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PhD Yearbook | 2022

Chair:
Prof. Marco Mussetta

DOCTORAL IN ELECTRICAL ENGINEERING

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.

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UNITED WE STAND: HOW AGGREGATES OF DISTRIBUTED ENERGY RESOURCES CAN SHAPE THE FUTURE ENERGY SYSTEM.

Filippo Bovera - Supervisor: Prof. Maurizio Delfanti - Co-Supervisor: Elena Fumagalli

The thesis work deals with the possibility to integrate the optimization of Smart Multi Energy Districts (Smart MEDs) operations with the provision of dispatching resources to the public grid under the form of frequency regulation and balancing services. This is achieved introducing a multi-stage optimization framework, so-called General Advanced Intelligent Architecture (GAIA), where decision steps are linked to balancing market's sessions timing.
The Smart MED should firstly evaluate the cost-opportunity of providing balancing capacity resources within balancing market auctions held every week (Long-Term Scheduling). Results of market auctions impose a capacity retention level to the day-ahead problem (Short-Term Scheduling). Its target is twofold: first, to calculate the optimal exchange program with the public grid, thus defining the offers to purchase or sell to be presented on Day-Ahead Market (DAM) sessions; second, to set the optimal bidding profile for the integrated scheduling phase of the Ancillary Services Market (IS ASM). Differently from the LTS problem, the STS one is addressed with a stochastic approach. Market realization scenarios for the stochastic problem are generated through a novel statistical tool, applied to Italian balancing markets, where a Random Forest algorithm is coupled with a Monte Carlo approach to produce expected market's results, which are then clustered to obtain a set of reference market scenarios for the STS problem.
Chapter 1 introduces the concept of Smart MED, including it within the current and future energy system. Starting from a general overview of the energy transition , the chapter focuses on European and Italian policies implemented to reach decarbonization targets fixed by the Clean Energy Package (and updated by the Green Deal more recently).
Chapter 2 focuses on the role that electricity markets evolution has within the power system decarbonization process. The European perspective is described moving from network codes and guidelines recently approved, in particular concerning balancing markets design. The Italian electricity spot markets design is then introduced. Inherently, the Italian Regulatory Authority has recently (2019) defined in a consultation document (DCO 322/2019) the main intentions regarding electricity markets' reformation: this is hence discussed dealing with both market's products characteristics and roles of the different power system actors involved. The remainder of the chapter is dedicated to an in depth analysis of two concepts: Distributed Energy Resources (DERs) and aggregators.
Chapter 3 presents the GAIA domain, together with the fundamental set of constraints regulating its optimization procedure. The core of GAIA lays in the definition of the physical electricity exchange with the public grid, which results from the commercial trading of energy carried out in spot markets. Concerning district's energy assets, the optimization procedure can host: photovoltaic and solar heating plants, energy conversion facilities (internal combustion engines, heat pumps, compression chillers, absorption chillers, boilers), energy storage technologies (electricity, heat and cold) and electric vehicles.
In particular, electrochemical storages are modelled through a novel approach where performances depend on both the battery's state-of-charge and the requested charge/discharge power. Also, the optimization problem introduces a detailed modelling of natural gas and electricity bills: this is fundamental considering practices such as peak-shaving or load shifting, where it is important to properly value all the components of the bill (variable, power and fixed fees). The end of the chapter specifically discusses how Long-Term and Short-Term Scheduling problems have been addressed.
Hence, Chapter 4 is dedicated to the description of the statistical tool developed to generate market realization scenarios. The chapter investigates a novel approach based on a Random Forest algorithm.
Firstly, a set of input features is elaborated starting from available data concerning: power system structure, energy markets results, weather conditions and market participants' bidding strategies. The market realization forecast model is then trained on data from North Italy bidding zone (looking at the case study location). The developed model still shows some performances improvement possibility, especially because of the very high imbalance between the number of bids rejected and accepted on the Italian ancillary services market. To cope with model's performances, and exploit it to generate market's realization scenarios for the STS stochastic problem, a novel approach is applied. The Random Forest forecast is corrected through out-of-bag errors randomly sampled from the model's training process; this way, it is possible to fit the model on an input sample many times, obtaining different predictions, which are directly influenced by the model accuracy. Hence, exploiting a Monte Carlo approach, it is possible to generate a set of market realization scenarios, whose distribution can be used as a proxy for market results uncertainty. Finally, to synthetize some reference market scenarios for the stochastic procedure, clustering techniques are exploited, and the occurrence probability of each cluster (hence of each reference scenario) is calculated based on the cardinality of the cluster itself.
Chapter 5 is dedicated to the description of the case study used to test GAIA's LTS and STS procedures. This is the university campus of Leonardo, the headquarter of Politecnico di Milano. Leonardo campus hosts a private MV electricity network, a district heating and a smaller district cooling network. In 2015, a cogeneration power plant (rated 2 MW_{el}) has been installed, together with some boilers (current installed capacity of 12 MW_{th}) and an absorption chiller (1.4 MW_{cool}). With a yearly consumption of 12 GWh of electricity, 10 GWh of heat and 5 GWh of cold, Leonardo campus is one of the main Italian Smart MEDs in the tertiary sector. Its degree of complexity is expected to increase in next years thanks to the installation of: electric vehicles' charging points, thermal and electrochemical storages and a relevant photovoltaic generation capacity. Based on these information, five reference weeks have been selected to fairly represent the yearly activity within the campus.
Finally, Chapter 6 reports the results obtained from the LTS and STS testing. The LTS procedure is tested on three main reference assets' configuration (namely Horizon 2021, 2024 and 2026). Additionally, a sensitivity analysis on the main parameters characterising the weekly balancing auctions is included.
First, diverse prices for balancing availability are tested on both upward and downward provision. Second, balancing availability period is moved from load-ramping periods of working days (morning and late afternoon) to the weekend. Last, the minimum duration required for the balancing service is changed, influencing the exploitation of limited energy content technologies.
The second part of the chapter is dedicated to STS procedure. STS testing focuses on two specific days: a winter (December the 16th) and a summer day (June the 24th). First, the STS optimization problem is solved through a deterministic approach; then, a stochastic procedure is applied to find the optimal market scheduling (DAM program and ASM bids) based on a set of possible balancing market scenarios. Considering a real market realization, randomly sampled from all possible scenarios, the two approaches are compared in terms of: capability to respect upward and downward balancing calls, imbalance volume realised and value of the objective function. Hence, the last chapter is dedicated to a discussion of the main evidences from the thesis work.

