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 | 2024

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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OPTIMIZED STRATEGIES FOR THE SCHEDULING AND DISPATCH OF DISTRIBUTED ENERGY RESOURCES: A MILP-BASED FRAMEWORK

Francesco Gulotta - Supervisor: Davide Falabretti

Electric power systems are currently undergoing a transition towards decentralization, with small-scale distributed units playing an increasingly pivotal role in energy generation. As the phasing-out of fossil fuels continues, the significance of distributed energy resources is growing, not only as sources of primary energy but also as providers of crucial ancillary services. To facilitate this transition, it is imperative to open the national ancillary service market to a broader spectrum of units and develop holistic strategies to optimally exploit these resources. This doctoral research introduces a comprehensive architecture designed to optimize the scheduling and operation of an aggregated set of distributed resources across all decision-making phases. The system operates as follows:

i) The participation in the reserve balancing auction is performed by a MILP-based model that evaluates the flexibility margin available by simulating the aggregate medium-term planning.
ii) The participation in the day-ahead market is optimized through a two-stage stochastic programming model, which accounts for forecast uncertainties in energy requirements for the following day.
iii) The real-time dispatch of the flexible resources is obtained by adopting an innovative rolling-horizon stochastic programming model, which considers also the evolution of the short-term uncertainties.
iv) The aggregate's bidding strategy on the ancillary service market is optimized using an iterative MILP model combined with a constrained k-means clustering method.

Numerical simulations are conducted to prove the effectiveness of the proposed models, using as a reference the current Italian regulatory framework. The proposed architecture is tested considering an aggregate composed of residential prosumers equipped with; rooftop photovoltaic (PV) plants, non-flexible loads, Energy Storage Systems (ESSs), water heaters, and Electric Vehicle (EVs) charging stations (see Figure 1).
The novel approaches are compared with state-of-art methods and business-as-usual scenarios to assess the benefits. The techno-economic analyses are performed both from local and systemic perspectives. The local perspective evaluates the economic advantages of the proposed strategies both for users and aggregators, while the systemic one enables the assessment of the benefits of the ancillary service provision by distributed energy resources in a predominantly decarbonized electric power system. In this regard, a 2030 energy scenario compliant with the latest European Green Deal is simulated and the values of the flexibility margin of distributed energy resources are accurately evaluated.

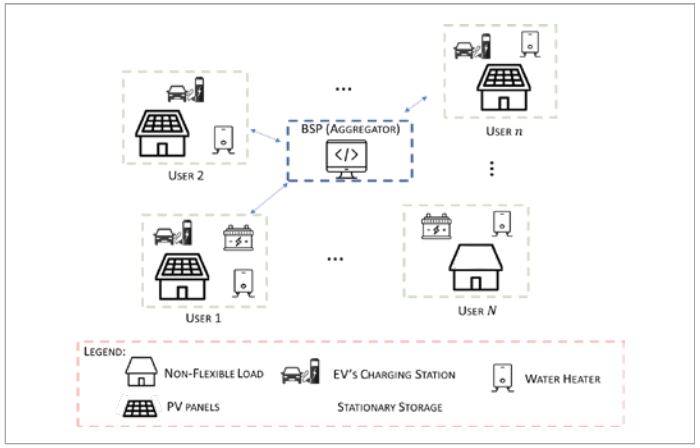

Fig. 1 - Schematic representation of the aggregate under study.

POWER ELECTRONIC DEVICES FOR POWER QUALITY AND CUSTOM POWER TO ENABLE END-USERS AND DISTRIBUTION SYSTEM OPERATORS IN LOW VOLTAGE SMART GRIDS : THE EVOLUTION OF OPEN-UPQC

Akkala Naga Venkata Kishore - Supervisor: Roberto Faranda

Electrical Power System is in an ongoing transformation towards becoming a sustainable energy supply network shifting towards new paradigms called Smart Grids and Microgrids. The majority of this transformation is happening in Low Voltage (LV) networks where the End-Users and the Distribution System Operators (DSOs) emerge as key stakeholders. Due to this, the End-User forms a new entity called Prosumer and the role of DSOs changes from an energy supplier to a service provider managing the network.

