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 | 2025

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.

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A TWO-PHASE REFRIGERANT BASED COOLING SYSTEM FOR TRACTION ELECTRIC MOTORS

Samuele Barachetti - Supervisor: Matteo Felice Iacchetti

Tutor: Roberto Perini

The research work presented in this thesis provides a contribution to the development of a new disruptive electric motor cooling concept for Electric Vehicles (EVs) to boost power-train performance. This innovative cooling approach is based on the use of low-temperature, two-phase refrigerant that is inherently available in vapour-compression Heat Ventilation Air Conditioning (HVAC) systems, which are typically on-board vehicles. The thesis explores the potential of bleeding a refrigerant fraction from the HVAC vapour-compression core cycle and channelling it into the traction motor windings to extract the rejected heat from winding losses and achieve radical cooling. The central aspect of the proposed solution is the refrigerant phase-change unlocking extremely high heat-transfer coefficients, so as to maintain the motor windings at relatively low temperatures. The ambition is to capitalise on the consequent electric resistivity drop with temperature to reduce winding Joule losses and improved the electric motor drive efficiency. In order to evaluate the features and performance of this integrated two-phase motor cooling concept, the thesis proposes and explores different configurations to bring the refrigerant in close contact with the windings and their pros and cons. Furthermore, the thesis presents a simplified modelling technique that integrates the HVAC vapour compression cycle with the motor cooling sub-models. This is done by building an integrated modelling tool in Matlab and evaluating some practical slot-channel configurations for the evaporator structure. The key objective is to assess the reduction in winding losses against the inevitable increase in the HVAC compressor power demand and identify the best design trade-off.

INDUCTIVE COUPLING FOR WIRELESS POWER & SIGNAL TRANSFER: A ROTORCRAFT APPLICATION

Massimo Brunetti - Supervisor: Marco Mauri

Tutor: Francesco Castelli Dezza

The More Electric Aircraft (MEA) is an established trend towards a larger number of electrical systems and a higher level of electrical power generation onboard. Electrification can indeed reduce the maintenance, improve the efficiency and mitigate the environmental footprint of aircraft. On existing helicopters, the most powerful electrical system is represented by the Full Ice Protection (FIPS), which depends on mechanical current collectors (or slip rings) to supply the rotor blade heaters, as well as to read the blade temperature sensors for closed-loop control. However, slip rings are based on brushes and bearings that subject to harsh vibrations and high rotational speeds, suffer from quick wear out and frequent malfunctions (especially on the tail). In order to solve this problem and pave the way for future MEA applications, Leonardo conceived and patented in co-operation with Politecnico di Milano a special combination of rotary transformers and power electronic circuits, also regarded as Contactless Power Transfer Unit (CPTU) and suitable for signal transfer too. Compared to traditional Tail Rotor Slip Rings (TRSR) this unit should have a much longer lifespan and make for a better helicopter "serviceability", while totalling a similar weight (thanks to the high switching frequency and active parts miniaturization). Triggered by these objectives, the present research addressed the conceptual design of such a unit, from first principles to laboratory testing, covering a Technology Readiness Level (TRL) transition of 1-to-5, in approximately five years. Following an introduction to the reference application and technology state-of-the-art, it was heuristically selected the co-axial rotary transformer topology and the full-bridge circuit. As part of the initial research bootstrap, it was collected a list of functional, installation and environmental requirements. According to the selected system architecture, the power transfer was first evaluated using a set of analytical models and then optimized in terms of the transformer gravimetric and volumetric power density. This goal was achieved using a mix of numerical simulations, including but not limited to grid searches (to preliminary explore the transformer design space), genetic alghorithms (to refine the previously selected "best candidate") and the Finite Element Method (to identify the transformer equivalent circuit model). Each solution being compliant with the minimum power transfer requirement and not exceeding the magnetic saturation or the current density limit. In particular, by electromagnetic FEM analysis, it was verified that the segmentation of the core and a moderate reduction of the annular filling factor could benefit the mechanical robustness and the power density of the unit. The use of FEM was also instrumental to verify the coaxial topology stability in terms of magnetic coupling and power transfer, regardless of the core eccentricity. Moreover, a set of power processing techniques was explored to see if/how to improve the integration of the unit at aircraft system level. For instance, in order to trim the output power, consistently with the heaters specifications, it was introduced an off-time, realized commanding the switches with a uni-polar technique. For the purpose to ensure the electromagnetic compatibility with the rest of the radiocommunications, it was simulated the use of a three level Pulse Width Modulation (in lieu of a Square Wave) and which may reduce the Total Harmonic Distortion. Assuming to introduce a boost converter (to double the aircraft DC voltage) it was verified the possibility to adopt a thinner wire gauge (...) The signal transfer functionality was instead explored according to two different main strategies, either keeping all the electronics in the fuselage or measuring the blade temperature directly on the rotor. In the first case, it was adopted an Extended Kalman Filter (EKF) to assimilate the blade temperature data with a priori state model of the system; in the second case, it was exploited a Pulse Code Modulation (PCM) to transmit the blade temperature data through the transformer; in both cases data was generated upon a Analog-to-Digital conversion of the temperature sensor signal. Then, once selected the most suitable strategy, the behavior of the system was assessed by means of an all-encompassing dynamic simulation, thoroughly reproducing the signal conversion, under relè temperature control, and capturing several non-idealities of the specific system architecture (including power supply voltage ripples, current pulse distortions and numerical conversion approximations). This simulation was carried out using an equivalent blade thermal model (identified on the basis of experimental flight data) and allowed to confirm the temperature accuracy required by FIPS. Finally, the results predicetd by modelling & simulation were validated using a set of full scale prototypes representative of the proposed design. A mechanical mockup was installed on a real helicopter tail rotor to check the minimum air gap without contacts; a power transformer was built on the previous and driven at full voltage to verify the attainable heating; a signal transformer with a similar arrangement was exploited as bidirectional "bridge" to supply and communicate with a temperature acquisition board. Notably, during these tests, the measured output power was always found in good agreement with the forecast whereas the input active power showed some evident mismatches. A fact later interpreted on the basis of the Proximity Effect, and which suggested to revise the adopted loss models and the CPTU preliminary design (e.g. replacing the use magnet wire with litz wire, or IGBT with MOSFET transistors). Moreover, to cope with larger air gaps, it was discussed the use of a resonant (LLC) inverter. This architecture could indeed exploit the transformer leakage inductance to realize a voltage step up proportional to the gap and also minimize the magnetization current, enabling at the same time a Zero Voltage Switching to the benefit of the efficiency and the electromagnetic compatibility of the system. Therefore, given the encouraging results achieved so far, the importance of the ice protection and the opportunities disclosed by the rotor electrification, the project is now heading for TRL 6, corresponding to a flight demonstration onboard of a real helicopter. If successful, chances are that the concept explored under this project (and which already represents an intangible asset) will turn into a tangible product, contributing to the safety of flight and substantiating the potential of open innovation in the field of applied research.