MODULAR MULTILEVEL CONVERTER WITH INTEGRATED STORAGE SYSTEM FOR AUTOMOTIVE APPLICATIONS

Davide De Simone - Supervisor: Prof. Luigi Piegari

Battery-powered vehicles are composed of many power converters. The most relevant are the traction drive, the battery management system (BMS), and the on-board battery charger.
In power electronics, double star chopper cell (DSCC) converters, Fig. 1, are mostly known for their application in high voltage transmission systems. DSCC converters are a kind of modular multilevel converter (MMC), characterized by the presence of an accessible dc-bus. In the last decade, some researchers demonstrated the possibility to use a DSCC to realize a traction drive inverter integrating batteries. The use of DSCCs in battery electric vehicles (BEVs) comes with the advantage of replacing the three power converters functionalities with one highly modular and easily scalable device.

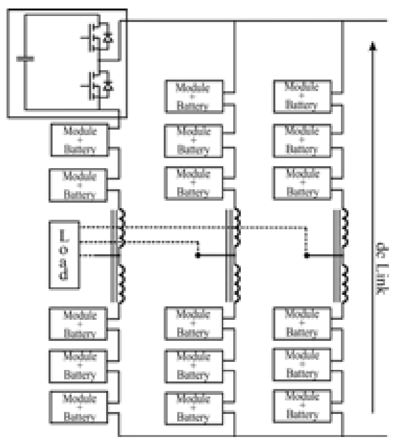

Fig. 1
DSCC converter.

Over the last decades, advancements in battery technology and power electronic devices favoured the spread of BEVs. Although some research has already been done, DSCCs are still not optimized for battery integration and variable speed drives. This thesis proposes last level PWM (LLPWM) and windowed PWM (WPWM), two modulation techniques designed for MMCs. Their aim is to improve the powertrain efficiency by applying PWM on specific portions of the multileveled output waveform. LLPWM modulation reduces converter switching losses by triggering the PWM modulation on the top last module that composes the output voltage which corresponds to the lowest derivative regions of the output waveform. Although a reduction in converter losses was achieved, the simulations highlighted that the total harmonic distortion (THD) on the output waveform was degraded. Since a variable speed drive equivalent circuit is highly dependent on the instantaneous working condition, for particular operating points, the distortion introduced by LLPWM might not be acceptable. For that reason WPWM, a generalization of LLPWM was proposed. Similarly to the approach of LLPWM, WPWM applies PWM modulation on specific regions of the output waveform. In WPWM the PWM triggering is angle-based rather than module-based. If the space vector of a three-phase reference is considered, WPWM applies PWM when the space vector is within certain, user-selectable, angle ranges. In the newly proposed WPWM, the PWM region is not discretized and is independent on the number of modules installed in the converter. WPWM performance in terms of voltage distortion and converter efficiency was tested through simulations and validated using a small-scale prototype. In future implementations, lookup-tables that relate the drive system's working condition to the highest efficiency PWM window can be precomputed and used to improve the global powertrain efficiency.
When a DSCC operates, its dc-bus voltage is fixed. In a variable speed drive, constant dc-link voltage implies that all the converter modules are operating even when the motor speed and the related voltage are below the nominal.
Lithium-based battery wear can be related to the net charge exchanged. Since in a battery-powered system, the battery pack has a significant impact on the system cost, battery pack wear is a major concern; in this thesis, variable dc-bus voltage control and common mode voltage (CMV) injection, two DSCCs control strategies focused on the reduction of battery stresses, were proposed.
Variable dc-bus voltage control adapts the converter dc-bus voltage to the instantaneous output voltage, reducing the number of modules connected to the system. The control strategy was validated by simulating a BEV with NEDC and SC03 driving cycles. Results highlighted up to 45% increase in the travelled distance before battery degradation.
Some research identified a link between battery wear and the thermal effects related to current harmonics. The structure of DSCC converters injects a current second harmonic component within the modules. This thesis proposes a hybrid DSCC structure capable of shifting the second harmonic toward higher frequencies, making it feasible the filtering process.
In the last decade, the spread of BEVs experienced exponential growth. In the next years, recharging facilities will have to face new challenges to increase the delivered power and to be able to satisfy the growing energy demand. One of the more critical aspects will be to follow the power ramp rates expected when one or multiple vehicles are connected to the grid within a short time. By integrating batteries within the charging station, it is possible to smooth the power ramp and offer to the vehicles a charging power higher than the one provided by the grid. This thesis proposes a control strategy for DSCC capable of decoupling the power on the ac-port and dc-port of the converter. Moreover, the converter's multilevelled output waveform enables a direct connection to the grid, reducing the transformer-related costs. The concept was validated by simulating a one-dock charging facility that charges three vehicles with different specifications in a row. One of the vehicles presents a charging power higher than the power available on the grid point of connection. Simulations highlighted that, by using proper algorithms, the DSCC converter could exploit the internal battery as a buffer without compromising the power exchanges with the other ports.
The design and build of a small-scale, 6 modules-per-arm, 14kW prototype was done, Fig. 2. This work covers the main steps in the design process and the main challenges faced during the prototyping process.

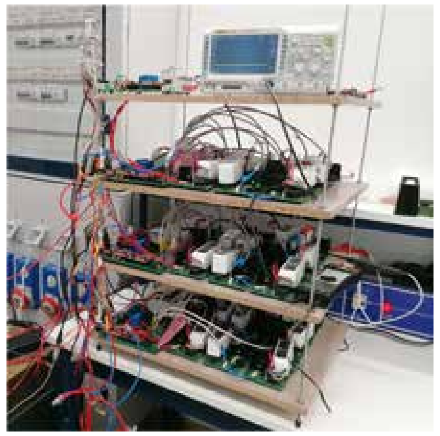

Fig. 2
Modules DSCC prototype.

Among all the challenges related to the development of the converter, the high number of input and output ports of the control hardware required to realize the control platform with four devices. Splitting the control hardware among multiple microcontrollers introduced many issues in terms of high speed data transfer, data integrity in presence of electromagnetic noise, microcontrollers synchronization and, lastly, fault management. By solving these criticalities the prototype was finally operative and validated by driving an induction motor with a V/Hz control strategy to follow a custom speed profile.

SIMULATION AND ANALYSIS OF MODULAR MULTILEVEL CONVERTERS BASED ON ISOMORPHISM AND PERIODIC SMALL-SIGNAL ANALYSIS.