Under this new framework of Smart Grids, Prosumers must be capable of microgeneration and manage their energy production/ utilization. In addition, they have to participate in ancillary services like demand response and grid support. They also need to be an ideal load connected to the network by managing their reactive power and harmonic injections. Under certain conditions they must also be able to operate in islanded mode. On the other hand the DSOs face challenges related to the network operation and management, where power quality is a major issue. Power quality issues for DSOs can mainly be attributed to the Voltage. These can be characterized as swells/sags, flickers, deviations in the voltage from nominal value. Moreover, given the LV network is less monitored, DSOs require a system which can provide visibility and controllability of the network within the Smart Grid framework.

In order to address the issues mentioned, the novel concept of Open-Unified Power Quality Conditioner (Open-UPQC) is a promising solution, both from End-User and the DSOs perspectives within the context of Low Voltage (LV) Smart Grids.

The aim of this PhD research is to advance the technology of Open-UPQC which consists of Shunt Units which enables the End-Users and the Series Unit which enables the DSOs for the Smart Grids. This thesis provides promising algorithms and system designs for the Open-UPQC. For the Shunt Unit, capabilities to harvest the solar energy from Photovoltaics are integrated to address residential prosumers, and a new three-phase unit is designed to address the medium power prosumers. These advancements provide desirable functionalities to the End-User transition to prosumer and an easier integration into the Smart Grid framework. For the Series Unit, novel algorithms which allow voltage compensation in the active bidirectional network, deterministic active power management, Fault Current Limiting (FCL) are designed. These novel algorithms make the Series Unit an effective device and a powerful tool for DSOs in managing the network voltage and hence power quality.

The advancements to Open-UPQC are validated using simulations and experimentally validated in the real network for the Series Unit. The results demonstrate the novel designed capabilities of the Open-UPQC, equipping the End-Users and DSOs for the LV Smart Grids. The designed algorithms and systems are of particular interest both in industry and academia. Given the contributions from this research work to Open-UPQC, it can be considered a major iteration which can be further advanced and tested in real network.