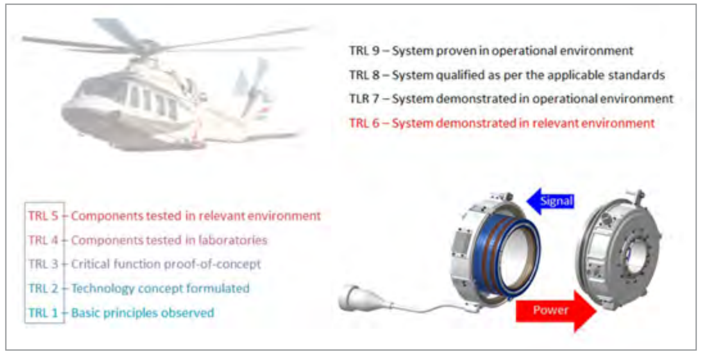

Fig. 1 - TRL transition covered during the project and next steps

LITHIUM-ION BATTERY MODELING AND APPLICATIONS

Silvia Colnago - Supervisor: Luigi Piegari

Co-Supervisor: Giovanni Dotelli

The increase in global warming and the depletion of fossil fuels are spurring governments to incentivize the use of renewable energy and electric mobility. Both technologies rely on energy storage systems. In this context, lithium-ion batteries are the preferred technology due to their high power and energy density, low self-discharge, and relatively long lifecycle.
The growing use of lithium-ion batteries across various applications creates an increasing need to enhance their performance. This can be achieved either by developing new materials or by improving battery control strategies. The latter involves creating simple yet precise battery models capable of predicting the electrical and thermal behavior of lithium-ion batteries, thereby helping system design, analysis, and management strategies.
Another crucial aspect is battery degradation, which is influenced by external conditions. Aging affects battery performance and alters the parameters of electrical and thermal models. Therefore, monitoring degradation and predicting battery behavior based on external conditions and usage history are essential.
The thermal, electrical, and degradation aspects of batteries are interdependent. The chemistry of batteries evolves under specific electrical and thermal conditions due to parasitic reactions that contribute to degradation. In turn, these chemical changes affect the batteries' electrical and thermal behavior by altering its parameters. Consequently, developing a general battery model that can predict electrical and thermal behavior under specific conditions is essential. Such a model should also dynamically adjust its parameters based on degradation.
Achieving this requires a deep understanding of the interactions among these three factors.
In this context, the objective of this thesis is to contribute to the development of such a model by conducting a comprehensive analysis of the electrical, thermal, and degradation behavior of lithium-ion batteries. The goal is to enhance the overall understanding of lithium-ion batteries, with a particular focus on the interrelationships among these three aspects.
This thesis involves the development and validation of an electrical model for a lithium-ion battery cell (Figure 1) and an electrothermal model for a battery pack (Figure 2). The results of these models demonstrate excellent agreement with experimental data. Subsequently, the thesis explores degradation by analyzing both capacity fade and resistance increase. In particular, the aging behavior of the open-circuit voltage curve is thoroughly

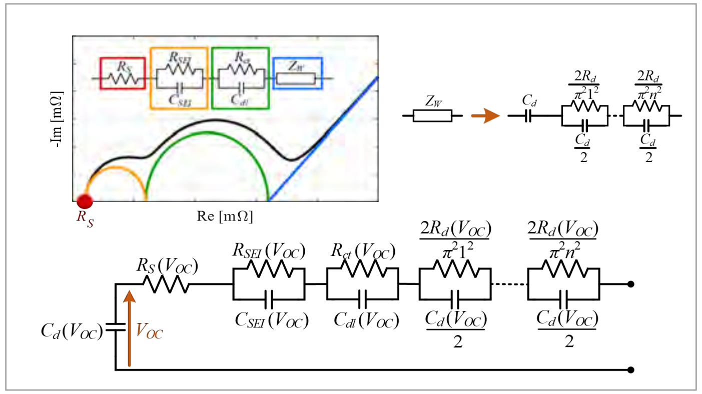

Fig. 1 - Electrical model of lithium-ion battery cell

investigated, and a model for both calendar and cycle aging is developed.
Furthermore, the thesis examines the impact of aging on the temperature dependence of capacity and internal resistance, leading to the development of analytical models capturing these trends. Additionally, internal resistance hysteresis, similar to that affecting the open-circuit voltage, is identified and analyzed in relation to temperature and aging behavior.
In the final part of the thesis, the developed models are applied to practical scenarios. The open-circuit voltage model is used to estimate the capacity of a battery for electric vehicle based on just two open-circuit voltage points. Various aging models from literature, combined with insights into different battery chemistries, are employed to assess the feasibility of using specific chemistries or their combinations in a fast-charging station. Optimization of sizing is also considered, incorporating aging effects. Finally, the battery model developed in this thesis is used to investigate the influence of battery aging on a DC-DC converter connecting the battery to a photovoltaic system.
The path toward the development of a general battery model is ongoing, and this thesis represents a significant step in that direction.