Davide Del Giudice - Supervisor: Prof. Federico Bizzarri

The current shift in generation mix towards renewable energy sources, typically interfaced to the grid through power electronics converters, is significantly changing many facets of modern electric power systems, such as planning and operation. In this context, power system simulation is crucial because it enables scholars and power system operators to investigate the fast dynamics of converters, their controls, and interactions with traditional power system elements. However, to do so in a fast and accurate manner, conventional simulation tools need to be updated by implementing techniques specifically tailored for converters.

Despite being relatively new in the power system field, semiconductor devices inside the converters have constituted the basic building blocks of electronic systems for a long time. Some of the challenges given by the increasing integration level and downscaling of these components have already been addressed in the field of electronics by developing a family of accelerated transistor-level simulators, known as FAST-SPICE simulators. These simulators resort to ad hoc innovative heuristics, unique methodologies, and computational techniques, which implement different trade-offs between simulation speed and accuracy to attain a significant gain in simulation efficiency and capacity compared to the traditional version of SPICE. The logical follow-up would be to apply these solutions to simulate modern electric power systems. However, this is not an easy task, because it requires overcoming a certain reluctance from power system experts and scholars to update the established tools offered by conventional power system simulators, such as PSCAD, EMTP-RV, and DIGSILENT.

The main goal of this research project was the exploitation of two techniques originally developed in the field of electronics, namely the isomorphism-based approach and the periodic small-signal analysis, to efficiently simulate and analyse converters in electric power systems. In particular, the project focused on the modular multilevel converter (MMC). This technology was chosen because it has become a hot topic in the research community over the last few years. Its distinctive feature is the presence of a stack of up to several hundreds of identical submodules (SMs) in each of its arms. On the one hand, this modular structure grants the MMC reduced switching losses and scalability to high voltage and power ratings, which contributed to making it a popular technology in high-voltage direct current (HVDC) systems. On the other hand, the MMC topology and its complex control schemes pose several challenges in standard power system simulators tasks, such as power flow analysis, initialisation, electromagnetic transient simulation, and small-signal analysis. The research activity was mainly devoted to these last two aspects and originated in a PhD thesis consisting of four chapters and an appendix.
After a brief overview of different multilevel converter technologies proposed in the last decades, **Chapter 1** focuses on the MMC by describing its most relevant properties and a typical control architecture. In the Appendix, additional details are provided on how to modify the control scheme to make it compatible with unbalanced operating conditions. Then, the chapter summarises the main challenges posed by MMCs from a power system simulation and analysis perspective.

Chapter 2 presents the main models available in the literature to simulate MMCs. In addition, the MMC simulation approach based on sub-circuit isomorphism - one of the main aspects of the research - is explained. This approach, originally conceived to analyse modular electronic circuits such as RAMs, can be profitably exploited to simulate MMCs, since it exploits the common behaviour of structurally identical SMs by clustering them together. Each model and simulation method is described in terms of the degree of accuracy retained, computational burden incurred, and the most suitable types of analyses that it can carry out.

The isomorphism-based approach is validated in **Chapter 3** by simulating an HVDC benchmark system comprising two MMCs in several scenarios, ranging from normal operating conditions to symmetrical and asymmetrical AC and DC-side faults. These scenarios demonstrate the three following features of the proposed approach. First, the method is compatible with any submodule (SM) model, ranging from the simple bi-value resistor to the detailed full physics one. Second, this approach allows performing detailed simulations of MMCs in a reasonable CPU time. Indeed, the method minimizes the number of SMs to be simulated and, thus, of equations to be solved at each time step of the time domain analysis. As a consequence, this allows boosting simulation speed significantly while ensuring high simulation accuracy and retaining the individual behaviour of each SM. Lastly, regardless of the SM model adopted, the computational burden of the proposed method increases only linearly with the number of SMs in each MMC arm. This is in sharp contrast with conventional simulation approaches, where this trend evolves almost quadratically. It is worth highlighting that this feature is attained without simplifying neither the SM model nor that of the entire MMC, as instead is done in several accelerated simulation models in the literature.

In Chapter 4, the focus shifts on MMC small-signal analysis. To begin with, the most popular approaches to small-signal analysis in conventional power systems are introduced. Then, the chapter explains why these approaches are generally incompatible with grids comprising converters (MMCs included) and how they were modified in the literature to address this issue. The periodic small-signal analysis (PAC) is proposed as an alternative: despite being widely adopted for a long time by electronics designers, this technique - which is implementable directly at the simulator level- still represents an uncharted territory in the power system realm. After a theoretical introduction, the chapter explains how to apply this method to MMCs. Being a numerical method directly implemented at the simulator level, PAC analysis requires neither extensive pen-and-paper computations nor simplifications in the model of the system under analysis. In addition, the method can take into account intermodulation and frequency up- and down-conversion of a perturbing signal in the frequency spectrum. To showcase the potentialities of PAC analysis, the same benchmark system of the previous chapter is considered in different scenarios.

In summary, the results reported in the PhD thesis prove that the isomorphism-based simulation approach and periodic small-signal analysis can be profitably applied to MMCs. The former methodology is ideal for fast and efficient electromagnetic transient simulation of MMCs during component and system-level studies, which typically require detailed SM models. On the contrary, the latter approach is a promising solution for performing stability analyses of large or complex power grids, such as HVDC systems. Since it is a numerical method, PAC analysis has general validity and does not require simplifying the power system under study. Another feature worthy of note is its versatility: whenever changes in the analysed network occur, PAC analysis must be simply run again on the simulator to gather new results.

OPTIMIZATION IN ENERGY MANAGEMENT SYSTEMS: AN INDUSTRIAL PERSPECTIVE

Lorenzo Meraldi - Supervisor: Prof. Sonia Leva - Co-Supervisor: Ing. Pietro Raboni

The decrease of heat in the higher regions of the air does not cease to take place;
it is thus that the temperature is augmented by the interposition of the atmosphere, because the heat finds fewer obstacles in penetrating the air, when it is in light form, than in re-passing when converted into infrared form. In 1827 Fourier in his "Mémoire sur les températures du Globe terrestre et des espaces planétaires" was the first one to indicate the atmosphere as the main element increasing a planet's surface temperature. This intuition was more related to his quest for a universal theory of terrestrial temperatures for his work on the analytic theory of heat, rather than an actual research on climate change.