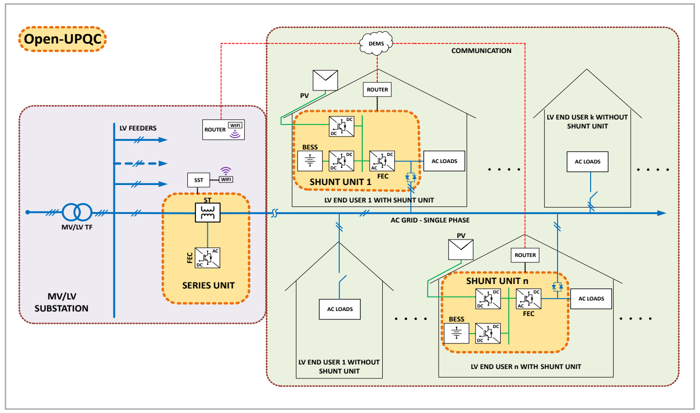

Fig. 1 - Open UPQC Block Diagram

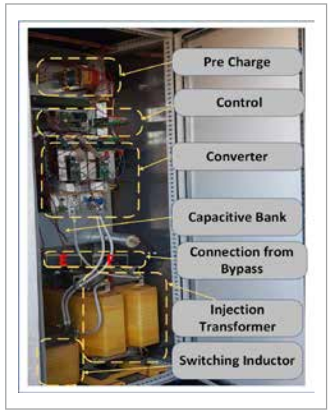

Fig. 2 - Series Unit

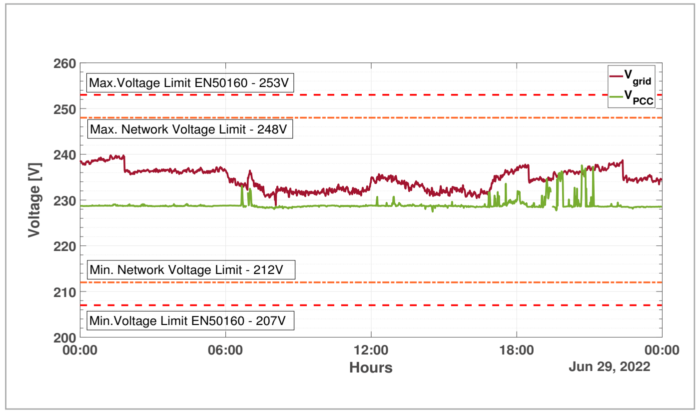

Fig. 3 - Experimental Results from Real Network

SPMSM-BASED ELECTRICAL DRIVE AT/ABOUT TORSIONAL RESONANCE: ANALYTICAL MODELLING AND CARRIER-SHIFT DAMPING METHOD

Dejan Pejovski - Supervisor: Roberto Perini

Electrical drives are inevitably subject to torsional vibrations originating from mechanical and electrical sources. The most common ones are harmonics in the motor power supply, non-sinusoidal back-emf, load oscillations, bearing and gearbox faults and shaft misalignment. Consequently, torsional vibrations increase audible noise, accelerate shaft fatigue, reduce the drive-train lifetime, and can cause mechanical damage with shaft breakdown as the worst outcome. Therefore, understanding and monitoring the vibrations, as well as applying suitable damping technique whenever necessary, is essential for any electrical drive.

In this doctoral thesis, the electrical drive under study consists of a three-phase voltage-source inverter supplying a surface-mounted permanent magnet synchronous motor (SPMSM) that is coupled to a dc generator. The mechanical coupling is realised by a torque meter and two joints connecting it to the shaft. In this way, as in any electrical drive, the shaft transmits the twisting torque from one end to another because of its finite stiffness. In such drives, torsional vibrations rise because of the inverter modulation technique, i.e. its discrete switching. In fact, voltage harmonics supplying the motor generate current harmonics in the windings, which, in turn, create electromagnetic torque ripple. These torque harmonics propagate through the shaft torque and the machine speed back to the drive control system. Classical rotor-field oriented control is engaged with maximum torque-per-ampere algorithm. In many drives, the control system has limited dynamic performances and cannot damp these torsional oscillations.

This electrical drive is described in the thesis from a mathematical point of view, as a seventh-order system of differential equations that account for SPMSM electrical dynamics, mechanical rotation aspects and speed/current control. The all-inclusive analytical model can predict electromagnetic and shaft torque harmonics originating from a voltage harmonic injected in the motor. The model is particularly useful when the drive operates at/about the mechanical resonance. Another important model output is paired current harmonics that exist at/about resonance: this phenomenon is explored in detail in the thesis and is used for predicting mechanical resonance by monitoring the line current harmonics. The robustness of the proposed analytical model is investigated with respect to the load torque, drive inertia ratio and control system bandwidths.

In case a torque meter is not available, various observers can be applied to estimate the angular position of both rotating machines as well as the shaft torque. In this thesis, a detailed step-by-step procedure is developed for defining and designing a nonlinear extended-state observer (NESO) for multi-input single-output system, such as the electrical drive of interest. The contribution here, besides the comprehensive procedure, is in the analysis of different aspects related to the observer design parameters.

Another section of the thesis proposes a non-invasive, efficient and cheap method for damping torsional vibrations by changing the carrier signal used in classical pulse-width modulation. The method consists in repeatedly shifting the phase of the carrier signal while the drive operates at/about torsional resonance. Consequently, the phase of a critical torque harmonic is altered by 180o and its harmonic content is modified so that no harmonics match the drive natural frequency anymore.