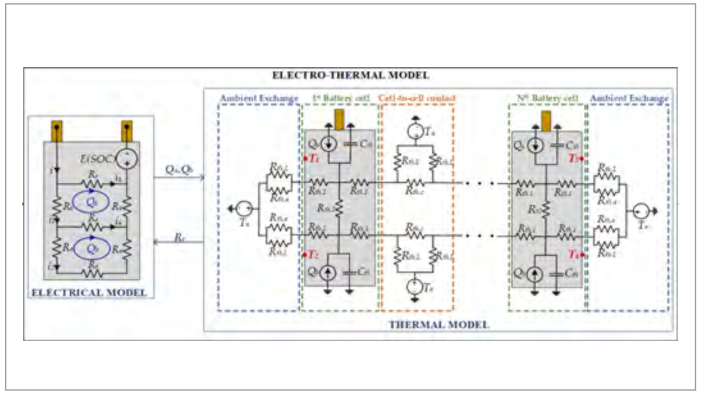

Fig. 2 - Electro-thermal model of a battery pack

MULTI-DISCIPLINARY APPROACH TO ELECTRIFICATION PLANNING

Aleksandar Dimovski - Supervisor: Marco Merlo
Tutor: Alberto Berizzi

Electrification is regarded as a leading driver of socio-economic development, delivering crucial benefits such as improved healthcare, education, and economic productivity, leading to an enhanced quality of life, industrial growth, and poverty alleviation. This aligns with the United Nations' 7th Sustainable Development Goal , which aims to ensure affordable, reliable, sustainable, and modern energy for all by 2030. Achieving this goal necessitates a comprehensive, multi-disciplinary approach to electrification planning, integrating technological, economic, social, and environmental perspectives. This thesis aims to contribute to the existing literature by not only proposing a exhaustive electrification framework, but also deepening the understanding of crucial aspects essential to addressing the topic. Fostering a comprehensive multi-disciplinary approach, it utilizes concepts from computational geometry, operations research, data science and electrical engineering, enhanced with the adoption of geographic information systems alongside geospatial datasets to integrate economic, technological, social and environmental perspectives. The thesis promotes an open-source and well-detailed approach that is provided as a software package, promoting transparency and ensuring effective strategies are accessible to all interested stakeholders.

The methodology proposed is structured into distinct blocks, properly addressing each of the necessary steps towards cost-efficient electrification pathways. A generalized flowchart of the procedure proposed is reported on Figure 1. Special attention is given to proper modeling of the distribution system expansion planning within the electrification framework, ensuring efficient energy and enhancing the quality for supply. Additionally, it enables a clear comparison among the different means of electrification and an accurate estimation of the related costs, which is an indispensable information for stakeholders. The ultimate electrification planning problem is designed as a linear optimization model with two distinct solving strategies, one exact approach utilizing a commercial solver, as well as an efficient customized heuristic algorithm. The framework was applied on two real life case studies, one in the region of Zambezia in Mozambique and the region of Butha-Buthe in Lesotho, that exhibit rather different situation in terms of size and initial access to electricity, which due to the different characteristics resulted in a different preference for the electrification solutions. An example of the outcome is presented on Figure 2, promoting not only parametrized, but also a geospatial representation of the electrification plan for Butha-Buthe, differentiating among grid extensions and off-grid solutions.

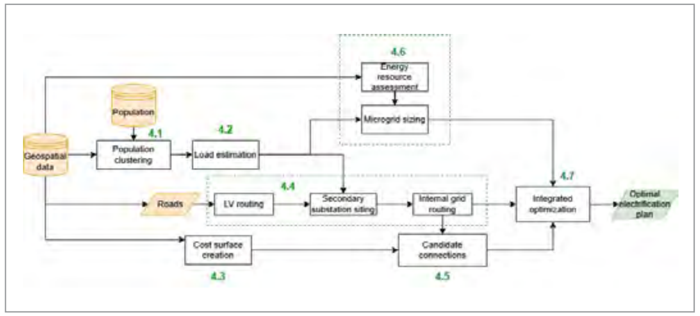

Fig. 1 - Flowchart of the proposed procedure

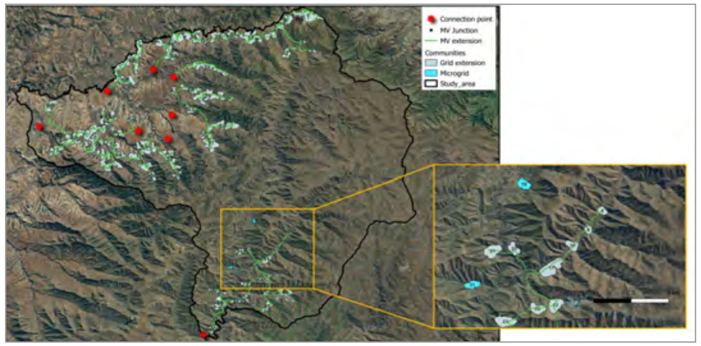

Fig. 2 - Electrification plan for Butha-Buthe

SENSING ARCHITECTURES BASED ON LASER TOF AND MEMS MIRRORS

Paolo Diotti - Supervisor: Michele Norgia

Co-Supervisor: Daniele Caltabiano - Tutor: Loredana Cristaldi

This Ph.D. thesis presents two distinct research projects: the development of a 3D imaging system based on LiDAR technology and the design of a control board for a Silicon Photonics system based on Mach-Zehnder interferometers (MZIs). The first project focuses on the design and prototyping of a 3D camera utilizing Laser Time-of-Flight (ToF) sensing and Micro-Electro-Mechanical Systems (MEMS) mirrors.

The development began with the definition of the system architecture, identifying the key components such as the laser source, MEMS mirrors for beam steering, a photodetector, and an FPGA for real-time data processing. Once the hardware structure was established, attention was given to the implementation of the laser driver and the control of the MEMS mirrors to ensure precise beam positioning. Simultaneously, an analog front-end was developed to acquire and process the reflected light signals, enabling accurate depth measurements.

