MECHANICAL ENGINEERING | PHYSICS | PRESERVATION OF THE ARCHITECTURAL HERITAGE | STRUCTURAL, SEISMIC AND GEOTECHNICAL ENGINEERING | URBAN PLANNING, DESIGN AND POLICY | AEROSPACE ENGINEERING | ARCHITECTURE, BUILT ENVIRONMENT AND CONSTRUCTION ENGINEERING | ARCHITECTURAL, URBAN AND INTERIOR DESIGN | BIOENGINEERING | DATA ANALYTICS AND DECISION SCIENCES | DESIGN | ELECTRICAL ENGINEERING | ENERGY AND NUCLEAR SCIENCE AND TECHNOLOGY | ENVIRONMENTAL AND INFRASTRUCTURE ENGINEERING | INDUSTRIAL CHEMISTRY AND CHEMICAL ENGINEERING | INFORMATION TECHNOLOGY | MANAGEMENT ENGINEERING | MATERIALS ENGINEERING | MATHEMATICAL MODELS AND METHODS IN ENGINEERING

PhD Yearbook | 2023

DOCTORAL PROGRAM IN ELECTRICAL ENGINEERING

Chair:
Prof. Marco Mussetta

The main objective of the PhD Program is to allow a direct, prompt and efficient involvement of PhD graduates in academic and non-academic research and development bodies. A PhD in Electrical Engineering has a solid basic knowledge of applied mathematics and physics. This is essential, particularly for handling and understanding advanced tools and methods as well as for proper modelling, analysis and design of electrical engineering applications, with particular regard to power applications.
A PhD in Electrical Engineering well knows methods and applications in the main disciplines of Basic Electric Circuits and Fields, Power Systems, Electrical and Electronic Measurements, Converters, Machines and Electrical Drives.
The most important part of the PhD program is the development of the research that will be the core of the PhD dissertation.
The main research areas are:
A) **Electric Circuits and Fields:** This area is intended to provide the basic knowledge of methods in electrical engineering for power applications. PhD students are specifically trained to develop critical ability and innovative approaches. The training method encourages the development of discussion and debate skills in a team environment.
The main research and training subjects are: Nonlinear networks and periodic time-variant networks; Analysis of three-phase and multiphase systems; Switching circuits; Electromagnetic field equations; Electromagnetic field numerical analysis; Electromagnetic compatibility; Design techniques devoted to electromagnetic compatibility
B) **Power Systems:** A PhD in the field of Power Systems deals with the following subjects: electrical energy production (e.g., frequency and voltage control, protections, renewable energy sources, Dispersed Generation, Microgrids); electrical energy transmission (e.g., power system analysis, real and reactive power optimization, security and stability, integration of renewables); electricity markets (e.g., models, ancillary services, regulations); power quality and Smart Grids (e.g., harmonic distortion, active filters, UPS, interruptions and voltage dips, DC distribution).
C) **Electric machines and drives:** This research field is strictly related to the rising demand for improved machine and converter performance, in terms of low price, efficiency, robustness, dynamic response and drive control. This need leads to device optimization and better design and testing criteria. Moreover, a system approach is required for accurate integration of technical and economic aspects for final application.
The main subjects in this field are: Use of new materials; Novel magnetic structures; Methodologies of model development for design and operating analysis; Optimization procedures; Use of finite elements code, simulation programs and environments for device study; Control system definition both on the device and system side.
D) **Measurements:** This research field concentrates on the fundamentals of metrology, particularly with respect to characterization of modern measurement systems based on complex digital signal processing structures. Some of the main subjects of study are: measurement methodology as it relates to power systems, including medium and high voltage systems and components, as well as both digital and analog signal processing. Methodologies and measurement systems associated with industrial automation and, in particular, microelectronic sensor applications, distributed structures and advanced methods and algorithms for maintenance-oriented diagnosis of complex systems are investigated in detail.
After graduation, PhD are typically employed at:
- Major research centres;
- R&D departments;
- Power generation, transmission and distribution firms;
- Engineering consultant offices;
- Metrology reference institutes and certification laboratories;
- Process and transport automation areas.