Nevertheless, the idea that the atmosphere is absorbing the radiative heat emitted by the Earth surface has been pivotal for the researcher of the late 1800. Arrhenius already at the end of the century made the first quantitative prediction of global warming caused by a hypothetical doubling of the carbon dioxide contained in the atmosphere. However, for the whole first half of the 20th century, the relevant role of CO2 in the energy balance of the atmosphere was not widely accepted. The advent of numerical models and computer power allowed to increase the climatologist simulation ability and thus the public awareness of the threat related to human-induced climate change: in 1988 the IPCC was established by the United Nations to provide objective scientific information relevant to the full understanding and monitoring of climate change. The latest 2021 AR6 IPCC report, clearly states that the CO2-induced climate change is already affecting many weather and climate extremes in every region across the globe. There is evidence that the observed changes in extremes such as heatwaves, droughts, floods, and tropical cyclones can be attributed to human influence and principally due to CO2 concentration increase in the atmosphere. The global surface temperature will continue to increase until at least the end of the century even considering a very low greenhouse gas emission scenario, with CO2 emission declining to net zero around 2050. Global warming of 2°C will be exceeded during the 21st century unless deep reductions in CO2 will occur in the coming decades. This projection requires an even increased effort to reduce greenhouse gas emission in the coming years.

According to IEA, in 2020 the global share of CO2 has been related mainly to the power generation sector (40 %), followed by transport (23 %), industry (23 %) and building heating (10 %). Coal power plants are the major source of emission accounting for 29 % of all the global emissions, moreover they constitute nearly 75 % of the whole emission of the power-generation sector. In the last decade RES, in particular solar PV and wind, have established themselves as the major clean technologies to replace carbon-based power generation. As of today, in some area of the world, PV is the cheapest energy source: in the middle east several PPA have been signed with tariff lower than 15 $/MWh, with a record-low of 10.4 $/MWh. Moreover, in contrast to all other fuel-based technology, renewables have grown by almost 7 % in 2020, showing an unexpected resiliency to the undergoing Covid-19 pandemic and the light decline of electricity demand. Even if long-term contracts and priority access to the grid underpins continuous installation of new plants and a stable growth in renewable installation markets, as of today the share of renewables in electricity generation does not overcome 30 %, with a 2020 record-high of 29 %.

The falling cost of renewable plants is pivotal to give an economically sustainable and viable alternative to conventional carbon-based generation. Nonetheless, it is worth noticing that from a technical perspective a high penetration of renewable poses some concerns about system stability. In fact, the potential of renewable generation is variable in nature since it depends intrinsically on non-controllable environmental quantities. Thus, a shortage in renewable generation may jeopardize system stability due to an unbalance between electrical generation and load demand. This issue has already been tackled in remote areas local grids, that were not connected to stable national grids. In these cases in fact, the high cost of fuel made renewables very competitive with respect to conventional diesel generators making fundamental the maximization of renewable generation share also for economic reason. To face system instability induced by the larger and larger renewable penetration, it has been necessary to install ESS, usually based on battery technology, able to compensate the variability of renewable generation.

Lately BESS technology has become an economically viable solution to solve renewable intermittence not only in remote areas but also in highly renewable-penetrated national grids. In fact, pushed by the electric mobility sector, Li-Ion battery technology has made over the last 10 years great strides with increased performance, extended lifetime and a simultaneous dramatic decrease of costs. Battery module prices has declined by almost 90 % between 2010 and 2020 passing from 1190 $/kWh to 137 $/kWh. This increased competitiveness of BESS has thus enabled the development of grid-connected applications, including both residential BTM and FTM systems. According to market evolution predictions, the FTM segment will be the major growth driver going forward in the next years, with a diverse set of services that will be targeted by the BESS: capacity reserve, frequency regulation, other ancillary services and, of course, renewable enhancement. This last application will involve mainly the combination of large solar plants and batteries to provide a more dispatchable and flexible renewable generation with an increased value in the overall power mix. It is worth noticing that, due to their composition and complexity, these new generation plants will involve many aspects that have been already developed for microgrid operation.

The increased competitiveness of renewables will revolutionize the power generation mix not only from a hardware perspective, but also from a software point of view. In fact, the coordination of such non-controllable sources with other complementary energy resources such has storages, generators and dispatchable loads is an extremely complex problem that requires predictive optimized control and management techniques to allow a strategic and efficient operation of the whole system from both an economical and sustainable standpoint.
In this framework, the development of advanced industrialized predictive management algorithms that optimizes and coordinates different energy sources, in both on-grid and islanded applications, is pivotal to complete the energy transition for a greener future.

This thesis focuses on the development and industrialization of optimization algorithms for microgrid management that leverage on demand and renewable generations power predictions for achieving improved performances. The work has been carried out in the context of PROPHET project, a collaboration between NHOA (Formerly EPS and ENGIE-Eps between 2018 and early 2021) and Politecnico di Milano. The proposed algorithms have been assessed in simulation environment, tested on PROPHET experimental facility and then industrialized in a real product, completing the technological transfer that is required to an industrial PhD.

DATA-DRIVEN FRAMEWORK FOR INTEGRATION ELECTRIC VEHICLES CONSIDERING PHOTOVOLTAIC SYSTEM AND POWER QUALITY DISTORTIONS BASED ON ADVANCED MACHINE LEARNING AND BIG DATA METHODS

Miraftabzadeh Seyed Mahdi - Supervisor: Prof. Michela Longo

Climate change is the most urgent issue humankind is confronting today. Carbon emission reduction is the inevitable only solution to improve climate stabilization. In contrast to the conventional internal combustion engine vehicles, which are one of the main responsibles for CO2 emission, e-mobilities produce zero tailpipe emissions. This dissertation studies problems arising in integrating electric vehicles (EVs) and analysis solutions for the transition toward EVs while using Renewable Energy Resources (RESs) to re-charging batteries, Fig. 1. The general objective of this dissertation is to design a data-driven schema to estimate the amount of energy obtained from RESs to charge EVs in advance, while Power Quality (PQ) distortions are taken into account. This study presents an innovative approach to determine the energy consumption of EVs in the future and predict renewable energy generations in the medium range accurately. The data-driven framework is designed to address three classes of the problem for integrating EVs in the power system and charging them with RES considering the following guidelines: interoperability, modularity, scalability, and usability.