The core of the system was then developed through the programming of an FPGA, responsible for managing data acquisition, processing signals, and computing distances in real-time. In parallel, a graphical interface was designed to display the reconstructed 3D images, allowing real-time visualization and calibration of the system. Finally, extensive testing and validation were conducted under different conditions to assess accuracy, resolution, and range. The results demonstrated the effectiveness of the system, confirming its potential applications in industrial automation, robotics, and consumer electronics.

The second project focuses on the design and implementation of a control board for a Silicon Photonics-based optical switching system utilizing Mach-Zehnder interferometers (MZIs). The research involved the development of a controller architecture capable of dynamically adjusting the optical phase shift to optimize signal routing. A Maximum Power Point Tracking (MPPT) algorithm was implemented to regulate the MZ switching behavior, ensuring efficient light transmission across different output channels.

The system was developed on a custom Silicon Photonics chip (Alcor) in collaboration with STMicroelectronics and was managed via an STM32 microcontroller. Experimental validation confirmed the effectiveness of the control strategy in achieving precise optical switching, demonstrating its potential applications in high-speed communication networks and optical computing.

MODULAR MULTILEVEL CONVERTERS APPLICATIONS FOR EV CHARGING STATIONS

Edoardo Ferri - Supervisor: Luigi Piegari

Ultra fast charging stations (UFC) pose significant challenges to the power grid due to their intermittent high-power demand. This issue is further exacerbated by the increasing integration of renewable energy sources, which introduces additional fluctuations in power availability. One promising approach to mitigating these grid-related challenges is the use of battery energy storage systems (BESSs), which can help smooth power demand, provide peak shaving, and enhance grid stability. How ever, the integration of BESSs within UFC stations introduces additional complexity, particularly concerning power conversion, control, and system scalability. Current UFC station architectures predominantly rely on conventional solutions concerning the power electronics interface, and require bulky transformers and additional filtering to meet grid power quality requirements. Furthermore, existing topologies necessitate multiple dc-dc converter stages to accommodate different charging voltage levels (e.g., 400V, 800V, or >1kV), further increasing system complexity. To address these limitations, modular multilevel converter (MMC)-based architectures for electric vehicles (EVs) charging stations are investigated in this thesis. MMCs offer several advantages, including lower total harmonic distortion (THD), reduced reliance on bulky transformers, scalability, and enhanced flexibility in integrating multiple power sources. In particular, various converter architectures and control strategies are proposed and analyzed, addressing critical issues such as power quality, grid stability, and system modularity. The key contributions of this research include: i) the analysis, comparison, and proposal of different converter topologies for UFC stations, including fully modular architectures and configurations integrating isolated DC-DC converters; ii) development of a novel double-star MMC topology for integrating photovoltaic (PV) sources and loads, with applications in green hydrogen production for fuel-cell electric vehicles (FC-EVs); iii) a study on high-power isolated DC-DC converters leveraging cascaded cells to improve efficiency and reduce reactive power, carried out in collaboration with Institute of Science Tokyo (formerly Tokyo Institute of Technology).

DATA-DRIVEN PREDICTIVE METHODS FOR THE STATE OF CHARGE AND STATE OF HEALTH OF THE LITHIUM-ION BATTERIES

Panagiotis Eleftheriadis - Supervisor: Sonia Leva

Tutor: Francesco Grimaccia

The European Union's (EU) strategy for a sustainable transition, as outlined in a key policy document, mandates a minimum 55% reduction in net greenhouse gas emissions by 2030. It also sets an ambitious goal of a 100% emissions reduction from cars and vans with internal combustion engines by 2035. This acts as a catalyst, hastening the advancement toward electrification in the transportation sector. Energy storage for electric motors can be provided by either batteries or fuel cells, both capable of providing adequate energy for this purpose as outlined in studies on batteries and fuel cells. Lithium-Ion Batteries (LIBs) are becoming increasingly attractive due to their advanced development, as stated by Bloomberg. Accurately modelling the battery, which is a highly complex electrochemical device, is essential for efficient battery pack utilization and future state prediction. During the life of the battery and as the battery pack deteriorates over its lifespan, the State of Charge (SOC) and State of Health (SOH) become important parameters that provide vital information for reliable and safe battery pack operation. Accurate and robust prediction of SOC and SOH is crucial for the Battery Management System (BMS) to monitor battery behavior and operate within safety limits while avoiding is- sues such as undervoltage, overvoltage, and overcharging. To achieve this, the BMS must make estimations based on measurements of terminal voltage, current, and surface temperature.

The SOC, which indicates the percentage of the maximum possible charge present inside the cell, is considered a critical parameter among various states. The SOC is nonlinearly related to the terminal voltage, terminal current, battery temperature, and potentially the SOH, as these parameters are correlated. Predicting the expected values of these states is a challenging task. Simultaneously, accurate SOH predictions are important to identify successfully the second-life characterization of the battery, usually set to 80% SOH level for the automotive sector. In battery research, the SOH is a fundamental parameter that underlines the total actual maximum capacity available in the battery over its initial rated maximum capacity. Various methods, ranging from simple to sophisticated, have been developed to capture this nonlinear relationship. Lastly, as previously stated, their joint estimation would be pivotal for the more reliable operation of the BMS.

In the last years, with the increased computation capacity and the abundance of available data, the dynamics of the battery cell can be effectively captured through data-driven techniques for the estimation of the states of the battery, and therefore of its SOC and SOH. Between them, the methods that got more attention are the Recurrent Neural Network (RNN) as a type of model, and furthermore, the hybrid approaches, which refer to either the combination of deep learning architectures or the utilization of an optimization algorithm in conjunction with a data-driven method. RNN models, using the previous states, previous forecasts, and past information of the measurements can obtain better estimation results for the SOC and SOH of the battery. Data-driven methods require careful hyperparameter selection as their results strongly depend on their choice. Heuristic methods involve manual tuning or exhaustive ways, which can be computationally demanding.

