrile, E. Carpaneto and R. Bojoi, "*VSG Simplified Damper Winding: Design Guidelines*," IECON 2019 - 45th Annual Conference of the IEEE Industrial Electronics Society, Lisbon, Portugal, 2019, Accepted for publication.
- M. Gregorio, F. Mandrile, R. Bojoi, A. Gillone and C. Damilano, "*Fully MCU-Based DCM Control of On-Board Charger*," 2019 International Symposium on Power Electronics (Ee), Novi Sad, 2019, In press.
- S. Rubino, R. Bojoi, F. Mandrile and E. Armando, "*Modular Stator Flux and Torque Control of Multiphase Induction Motor Drives*," 2019 IEEE International Electric Machines & Drives Conference (IEMDC), San Diego, CA, USA, 2019, pp. 531-538.
- D. Piumatti, S. Borlo, F. Mandrile, M. Sonza Reorda and R. Bojoi, "*Assessing the Effectiveness of the Test of Power Devices at the Board Level*," 34th IEEE Conference on Design of Circuits and Integrated Systems (DCIS 19), Bilbao, 2019, In press.
- S. Musumeci, A. Fratta, E. Armando, F. Mandrile and S. Borlo, "*Soft Switching Full-Bridge Isolated Circuit Solution for Auxiliary Power Supply in Power Converter Systems*," IECON 2019 - 45th Annual Conference of the IEEE Industrial Electronics Society, Lisbon, Portugal, 2019, Accepted for publication.
- S. Borlo, D. Cittanti, M. Gregorio, F. Mandrile and S. Musumeci, "*Comparative CCM-DCM Design Evaluation of Power Inductors in Interleaved PFC Stage for Electric Vehicle Battery Chargers*," 2019 7th International Conference on Clean Electrical Power (ICCEP), Otranto, 2019, In press.
- M. Gregorio, F. Mandrile and S. Musumeci, "*Comparative Evaluation and Simulation of Current Control Methods of LLC Converters in EV Battery Chargers*," 2019 IEEE 5th International Forum on Research and Technologies for Society and Industry (RTSI), Firenze, 2019, In press.
- E. Armando, R. Bojoi, A. Fratta, F. Mandrile, S. Musumeci and A. Tenconi, "*H-Bridge Converter as Power Electronics Workbench: An Effective Teaching Case of Learning by Doing*," 2019 International Conference and Exposition on Electrical and Power Engineering (EPE), Genova, 2019, In press.
- S. Musumeci, F. Mandrile, A. Novello, A. Raciti and G. Susinni, "*Very Low Input Voltage Synchronous Coupled Inductor Boost Converter with High Performance Power MOSFETs*," 2018 IEEE International Telecommunications Energy Conference (INTELEC), Turin, 2018, pp. 1-6.

List of attended classes

- 02LWHRV – Communication (15/2/18, 5h)
- 01SHMRV – Entrepreneurial Finance (21/3/18, 5h)
- 03SGVRV – Entrepreneurship and start-up creation from University Research(9/5/19, 40h)
- 01PJMRV – Etica informatica (14/3/18, 20h)
- 08IXTRV – Project management (15/2/18, 5h)
- 01RISRV – Public speaking (15/2/18, 5h)
- 02RHORV – The new Internet Society: entering the black-box of digital innovations (13/3/18, 6h)
- 01QORRV – Writing Scientific Papers in English (21/2/18, 15h)
- 01ROERV – Sensorless control of electric machines (21/1/19, 25h)
- 01SFURV – Programmazione scientifica avanzata in MATLAB (11/4/18, 20h)
- 01RGBRV – Optimization methods for engineering problems (13/6/18, 30h)
- 02ITTRV – Generatori e impianti fotovoltaici (11/4/18, 25h)
- 01LCPIU – Experimental modeling: costruzione di modelli da dati sperimentali(4/2/18, 33h)
- Seminario “Design e topologie di convertitori DC/DC di ultima generazione” (6/3/19, 8h)
- ECPE “New Technologies for Medium-Frequency Solid-State Transformers” (14/2/19, 14h)
- ECPE “Model Predictive Control for Power Electronics, Drivers and Power Grid Applications” (2/7/18, 13h)
- European PhD School 2018 (25/5/18, 30h)

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