The first class of problem is related to EV energy consumption prediction for single and large-scale cars. Two different methods to acquire the driving information of people from the real world to forecast EVs' energy consumption are proposed. The first proposed model, Fig. 2, uses Google Map API and weather information to build a dataset; then, based on this information, two Machine Learning (ML) models, namely decision tree regression and multilayer perceptron, are developed to predict the energy consumption of EVs with high accuracy.

Secondly, a real dataset of taxis is utilized to model the driving movement patterns and estimate the energy consumed by these taxis if they were an electric model. One of the main outcomes of this study is the identification of demand patterns at any time intervals (day, month, or year) with any desired level of accuracy to adjust the power generation's schedules and prevent any disturbances due to the consequences of charging a massive amount of EVs simultaneously.

In the Second class of problems, the Photovoltaic (PV) power generation of a parking lot was studied to build an accurate a-day ahead prediction model. PV power generation prediction can efficiently improve the quality of operational scheduling of PV power plants to assure charging EVs with green energy sources. Two models are proposed for online prediction while the historical PV dataset is unavailable and a high-resolution offline prediction considering all PV and meteorological information. The results indicate the reliability and accuracy of two predictive models for a day-ahead PV prediction.

Fig. 1
The overall view of a smart city from the power system point of view

Lastly, this study analyzes the synergic dataset of power quality distortions to make the automatic fast-response classification system for distributed systems such as parking lots connected to RESs such as PVs. In order to increase the speed of classifiers in the big data domain, the importance of each impact feature was analyzed and investigated. Eight dominant features out of twenty-five were identified. The results show that classifiers perform their tasks in seconds with the same accuracy in all corresponding datasets by considering only these eight dominant features.

This thesis presents various original and innovative data-driven frameworks for integrating EVs considering PV systems and PQ distortions based on ML and big data methods. All developed methods and models achieve high accuracy, efficiency, reliability, and scalability since they are developed with big data tools having powerful computational speed capacity.

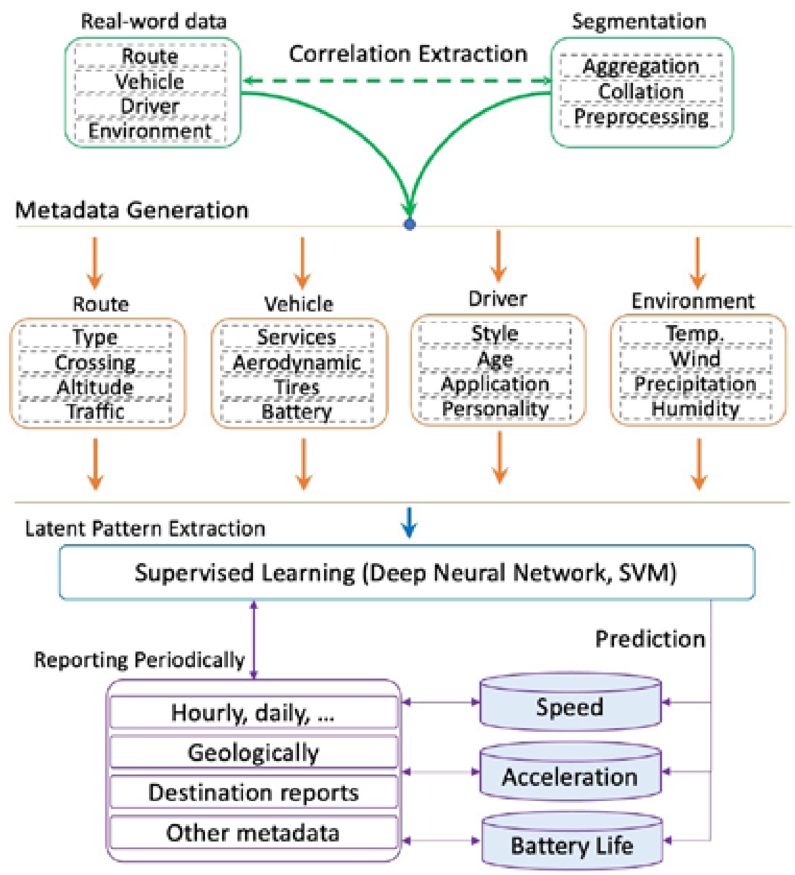

Fig. 2
The proposed framework for energy consumption prediction of electric vehicles.

HOLISTIC MILP MICROGRID PLANNING FOR RURAL ELECTRIFICATION

Marina Petrelli - Supervisor: Prof. Alberto Berizzi

Introduction
An extensive adoption of microgrids is crucial to reach universal access to electricity by 2030. Standard planning algorithms identify the least-cost solution and its corresponding optimal design and operation of the plant. This research aims at filling literature gaps, concerning both the way the microgrid planning problem is described and the mathematical programming tools adopted to identify the optimal solution. Hence, two objectives are pursued:
1. Formulate a holistic MILP (Mixed Integer Linear Programming) microgrid planning model, describing the full project lifetime and enabling an informed and comprehensive decision-making process, accounting for long-term uncertainty.
2. Develop novel algorithms enabling the use of MILP methods for complex and computationally-intensive applications.

A. Methodology
Three main issues are addressed: (i) representing the whole project lifetime including asset degradation within MILP algorithms, (ii) broadening the decision process to environmental and social criteria, (iii) accounting for the long-term uncertainty of demand patterns. The algorithm is tested on an isolated community in Soroti, Uganda.

i. Iterative MILP considering storage degradation
The proposed methodology is based on an iterative approach with a MILP planning core that accounts for a detailed modelling of the battery efficiency and degradation. Hence, the MILP cost minimization is not directly used in a single shot, as in the literature, but it is embedded in an iterative scheme updating degradation parameters for the purpose of accuracy, while preserving tractability. By doing so, the burden of each MILP problem is significantly reduced, but the overall approach is able to simultaneously take into account both the operational planning and the degradation of the asset performances over time, which in turn depend on the hourly scheduling.
The proposed iterative multi-year procedure (IMY) is compared with the same iterative multi-year procedure when neglecting the effects of battery degradation and variable efficiency (IMYwoB). The Net Present Cost with IMY is approximately 16% higher than IMYwoB, which suggests that neglecting such phenomena may lead to a suboptimal design of the system. As a matter of fact, in IMYwoB, the load is largely powered by renewable sources, due to a larger PV plant supported by storage. In the real operation, the battery degradation would reduce the capability of the system to defer to the renewable production; hence, increased reliance on the fuel generator or higher ENS (energy not served) are likely to occur. By considering battery degradation and variable efficiency since the planning phase as in IMY, the result will be tailored to the actual system's behaviour; in fact, the optimizer tends to employ more diesel and to leave a less prominent role to PV and BESS.
In order to stress the efficiency of the procedure, it has also been compared with a One-Shot Multi-Year (OSMY), i.e. a standard literature-based methodology equivalent to IMY but developed in a full MILP environment with no iterative algorithm. OSMY has not converged within the time limit of 5 days. This underlines the complexity for standard MILP formulations to handle the proposed planning problem, while the IMY approach successfully converged in 6.9 hours, reaching the target tolerances in 3 iterations. Therefore, the gain in terms of tractability of the algorithm is impressive. The quality of the results has been validated by comparing IMY and OSMY using typical days, highlighting an NPC difference below 1%.