In this Ph.D. thesis, the research conducted offers a substantive contribution through a comprehensive literature overview and the subsequent development of predictive methods for the SOC, the SOH and their joint estimation.

For the latter, a new dataset was meticulously curated and collected in a battery laboratory. This dataset encompasses data from the initial phases of the battery's life through to its degradation phase, covering a complete life cycle. This comprehensive coverage makes it aptly suitable for a joint estimation, thereby making a valuable contribution to the research.

The ultimate goal is to develop a unified model capable of accurately predicting SOC, SOH and their joint estimation across various ambient temperatures. The proposed framework for all predictive methods, a Bayesian Hyperparameter Optimization (BHO) with a Gaussian process is proposed, exploiting the benefits of the probabilistic approach to hyperparameter tuning to reduce computational effort. For accurate prediction, the BHO technique is implemented on a stacked Bidirectional Long Short-Term Memory (BiLSTM) Neural Network (NN), incorporating a novel set of hyperparameters. The presented method is validated using two well-documented public datasets for SOC and SOH esitmations. Results are compared using datasets with different time granularity, revealing accuracy and computational differences while exhibiting superior yield capabilities compared to other state-of-the-art methods.

For the SOC estimation, to assess the computational effort associated with data size and model creation, a time granularity analysis was performed. The analysis demonstrated that decreasing the timestep resulted in reduced network creation time while maintaining similar error levels. While for the SOH estimation an input selection analysis and different voltage ranges were performed to identify the best input features and the minimum voltage range to yield the best result with the minum computational and storage effort. Moreover, to ensure the comparability of the method, the metric of FLoating-point OPerations (FLOPs) was integrated to quantify the network's computational volume. Finally, a sensitivity analysis performed on the time-series window span showed accuracy and computational load differences highlighting the need for caution and careful consideration.

Finally, for their joint estimation, the efficacy of the method is demonstrated using a dataset specifically acquired for validating the framework, representing a significant contribution to this research. This dataset encompasses the complete first life of an automotive battery cell, offering a comprehensive solution for integrating the framework into a BMS of an Electric Vehicle (EV).

OPTIMIZATION AND CONTROL OF MICROGRIDS WITH HIGH RENEWABLES PENETRATION FOR THE SUPPLY OF HYBRID AND ELECTRIC VEHICLES

Domenico Gioffrè - Supervisor: Sonia Leva

Tutor: Marco Mussetta

This doctoral thesis focuses on the development, numerical evaluation, and experimental validation of advanced hierarchical and centralized Energy Management Systems (EMS) adopting a rolling horizon approach. These systems are based on Mixed Integer Linear Programming (MILP) and are designed to optimize the integration of local renewable energy production with the energy demands of electric vehicles in microgrids and smart households. The contributions of this work are structured into the following key stages:

- Development of a General MILP Formulation for Predictive Optimization: Chapter 3 introduces a general MILP formulation for predictive optimization in EMS scheduling problems. The initial focus is on a deterministic approach, where forecast errors are mitigated through a second-layer corrective mechanism. Subsequently, a stochastic formulation is developed, explicitly incorporating uncertainty into the decision-making process to enhance reliability and robustness.
- Modeling of Uncertainty: Chapter 4 outlines methodologies for generating probabilistic forecasts of variables significantly affected by uncertainty. Real-world datasets are utilized to produce probabilistic scenarios, which are then integrated into the stochastic MILP framework. The chapter emphasizes balancing the quality of scenario representation with the computational burden posed by the number of scenarios.
- Extensive Numerical Assessment of Home EMS (HEMS): Chapter 5 provides a comprehensive evaluation of the HEMS.
  - The deterministic HEMS is benchmarked against a non-predictive heuristic algorithm, representative of the standard management approaches in current smart homes.
  - Case studies encompass diverse scenarios, including variations in user behavior, photovoltaic generation levels, BESS presence, mono- and bidirectional EV charging capabilities, EV models, and weekly commute patterns.
  - Quantification of the impact of forecasts accuracy.
  - Innovative approaches for the HEMS are explored, including:
    - Management of schedulable appliances to increase the flexibility within the deterministic framework of the HEMS.
    - Stochastic upgrade of the HEMS to integrate uncertainty into the decision-making process.
- Experimental Validation of the EMS: Chapter 6 describes the experimental campaigns conducted to validate the developed EMS methodologies in real-time operations. These experiments were carried out in both a laboratory-scale microgrid environment and a real residential setting.

The mathematical formulations incorporate state-of-the-art MILP-based optimal scheduling models, carefully tailored to ensure practical deployment in real-world applications. Regarding the deterministic HEMS, its cost-effectiveness has been demonstrated compared to nonpredictive heuristic management. The HEMS achieves yearly cost savings exceeding 20% in all cases, with savings reaching up to 900 €/year in configurations with large PV systems. The economic advantage of the EMS over the benchmark heuristic algorithm remains substantial even when systematic forecast errors for EV usage are present. However, the installation of stationary BESS was found to be economically non-advantageous. Bidirectional chargers, on the other hand, offer additional savings, particularly with more frequent remote working days, reaching 10–15% savings in configurations without BESS. The results suggest that the economic benefits of the HEMS can be further enhanced by improving forecast accuracy. Preliminary tests revealed that better EV usage forecasts have the greatest impact, especially during summer in configurations with large PV systems, leading to 40% potential increased revenues. Improved forecasts for PV generation and domestic loads could contribute an additional 10% in savings or revenues.

The innovative approaches for the HEMS also provided valuable insights.