The Steering Committee is made by:

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- FREE2MOVE ESOLUTIONS S.P.A.
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MULTILEVEL POWER CONVERTERS TO INTEGRATE RENEWABLES AND STORAGES INTO ELECTRICAL GRIDS

Marzio Barresi - Supervisor: Luigi Piegari

In this phase of the energy transition, substantial investments aimed at improving the existing electrical grids and power plants-based renewable energy sources (RESs) are necessary to cope with the several challenges arising from this scenario. In particular, there is a need to interconnect several power systems of different natures and located in different regions in such a way as to ensure high stability, reliability and efficiency.
However, the grid integration of renewable energy sources has important implications. Firstly, they are stochastic and intermittent sources; thus, it is complicated to continuously ensure the balance between the power supply and load demand curves. Consequently, grid voltage and frequency fluctuations may arise in the electrical grids. Using large-size energy storage systems (ESSs) is a potential solution to overcome this problem.
Furthermore, the phasing out of synchronous generators leads to an increasing reduction of the power system inertia and, consequently, an increase in system instability events. However, since the converters used to interface renewable energies cannot actively provide inertia support to the system, power electronic converters must be adequately controlled to replicate the behaviour of traditional synchronous machines. For these reasons, to facilitate RESs penetration and comply with strict code regulations, power converters are required to provide ancillary services, such as ride-through operation or voltage and frequency support. Based on the previously mentioned issues, the design and operation of power electronics converters play a crucial role in meeting the grid requirements and growing energy demands and mitigating the effects of global warming. Therefore, the converters integrating RESs or ESSs should be flexible, reliable and cost-effective.
In this regard, modular multilevel converters (MMCs), represent a novel and effective solution to integrate RESs and ESSs into the electrical grids. In particular, compared to traditional two- or three-level voltage source converters, they achieve high voltage and power ratings with reduced switching losses. Additionally, they require smaller output filters and offer high modularity and scalability. Although they feature a more complex structure, the intrinsic converter degrees of freedom can be exploited to optimize the system's performance. This thesis focuses on the operation of MMCs integrating battery energy storage systems (BESSs) and photovoltaic (PV) panels at the submodule (SM) level (Fig. 1). First, an in-depth cost-efficiency analysis of MMC topologies integrating BESSs is performed. In particular, the double-star chopper cells (DSCC), shown in (Fig. 2(a)), and the star-connected cascaded H-bridge (CHB) converter, shown in (Fig. 2(b)), configurations were analyzed. A design procedure is proposed to derive the optimal converter configuration according to the system and efficiency requirements.
The suggested methodology considers different parameters, such as the adopted modulation strategies and SM topology.
To improve the performance of these converter topologies interfacing BESSs through the SMs, specific control strategies are required to balance the internal converter energy.
In this way, it is possible to guarantee the system stability and improve the converter efficiency, avoiding generating undesired harmonics. In this regard, a balancing algorithm for the DSCC converter is proposed. By injecting specific circulating current components, power transfers between the upper and lower arms and among the legs of the converter are established, equalizing the energy of the BESSs interfaced through the converter SMs. Additionally, a dynamic saturation of these components is provided to respect the system constraints without degrading the balancing performance.
The MMC structures can be effectively exploited to integrate PV arrays in each converter SM. In this way, a distributed maximum power point tracker (DMPPT) can be adopted, consequently improving the PV power production, especially under partial shading conditions. Novel DSCC-based PV single-phase and three-phase system topologies were proposed and investigated. Additionally, a hybrid solution is examined, including a BESS interfaced through the converter DC-side and PV arrays through the converter SMs. After analyzing the main current and voltage components necessary to maximize the energy extraction, the converter control structures were derived. In particular, in case of internal power mismatch, the circulating currents are generated to extract the maximum PV available power. For the DSCC three-phase system integrating PV arrays exclusively, a novel topology, including a capacitor connected to the converter DC-side is proposed. In this way, since the three converter phases are decoupled, when in the case of non-homogeneous irradiance conditions, it is necessary to inject the circulating currents, lower power losses are experienced.
Lastly, the DSCC-based PV three-phase system operating in grid-forming mode is investigated. In this operating condition, the converter is not required to work at the maximum power point. However, it behaves as a controllable voltage source establishing the network voltage and frequency and providing full grid support based on the power reserve availability. As previously mentioned, a distributed approach can be achieved with this converter configuration, improving PV power production. Based on that, exploiting the circulating current injection, the power reserve allocation can be differently performed among the converter arms, maximizing the converter support capability. In this regard, an optimization-based power reference calculation is proposed to minimize the converter's circulating currents while meeting the grid requirements according to the ambient conditions.

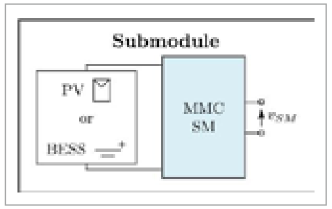

Fig. 1 -BESS or PV panels interfaced through the converter SM.analysed.