The main thesis topics, i.e. the analytical drive model which predicts electromagnetic and shaft torque and paired current harmonics at resonance, the NESO for torque harmonics estimation and the carrier-shift vibration damping method are validated by extensive Matlab/Simulink simulations and by laboratory tests using a setup of 6.9kW SPMSM. A rather good match between the results of the mathematical models, simulations and experimental tests is obtained, along with an in-depth discussion of the discrepancies noticed.

STOCHASTIC PROCESS MODELING AND DISTRIBUTED DECISION MAKING FRAMEWORKS IN SMART GRID SYSTEMS

Federico Rosato - Supervisor: Marco Merlo

Renewable energy sources are typically more environmentally friendly than traditional sources of energy. In addition, they can help to reduce strategic dependence on foreign sources of energy and can potentially provide more stable and secure power supply. However, their integration in the grid is limited by their stochasticity and non-controllable peak production times. At the same time, the increasing diffusion of smart loads such as Electrical Vehicles, stationary batteries and flexible appliances unlocks novel degrees of freedom that can be leveraged to tackle this problem by storing energy production and shifting energy consumption. Moreover, emerging and flexible models for the organization of the economic transactions associated with the energy flows, such as Energy Communities, offer a vehicle for exposing incentive signals to the final users, steering their behavior in a way that is most advantageous for the energy system at large.
All these elements paint a complex techno-economical scenario in which comprehensive solutions for the control of flexibility have to be implemented for meeting these needs. Simplicity of implementation is also an important element, favoring solutions based on non-invasive control of independent, autonomous agents based on incentives. In this work, the use of dynamic optimization techniques for training automated controllers able to deal with this multi-faceted situation is proposed. The framework produces sensible solutions that take into account at the same time user preferences and comfort, price signals, stochastic energy production and stochastic usage of the appliances. The problem is framed in the formalism of Stochastic Games, the random phenomena involved are accurately modeled and, after a detailed contextualization with respect to current research, an algorithm is proposed for the elaboration of sensible strategies.
The strategies are then analyzed and visualized to gain insights into the behavior of the automated agents. The operation of a community of agents as a provider of flexibility within the current market and legal framework is sketched; with the aid of the tool, the economic viability of this setup is analyzed, as a function of the appropriate parameters.
Finally, a simulation of the agents togeter with synthetic electric grids is performed to verify their grid impact and the effect of the tunable parameters on the impact itself; in order to create a suitable testbed for the simulation campaign, an urban grid synthesis tool from public geographical data is developed and presented.
In essence, the main scope of this work is to present a modelization of the flexibility management problem as a stochastic game and a novel flexibility quantification tool that can be used to predict the reaction of autonomous agents managing flexibility in the face of exogenous signals and under different parametrizations of the model.

REAL-TIME ASSESSMENT AND MONITORING OF OSCILLATIONS IN POWER SYSTEMS

Andrea Vicario - Supervisor: Alberto Berizzi

Electromechanical mode estimations have been largely analyzed since the beginning of the interconnected power systems, but they have gained a lot of interest in the last decade. As a matter of fact, the increasing size of the grids and the huge deployment of renewable energy sources based on electronic converters are reducing the damping properties of the systems, leading to instability.

This work aims to provide a methodology to estimate electromechanical modes using PMU data in real-time. In particular, this Thesis presents the studies and the assumptions that led to the practical implementation of the Dynamic Mode Decomposition approach adopted by the Italian Transmission System Operator, Terna, in its control room for the real-time monitoring of frequency oscillations in the Italian power system. Furthermore, it presents the detailed approach and the criteria to generate a reliable alarm signal in the case of critical interarea oscillations in a power system. Indeed, the proposed method allows system operators to identify the frequency, damping, and mode shapes of the most significant modes and issue suitable alarms in case of instabilities. Such criteria are the outcome of a massive testing campaign conducted in 2020 and 2021, where different variants have been tested and the best approach set and tuned.