- The demand-side management of significant household appliances was carefully modeled within the deterministic methodology, incorporating user behavior in setting up appliances. The HEMS effectively leveraged this flexibility to achieve cost savings by taking advantage of lower electricity prices and enhancing PV self-consumption. However, these savings were limited, as appliance energy demand constitutes only a small fraction of overall consumption, particularly in configurations with EVs.
- The stochastic HEMS, developed in partnership with the Department of Electrical Engineering of KU Leuven, was introduced to account for the primary sources of uncertainty.
  - The deterministic methodology was extended with a forecast module that generates probabilistic scenarios for residential consumption, PV generation, and EV usage. Particular attention was paid to scenario quality, emphasizing the trade-off between accuracy in representing uncertainty and the computational burden of optimization.
  - The 1st layer was upgraded to a two-stage stochastic MILP, incorporating various formulations for first- and second-stage decisions. Due to the discrete nature of uncertainty in EV availability, the problem was divided into two subproblems, each solving the two-stage SMILP over distinct scenario sets based on EV availability at the first timestep.
  - Different stochastic HEMS formulations were tested across two periods of the year, using datasets for EV availability from workplace and residential contexts. Two 2nd layer setpoint strategies were also considered: the expected value of second-stage variables and scenarios minimizing PV and load errors. The stochastic methodology proved to be resilient and effective, consistently outperforming the deterministic HEMS under all but one condition. Furthermore, the 2nd layer setpoint based on the expected value of second-stage variables demonstrated greater reliability and consistency than strategies focused on minimizing PV and load errors.

The stochastic HEMS was also shown to be deployable in real-world applications. The considered case study involving 2700 scenarios generated from the three independent uncertainty sources confirmed robust computational performance, with all operations executed within acceptable timeframes. The experimental validation of the developed EMSs was a significant activity in this doctoral thesis. The first activity was conducted in the MG2Lab at the Department of Energy in Politecnico di Milano to investigate the impact of load and solar forecast accuracy on the operational cost of an existing microgrid. A detailed analysis of EV forecasting error impact was conducted within a hierarchical predictive control strategy to optimize an EV charging station microgrid. Experimental results validated the operation of a multi-good microgrid using both PHANN PV and LSTM EV load predictions, combined with an EMS to minimize operational costs. The study confirmed that higher combined forecast accuracy improved EMS performance, though interactions between forecasters could lead to unexpected outcomes. For example, while LSTM provided the highest EV load accuracy, it resulted in poorer EMS performance when coupled with the PHANN PV forecast. Besides the interactions, LSTM is less accurate than persistence when electricity prices are high, resulting in higher operational costs. Experimental activities were also carried out for the deterministic HEMS. In collaboration with Edison, beta-testing experimentation evaluated the HEMS's capability for smart EV charging. The results were positive: the HEMS successfully satisfied user requirements, remained within household contractual limits, and replicated the economic and operational efficiencies demonstrated during offline simulations.

IMPROVED MODEL-BASED PM TEMPERATURE ESTIMATION FOR PERMANENT-MAGNET TRACTION MOTORS

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Within the context of global efforts to mitigate climate change, international policies targeting net-zero emissions have become a pivotal focus. The urgency to curb greenhouse gas emissions has led to the formulation and adoption of comprehensive strategies by governments and international organizations. These policies encompass the promotion of renewable energy sources, advancements in energy efficiency, and the integration of cutting-edge technologies across various sectors. Among these, electric vehicles in the automotive sectors have attracted enormous attention over the last two decades.
Among the available options for the electric traction motors, Interior Permanent Magnet Synchronous Motors (IPMSMs) are still widely used in the automotive sector, because of their high torque density and efficiency and wide operating speed range, despite their market price instability.
Besides international policies, the automotive industry requirements for performance accuracy are becoming increasingly severe and often cannot be achieved without considering permanent magnet (PM) temperature variations. In fact, PM temperature changes can lead to several problems such as: non-optimal operating conditions, a decrease in vehicle performance, and motor failure. Nevertheless, methods to directly measure the PM temperature are not yet palatable for automotive industry due to their cost and complexity. Therefore, real-time temperature estimation techniques are a viable and interesting alternative for the automotive industry.
Within the aforementioned context, this thesis examines innovative methodologies for real-time temperature monitoring of PMs, emphasizing their significance in enhancing motor performance and reliability in the context of sustainable development and performance requirements.
Among different estimation techniques, the main candidate is model-based temperature estimation relying on the IPMSM model at the fundamental frequency. However, to work properly, these estimators require an accurate IPMSM magnetic model, which is not always adequately considered in the implementation. Temperature estimators proposed by the research community adopt accurate models which are often based on experimental data from a single prototype motor, but this approach is not always adequate in the context of mass production. This thesis tries to fill this gap by adapting model-based estimators to temperature-dependent FEA-based accurate magnetic modelling and proposing a calibration strategy based only on a few tests.
Chapter 1 serves as an introductory framework for the rest of the work.
Chapter 2 addresses a topic merely instrumental to the PM temperature estimator investigated in the next chapters, by proposing a robust Flux-Weakening control scheme in order to properly work at high-speeds and with significant variations in the supply voltage.
In Chapter 3, two model-based PM temperature estimators are reformulated to couple them with a PM-temperature-dependent magnetic model which is fed by data already available for optimal motor control. Furthermore, thanks to a detailed sensitivity analysis, a hybrid PM temperature estimator combing a model-based PM temperature estimation method and a simplified thermal network is proposed. Chapter 4 discusses the results obtained from simulations and experimental tests to validate the PM temperature estimator accuracy.
Chapter 5 aims to generalise the temperature estimator for mass-produced IPMSMs by proposing a novel tuning approach which requires only the value of the no-load PM flux linkage at a reference temperature, therefore calling only for a single motor test at the end of the production line. Chapter 6 summarizes the main findings of this research and presents the recommendations for future work and developments.

EFFICIENCY OF AN ELECTRIC TRACTION SYSTEM CONCERNING THE IMPROVEMENT OF ELECTRIC ENERGY QUALITY AND THE REDUCING OF EMI THROUGH MULTI-DOMAIN DESIGN OF ELECTRIC DRIVE SYSTEMS, INCLUDING POWER CONVERTERS

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This thesis was developed as part of the *ETOPIA* project "European Training network Of PhD researchers on Innovative EMI analysis and power Applications: ETOPIA", funded by the European Commission, under the Marie Sklodowska-Curie Innovative Training Networks action, grant nr. 812753 [28].