ii.Multi-objective optimization for comprehensive decision making
A further step towards a comprehensive analysis consists in broadening the decision process. In particular, four additional objectives have been added: minimization of CO_2 life cycle emissions to account for global environmental impact and compliance with national strategies, minimization of land occupation to account for local environmental impact, maximization of job creation to account for socio-economic impact, maximization of street lighting to account for improvement in safety and social life.
Most of the recent literature still considers AUGMECON2 as the most up-to-date and efficient development of theε-constraint method, a well consolidated methodology suitable for MILP multi-objective optimization. However, the approach presents some drawbacks: (1) the number of points to be analysed grows exponentially with the number of objective functions and the desired density of the Pareto curve; (2) the results tend to present conglomerates of very similar points and therefore not of interest. The latter is usually dealt with by applying post-optimization filters or clustering algorithms, without addressing the first problem, but rather intensifying it. The novel Advanced-AUGMECON2 (A-AUGMECON2) is developed to face these two main shortcomings, in order to provide better computational performances and improved readability of the Pareto frontier by means of an online filter of redundant optimizations.
The most relevant takeaway of the results of the multi-objective optimization is the significant similarity of the points at minimum NPC and emissions. The cost decrease of RES generators and storage has led least-cost solutions to be characterized by high renewable fractions (> 80%) and limited emissions. Total public lighting coverage increases costs by less than 20%; it may be considered as an affordable service, depending on priorities and budget constraints, to be recommended to decision makers. If restrictions limit the initial investment, a higher reliance on fuel-fired generators allows reducing upfront costs. Fuel-based options are also characterized by limited land use and high employment opportunities, because of consistent O&M needs and fuel procurement operations.

iii. Stochastic optimization and multi-step sizing
Rural electrification projects are characterized by a significant long-term uncertainty, as their outcome is influenced by socio-economic and environmental factors which are hardly predictable at planning stage. Therefore, a stochastic approach is adopted to account for 5 different demand growth scenarios and the possibility of deferring installation costs according to the demand realization is introduced by adding two capacity expansion windows. The presence of capacity expansions reduces the total cost by a significant amount, ranging from 10% in the least-cost solution up to 23% in case of minimum land use. The multi-step investment approach allows to defer expenses and, consequently, to rely more intensely on renewable and storage components, characterized by a high upfront cost and thus less efficient with respect to fuel-fired generators in a single-step investment configuration.

B. Conclusions
The modelling framework proposed in this work aims at providing decision makers with an effective, accurate and comprehensive planning tool, whose available features could be easily adapted to the needs of the specific application. This objective is reached by also developing novel algorithms aimed at reducing the computational burden of complex problems. The tool provides significant advantages with respect to traditional sizing methods, as it can easily identify the least-cost solution, accounting for long-term phenomena, and evaluating the trade-offs between- various decision criteria relating to the different scopes of sustainability, namely economic, environmental and social.

A STOCHASTIC FRAMEWORK FOR OPTIMAL MICROGRID OPERATION UNDER FORECAST UNCERTAINTY

Simone Polimeni - Supervisors: Prof. Giampaolo Manzolini, Prof. Sonia Leva

A Microgrid is a local electric network, capable of operating in parallel with or independently of the main grid, and comprising a group of loads and Distributed Energy Resources (DER). DERs include dispatchable generators, which operations can be scheduled, non-dispatchable generators, usually associated with the exploitation of RES, and different types of Energy Storage Systems (ESS). A key feature of MGs is their intrinsic versatility.
The scope of this work is to identify and test novel Energy Management Systems (EMS), that deals with the operations of off-grid MGs in real-time and allows high Renewable Energy Sources (RES) penetration.
The pervasive employment of RES, combined with the aleatory load demand, brings about a large uncertainty of the power production requirements by the programmable MG units and storage systems; it may prevent the maximum exploitation renewable power generation. An EMS must consider the uncertain and stochastic behavior of net load demand, to compensate for its unpredicted variations, also at different time scales. Figure 1 depicts the features of the net demand for the time scales managed by the EMS. This thesis deals with optimal management of islanded MGs.

The scheduling problem is solved according to the forecast of non-dispatchable generation and non-controllable demands. The forecasts are intrinsically untrue, meaning that, although accurate, there is always a mismatch between what is predicted and what is observed.
The dispatch considered during the solution of the scheduling problem cannot be directly applied to the real profile: the inclusion of forecasted information implies the necessity of correcting the identified solution as the real value of uncertain factors is observed. To better cope with forecast errors, the EMS is usually designed with a multi-layer structure: the first layer is in charge of the medium-term operation schedule (usually dealing with the operating strategy for the following 24 hours), while the second layer deals with the real-time balancing of the system. The evaluation of the optimal operation schedule consists in the evaluation of the most effective unit commitment (UC) of the controllable generators and loads, together with the economic dispatch (ED) of all the MG subsystems, exploiting the forecasts of the various internal consumption profiles and RES generation, while providing enough flexibility and reserve margins, to compensate for forecast errors, occurring in real-time operations.
The EMS architecture considered in this thesis is presented in Figure 2, suitable for the management of single-bus islanded MGs. The upper layer of the EMS deals with the strategic decisions, identifying the optimal commitment status of the programmable generators, the appropriate storage management for a prominent integration of renewables, as well as a tentative dispatch plan. The final dispatch is determined by the second layer, that interacts in real-time with the MG. The storage systems have been identified as a crucial technology to integrate the intermittent RES generation. An appropriate ESS management is a major challenge that must be faced to ensure economic and safe operations. In this work, this aspect is addressed by the new stochastic formulation, that considers a non-anticipative storage dispatch. For these reasons, the new formulation includes integer recourse rules for a flexible UC, that is adapted to the observations of uncertainty.