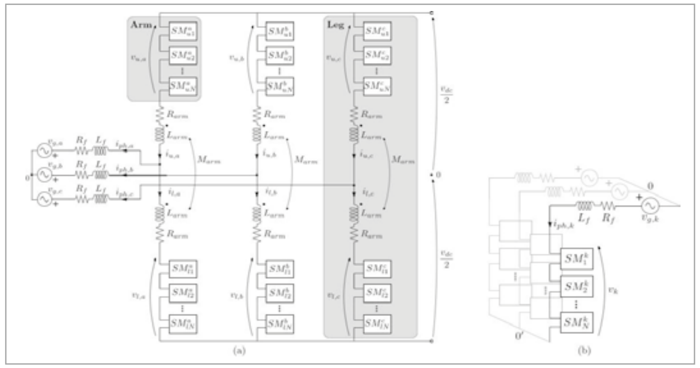

Fig. 2 - MMC topologies. (a) Double-star chopper cells converter; (b) Star-connected cascaded H-bridge converter.

ABATE THE BARRIERS : OPENING ELECTRICITY MARKETS TO STORAGE AND RES

Giuliano Rancilio - Supervisors: Maurizio Delfanti, Marco Merlo

The work considers the electricity markets in the presence of Battery Energy Storage Systems (BESS), Renewable Energy Sources (RES) and Distributed Energy Resources (DERs). It aims to provide a panoramic view of the possible regulatory evolutions of electricity markets, with particular focus on the Ancillary Services Markets (ASMs). The state-of-the-art of ASM and of the electricity balancing is reported, with focus on the standard balancing products for frequency control. The main stakeholders of the ASM are described: the System Operator (SO) and the Balancing Services Provider (BSP). A systematic review of sources is performed to assess the possible trade-offs in the ASM evolution, considering both the perspective of the SO and the BSP. The analysis qualitatively returns the compatibility of the ASM framework with DERs and BESS and detects the possible regulatory barriers for their effective participation. To quantitatively assess the performance of BESS in the provision of ancillary services, a numerical model of BESS is developed. This is aimed to overcome a set of lacks found in the battery models present in literature, that makes them unsuitable to be used for testing ASM participation. The model is a multi-parameter empirical model based on an experimental campaign on a real-world asset. The model parameters return the overall performance of the system, included the impact of the power conversion system and of auxiliary systems. The influence of the finite energy content of BESS on the provision of ancillary services is assessed. The importance of strategies for managing the energy content is highlighted, by proposing a comparative analysis among state-of-charge (SoC) management strategies. The analyzed strategies are defined "explicit" since they consider additional energy flows exchanged with the grid with the explicit purpose of restoring the SoC. The limitations of the explicit SoC management strategies enhance the interest for "implicit" strategies. A Multiservice Strategy is developed for providing SoC management via an additional (and remunerated) market service. The Multiservice Strategy exploits dynamic service stacking and guarantees revenue stacking. It is proposed and evaluated on two case studies. Then, the implicit SoC management strategy based on Multiservice is compared with the explicit ones. The BESS model and the previously presented analysis on the evolution of ASM are used to estimate the optimal ASM arrangements for the provision of services by BESS. Two different services are tested along with a set of ASM parameters, recognized as potential regulatory barriers.

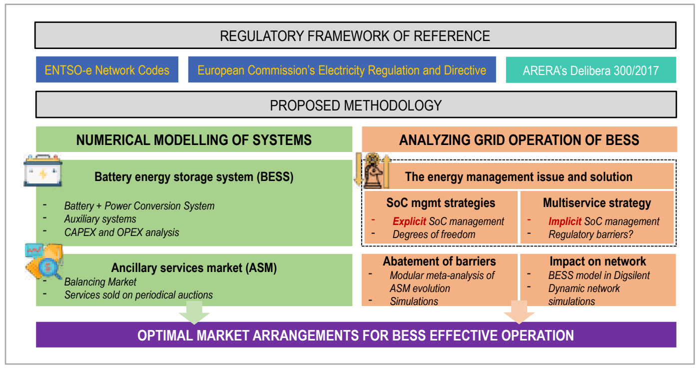

Fig. 1

The ASM arrangements are evaluated in terms of the flexibility that can be provided by the resources and the reliability of the provision. The optimal values of the ASM parameters for each type of service are returned. Finally, to check if the BESS participation in electricity balancing brings advantages to the system, the provision of frequency response by BESS is tested with a power flow analysis tool. Dynamic simulations are performed and the results are appraised in terms of quality of service (i.e., frequency nadir after an incident) and system needs (i.e., needed regulating power) in case of frequency regulation by either conventional thermal power plants or BESS.