This thesis had the goal of identifying issues in the power quality and electromagnetic compatibility within electric railway traction systems and suggesting improvements for these systems through multi-domain design analysis.

The research activities within the PhD were distributed across multiple sites of academic and industrial partners across the ETOPIA project. The low-frequency EMC issues

- Research of literature and modeling at University of Craiova, in Romania
- Converter EMC at various switching and output frequencies with no-load at Politecnico di Milano EMC lab, in Italy
- Converter EMC at various switching and output frequencies with constant load at University of Zielona-Gora EMC lab, in Poland
- Railway converter control for improving the EMC and PQ at industrial partner Softronic S.A., in Craiova, Romania

The thesis is structured in 4 chapters. The *STATE-OF-THE-ART*, *Chapter 1*, zeroes in on a series of directions of improving the PQ and EMC of ERTS were considered for development. These directions were chosen considering what could also be worked with industrial and academic partners of the ETOPIA project. The most cost-effective solutions were considered in applying EMC analysis techniques to determine conditions of optimal PQ and EMC performance in variable conditions of the ERTS. The applied research method in this chapter was literature research, both a quantitative and qualitative method.

Chapter 2, MODELLING OF ELECTRIC RAILWAY TRACTION SYSTEM FOR POWER QUALITY AND ELECTROMAGNETIC COMPATIBILITY, consists in developing, selecting and designing appropriate mathematical models for the entire ERTS, starting with the supply, leading through the entire energy chain to the electric motor, including power electronics and control methodology. These models were designed in MATLAB and MATLAB Simscape modules. The applied research method in this chapter was mathematical modeling of electric systems, a qualitative method.

Chapter 3, IMPROVEMENT OF THE FUNCTIONALITY OF THE POWER RECTIFIER FOR POWER QUALITY AND ELECTROMAGNETIC COMPLIANCE, is a presentation of a design process of a proportional-resonant control method of the four-quadrant rectifier that is the first part with power electronics on the rolling stock, connected to the railway power supply system.

For the rectifier optimization, the locomotives equipped with 4QR are controlled by symmetrical 3-level PWM techniques. The functioning of current topology, with the corresponding issues is creating resonant overvoltage on certain harmonic levels. The same type of locomotive, with the same hardware, but with the designed PR-controller presented the results. The designed control tested with a real locomotive show advantages of reduced harmonic distortion on the specified harmonic orders, and possibility of eliminating the identified harmonics, with addition of current harmonic orders in the process of designing the current control loop. The method to allow for the simplification of modeling was the large signal switched method, and the calculated control parameters showed valid results on test locomotives.

This validated method for the traction stage of the locomotive showed positive results, which can be developed for regenerative braking and stability analysis.

Chapter 4, IMPROVEMENT OF POWER INVERTER FED INDUCTION MOTOR DRIVE FUNCTIONALITY FOR POWER QUALITY AND ELECTROMAGNETIC COMPLIANCE, presents a series of practical contributions related to control selection for railway traction with simulated behaviors, and related to selection of switching frequency for asynchronous motors drives, which are the traction drives for most electric railway applications. The impact of the modulation frequency was tested with digitally controlled prototypes for both loaded and unloaded asynchronous motor drives, and for both constant and varying output frequency from the inverter. The control methods of rotor-field oriented control and direct torque control were selected for simulations due to them being the most robust and most used control methods for traction applications. Thus, the research on *Inverter Optimization, in* the case of vehicles, shows that the DM current will leak through the mechanical moving parts, causing them to deteriorate faster, and will vary depending on frequency parameters of the switching devices and output of the inverter. Industrial producers of VFD equipment should test the systems with such conditions, adding an application specific load profile to the motor, to ensure that the electric drive serves reliably and does not distort the power quality and EMC in the grid.

The complex model of the ERTS will provide a good foundation for implementing novel design improvements for the functioning of the ERTS. It needs some more tuning to being a higher fidelity model to real object. The developed control methods also need stability analysis in future works to ensure that the control systems of the locomotives are robust to outside effects.

The electric drive and switching frequency variation output and impact on the PQ, EMC and LF-EMC need more research and development to improvement of analysis, evaluation of risk and work with novel standards in the field. The work with this field will continue as part of the TC7 in EMC Society.

ADVANCED ALGORITHMS FOR OPERATING PHOTOVOLTAIC AND BATTERY SYSTEMS WITHIN THE DIGITAL TWIN FRAMEWORK

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Tutor: Loredana Cristaldi

The urgent need to address climate change and reduce dependence on fossil fuels has led to an unprecedented integration of renewable energy sources in the global energy mix. Over the past decade, the adoption rate of photovoltaic (PV) systems has seen a particular surge driven by their declining costs, improved efficiency, and modular nature. Despite this rise, PV energy remains inherently intermittent and largely non-dispatchable. As a result, the inclusion of battery storage has become imperative for large-scale PV installations to comply with current and future grid regulations, as well as to provide valuable market-oriented services. This thesis proposes multiple model-based (MB) and data-driven algorithms for the purpose of optimizing operation, monitoring and predictive maintenance of PV and battery systems.

The first one is an existing MB algorithm for maximum power point tracking of PV systems which is able to quickly converge to the maximum power, thus outperforming the common tracking techniques during dynamic weather conditions However, to remain accurate, the MB algorithm also requires new data to periodically update its parameters, which was initially obtained by turning off the system, resulting in loss of production. To overcome this limitation, this thesis introduces a solution that occasionally switches to the Perturb and Observe (P&O) algorithm, allowing the PV system to remain operational while collecting the necessary data. The effective operation of the combined MB and P&O algorithm is demonstrated on a large dataset collected over a 6-month interval. Furthermore, the optimal parameter update strategy is presented, ensuring continuously accurate tracking while minimizing the computational burden on the hardware.