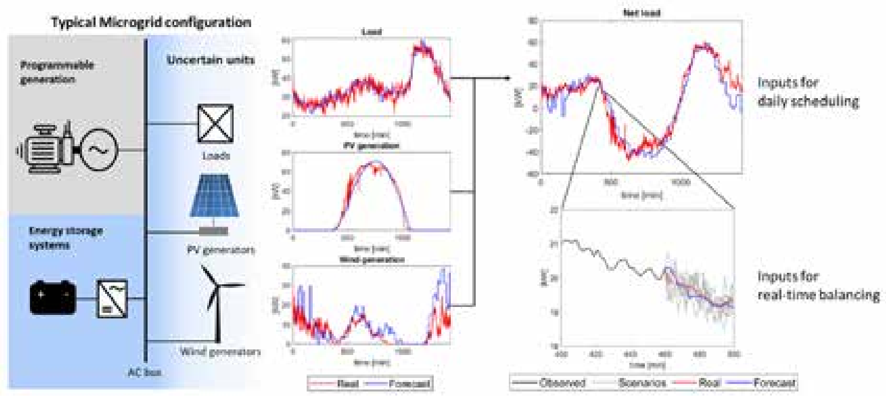

Fig. 1
Example of typical islanded Microgrid configuration, highlighting the sources of uncertainty

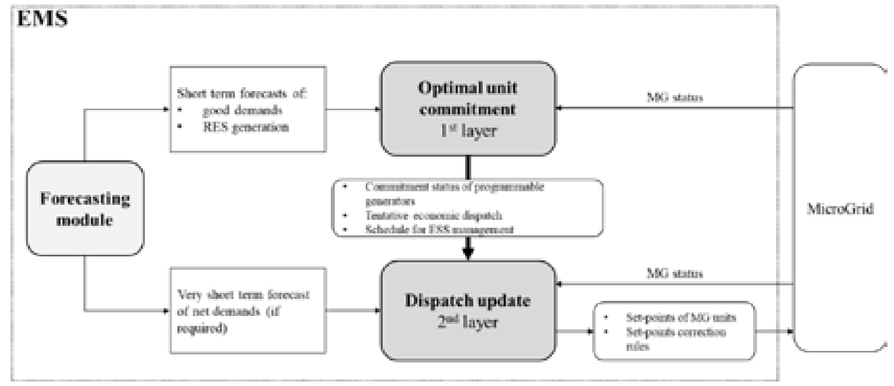

Fig. 2
General hierarchical EMS architecture

The second layer is formulated as an innovative stochastic Model Predictive Control (sMPC) with *disturbance feedback:* the forecast errors from the first layer act as disturbances for the real-time dispatch of the MG units.
The effectiveness and the reliability of the EMS must be demonstrated in MG test systems: the proposed EMS is implemented and tested on a laboratory-scale MG.
The choice of stochastic optimization as core model for the EMS relies on the fact that it allows to explicitly account for uncertainty, overcoming the intrinsic limits of the deterministic and robust optimization, mainly related to the conservativeness of the solution. The novel stochastic models allow to define explicit recourse rules that define a clear dispatch strategy also for realization of uncertainty that have not been considered during the solution of the optimization problem: indeed, the optimal values of the variables obtained by standard stochastic approaches are only defined for the in-sample scenarios considered during the solution.
Moreover, the stochastic approaches overcome the other methods in terms of total operating cost of MGs. From these motivations, the doctoral thesis builds up the following points:

- **Definition of a novel stochastic model for the optimal scheduling of off-grid MicroGrids (MG).** The new model relies on a transformation of the uncertainty vectors, that define several scenarios of future net demands for the MG. This transformation allows the model to consider piecewise affine (PWCA) decision rules for the management of the units. In particular, they are used to enable integer recourse policies that permit do adapt the commitment status of the units according to the observed historical demands. Moreover, they define a non-anticipative storage management, that is missing in standard stochastic two-stage approaches.
- **Development of a stochastic Model Predictive Control (sMPC) system for the real-time dispatch.** The model relies on a *disturbance feedback* loop between the controller and the MG. The forecast errors are considered as the main disturbances of the economic operations. Very-short term forecasts are used to predict the behavior of the MG considering the fast dynamic of its units. In this way it is possible to track the optimal scheduling with optimized corrective actions.
- **Validation of the hierarchical EMS on an experimental facility.** All the proposed EMS configurations have been deployed in the Multi-Goods MicroGrid Laboratory (MG^{2}Lab), after the definition and the development of an online software; the EMS successfully managed the MG. In addition, a careful validation scheme is considered to verify the accuracy of the numerical simulations.

The proposed solutions are analyzed through a comparative performance assessment of the scheduling problem of the complete EMS with respect to standard stochastic and deterministic formulations.

MODEL PREDICTIVE CONTROL ALGORITHMS FOR MEDIUM VOLTAGE POWER ELECTRONIC SYSTEMS

Mattia Rossi - Supervisors: Prof. Francesco Castelli Dezza, Prof. Petros Karamanakos