The growing presence of PV plants has resulted in a reduction of the grid's inertia, thereby diminishing its capability to perform the vital function of primary frequency regulation. Enabling direct participation of PV systems in this process, without costly battery storage, can only be achieved by operating PV plants with a constant active power reserve across various environmental conditions.

This thesis enhances the MB algorithm precisely for this purpose. Firstly, the algorithm's capability to operate at any power ratio between 20% and 100% of maximum available power is demonstrated. Subsequently, it is shown that the algorithm can indeed enable a PV system to maintain a constant active power reserve during varying environmental conditions.

Lastly, a grid level simulation is implemented, showcasing a 100 kW PV system's ability to fully engage in primary frequency regulation when utilizing the developed algorithm.

Moreover, various data-driven models have been developed to predict the key battery parameters, state of health (SoH) and remaining useful life (RUL). Initially, models based on various machine learning (ML) strategies including linear and polynomial regression, random forest and support vector regression (SVR) were analyzed and compared for the purpose of SoH estimation. Among these, models employing SVR exhibited superior performance. Consequently, the efficacy of this ML strategy was further tested on a more substantial dataset, once again yielding successful results. Finally, a Long Short-Term Memory neural network was devised, for the purpose of RUL prediction, selected for its ability to retain information over extended periods, making it particularly suitable for this task.

ENERGY MANAGEMENT SOLUTIONS AND CONTROL OF RENEWABLES/STORAGE UNITS FOR SUSTAINABLE MOBILITY

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The increasing integration of renewable energy sources and energy storage systems into microgrids necessitates advanced control and energy management strategies to optimise efficiency, stability, and sustainability. This thesis explores novel methodologies for enhancing microgrid operations through digital twin modeling, intelligent energy management systems, and optimized power conversion techniques. Various smart energy management algorithms are explored, focusing on their role in balancing energy supply and demand while ensuring system resilience. Additionally, the study examines power converters, particularly DC-DC converters, essential for efficient energy distribution within microgrids.
The review highlights the challenges in existing energy management approaches and identifies research gaps, providing a strong foundation for the proposed methodologies in subsequent chapters.
The thesis introduces the development of a digital twin for the MultiGoodMicrogridLab, highlighting its role in virtualizing physical microgrid operations for enhanced monitoring and optimization. The digitized microgrid model incorporates generated photovoltaic (PV) power, load profiles, and battery energy storage system(BESS) dynamics, enabling a comparative analysis of grid power exchanges. This digital twin serves as a robust platform for implementing and evaluating energy management and control strategies through extensive simulations in MATLAB/Simulink. The accuracy and reliability of the digital twin are validated by comparing simulated results with real-world data, ensuring that the digital model effectively represents the actual microgrid behaviour. Furthermore, the integration of advanced analytics and machine learning techniques within the digital twin framework allows for real-time system diagnostics and predictive maintenance, improving overall grid performance and resilience. Focusing on energy management in autonomous systems, the research proposes a neuro-fuzzy-based energy management system for a PV-Fuel Cell grid-connected microgrid, which supports e-mobility by efficiently managing power flow. A cost-effective fuzzy logic-based demand-response system is also developed to optimise power distribution between batteries and PV systems. Additionally, a fuzzy logic-based approach for integrating solar and grid power in electric vehicle charging and load balancing is introduced. These methodologies are validated through simulations and have been partially published in peer-reviewed journals and conferences.
The thesis provides a detailed discussion of the computational framework, algorithm design, and simulation outcomes, demonstrating how these intelligent systems contribute to enhanced energy utilization and system efficiency. The proposed energy management approaches also incorporate real-time monitoring and adaptive control mechanisms, ensuring dynamic response to fluctuating energy demands and supply variations. Further advancements in fuzzy logic-based energy management are explored with the introduction of a Grey Wolf Optimized Fuzzy Logic Controller for DC microgrids, which enhances stability and efficiency. The research also examines a nonlinear sliding mode controller (SMC) for optimized energy management, demonstrating its robustness under varying conditions through experimental validation and MATLAB/Simulink simulations. A comparative analysis is conducted between conventional energy management strategies and the proposed optimization techniques, highlighting key improvements in response time, energy efficiency, and system reliability. Furthermore, sensitivity analyses are performed to evaluate the impact of different parameters on system performance, ensuring the robustness and adaptability of the proposed methodologies. The role of converters in hybrid energy systems is also investigated, particularly in integrating fuel cells, batteries, and supercapacitors using interleaved DC-DC converters. A dynamic model of these components is developed to understand their contributions to energy storage and supply. Closed-loop control strategies for these converters are analyzed to improve energy management efficiency. The performance of the optimized converter design is validated through MATLAB/Simulink simulations and has been presented in leading IEEE conferences. Additionally, the impact of different converter topologies on overall system performance is examined, ensuring the most effective design choices for various operational scenarios. Finally, the thesis explores real-time testing of DC-DC converters using Typhoon/SCADA hardware-in-the loop (HIL) simulations. A voltage tracking system for PV applications is implemented, demonstrating the effectiveness of the HIL setup, validating converter performance under various operational scenarios. The implementation of advanced control strategies within the HIL framework allows for real-time testing and optimization, ensuring reliable converter operation in diverse environmental conditions.
The methodology and results have been published in a Springer book. Overall, this research contributes to the advancement of microgrid energy management by integrating intelligent control techniques, digital twin modeling, and optimized power conversion strategies. The findings offer valuable insights into improving the efficiency, stability, and resilience of future energy systems, aligning with the growing demand for sustainable and autonomous energy solutions. The proposed methodologies provide a scalable and adaptable framework for next-generation smart grids, enabling more reliable and intelligent energy distribution systems. The conclusions drawn from this research pave the way for further developments in microgrid optimization, hybrid energy system integration, and real-time energy management applications.