Over the last decade, model predictive control (MPC) formulations have received significant attention and wide acceptance by the power electronics community as a promising alternative to the established control strategies. At the same time, interest in high-power grid-connected converters has been growing, motivated by the need for a flexible interface in applications such as renewable energy, high-performance industrial drives and now vehicles to be connected to the grid. Depending on the considered controlled variable, this dissertation focuses on the development of a constrained long-horizon indirect—*the manipulated variable is real-valued, thus, belonging to a continuous set*—and direct—*the manipulated variable corresponding to the converter switch positions, thus, belonging to an integer set*—MPC-based controllers (also called CCS-MPC and FCS-MPC, respectively) for high-power grid-connected three-level neutral-point-clamped (3L-NPC) converters with LCL filters. Advantages of MPC-based strategies over traditional control approaches include (but are not limited to), ease of implementation, flexibility, improved efficiency, and improved output quality. Depending on the formulation of the controller, several of these improvements may be achievable simultaneously, while the real-time implementation of the controller on industry-based platforms is rendered feasible.
Medium voltage (MV) applications represent a particularly challenging field in which the nature of the semiconductor devices requires the minimization of the switching frequency (i.e., switching losses) of the converter, while grid codes—such as the IEEE 519 and IEC 61000-2-4 standards—impose tight limits on the current and voltage harmonics amplitudes injected at the point of common coupling (PCC).
To this end, LCL filters are commonly adopted to interface the converters with the grid. The LCL filter, however, introduces additional control challenges due to the higher order of the resulting system (i.e., besides the control of the grid current, the control of the converter current and capacitor voltage are needed) and the filter resonance (i.e. to be adequately damped to avoid current harmonics amplification, or, even, stability issues).
The great potential of MPC (re-) formulations according to the given application needs/ requirements (i.e., meet grid standards and full hardware utilization becomes challenging), coupled with the increasing request of intelligent solutions to tackle conflicting control goals and physical limitations in high-power grid-connected solutions, motivates this dissertation to present the development and testing of both direct and indirect MPC-based controllers (e.g., see Fig. 1) showing that they can achieve steady-state performance that can bring improvements compared with conventional control methods, such as voltage-oriented control (VOC) with space vector modulation (SVM). This also includes the intrinsic ability of MPC to damp resonating effects (i.e., without adding external damping loops).
For both approaches, a detailed analysis on the algorithm formulation is presented, focusing on the mathematical programming properties and different way to solve the optimization problem (i.e., choice of the solver) in an efficient and feasible manner. First, all primary control objectives, i.e., reference tracking of the multiple output variables, are achieved and the relevant grid codes met, while the converter is operated at low switching frequency. Second, depending on the adopted formulation, the computational complexity of the optimization problems can be kept modest, even when long horizons are utilized for improved system performance.
Indeed, short-horizon MPC formulations, as mostly developed in the academic world, provide only relatively small performance improvements. Motivated by this, the developed long-horizon MPC algorithms are designed such that superior steady-state and transient performance is achieved. This, however, may come at the cost of an increased computational complexity. To address this, the dissertation also aims to propose control problems formulated such that a computationally efficient real-time implementation on commonly available industrial control hardware is feasible, thus, discussing the real-time certification of the derived embedded MPC.
Reliability prediction in high power electronic systems identifies filter capacitor banks and semiconductor switches as two of the most fragile elements. To this end, both the proposed MPC formulations include different types of bounds on the system outputs, thus, operation within the safe operating area of the system—given as trip levels—is achieved. Hence, damage (or aging) of the hardware due to overvoltages and/or overcurrents can be avoided (reduced).
In particular, it is shown that indirect MPC exhibits superior steady-state performance with fast transient responses and lower output distortion while operating the converter within its safe operating limits (enhanced reliability) through the introduction of soft constraints. By appropriately formulating the constrained optimization problem underlying indirect MPC as a quadratic program (QP), the grid and converter currents as well as the filter capacitor voltage can be simultaneously and successfully controlled while keeping the online calculation effort low, even in the presence of longer horizon. This is mainly due to efficient QP solvers which can be adopted in such framework. This facilitates the further development of a feasible implementation of this approach on an embedded platform.
Based on the proposed computational burden analysis, it can be concluded that the proposed embedded MPC algorithms meets the real-time certification and guarantees that the solution to the QP is always found at run-time without affecting its optimality. Throughout the dissertation, the performance of the proposed strategies is investigated within a self-developed scaled-down experimental test-bench (e.g., see Fig. 2) and a customized control platform based on a multiple processor system-on-chip field-programmable gate array (MPSoC FPGA). Although the controllers that are presented represent concrete and feasible alternatives to the established control strategies, there remains scope for future work in terms of testing and implementation strategies.

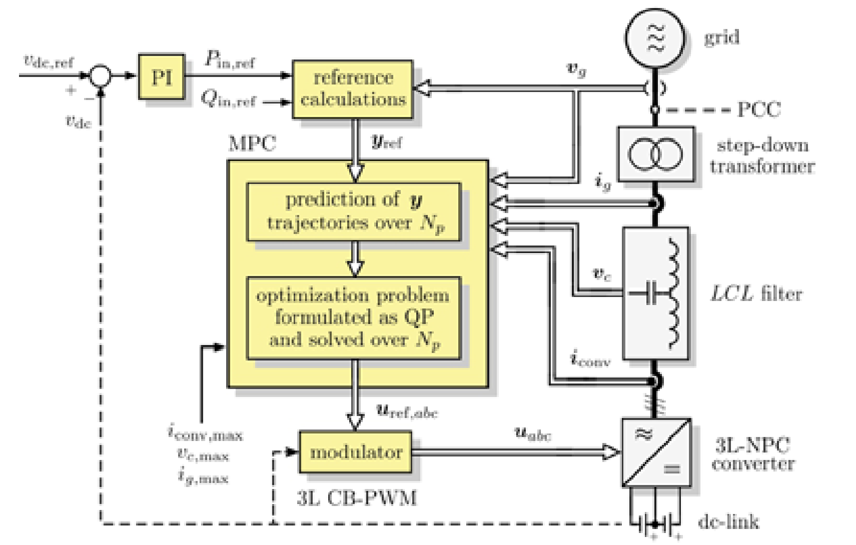

Fig. 1
structure of the indirect MPC scheme formulated as a multi-criterion QP

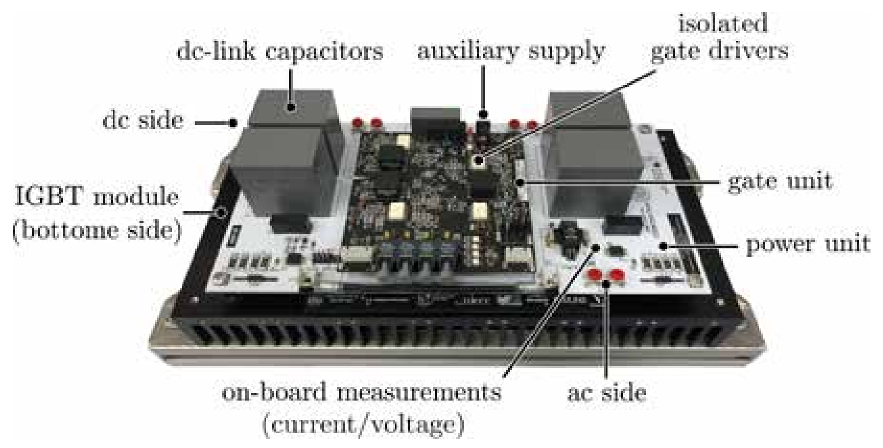

Fig. 2
Details of three-level converter included in the self-developed scaled-down test-bench (courtesy of ePEBB[s] Srl)