Even if the research on Dynamic Mode Decomposition theory is now well-established in power systems and applied to both synthetic and real data, its ability during fast transients, like short-circuits or normal load variation, the possibility to issue alarm in case of critical operating conditions, and its real-life implementation in a TSO control room have not been explored yet. This Thesis provides the complete analysis that leads to the implementation of the Dynamic Mode Decomposition in a TSO control centre where the data stream from WAMS is elaborated and processed. Indeed, since 2021 the Dynamic Mode Decomposition output has been used to monitor and control the Italian power system, managed by Terna, in its interconnected operation with the European system. The implementation has been possible thanks to the deep analysis carried out in a small test system, which provided the limitations but also the strengths of the Dynamic Mode Decomposition for this specific application. The main contributions of this Thesis can be summarized as follows:

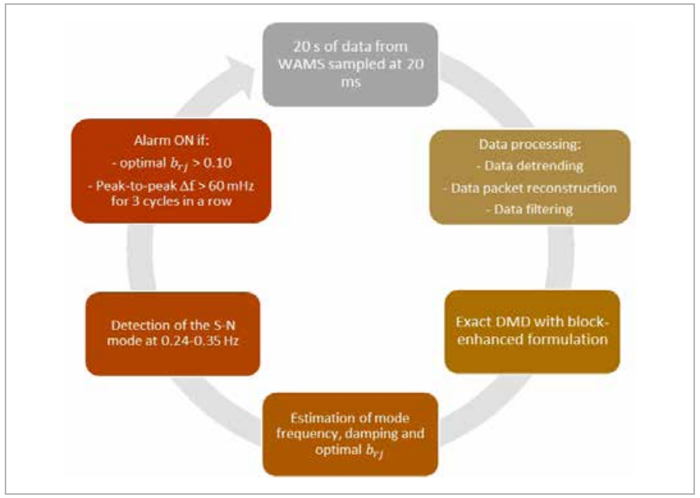

Fig. 1 - The flowchart of the proposed procedure.

- The application of the Dynamic Mode Decomposition to a small but significant test system to detect and characterize oscillatory interarea modes (frequency, amplitude, damping, and modes-shapes). The exact Dynamic Mode Decomposition formulation and the block-enhanced variants are deeply investigated, and the results are compared. In particular, the analysis focuses on the type, the number of data sets analyzed, and the time window size. The results are assessed in terms of the accuracy of the estimation to respect a traditional modal analysis.

- The proposal of three different mode indexes to identify the dominant modes. All three indexes are studied and validated with the analysis of the test system. Then, one is selected for the control room application in terms of reliability and selectivity. Indeed, it provides an amplitude index in p.u. in the range [0-1], regardless of the number of measurements processed, simplifying the setting of a possible threshold for alarm in case of sustained oscillations.
- The implementation and the validation of the method within the WAMS Terna's environment. In particular, the analysis of different real oscillatory events and normal grid operation, the determination of conditions to issue alarms for the control room to trigger possible countermeasures, and the investigation of the Dynamic Mode Decomposition properties in the presence of ambient signals characterized by normal load behaviour, noise, change of operating conditions and topology, etc.
- The analysis of another power system, working at a different frequency, to validate the estimation quality.

In particular, the best setup for the real-time monitoring of the Italian system tool is derived. The contributions have been identified after a two-year test campaign on the Italian power system, and thanks to the research activity spent with the dispatching engineers at the Terna control center. The results presented in the Thesis show very good robustness in all different power system conditions and very good accuracy compared to other methods tested. Also, the identification of mode shapes is accurate and in agreement with the operational experience of the control room engineers and the ENTSO-E (the European Network of Transmission System Operators for Electricity) studies.

Thanks to its adoption in the control room, this method makes it possible to alert operators in the case of sustained interarea oscillations. The approach utilizes the most interesting properties of the method, such as the decomposition over time and space, the optimization over a time window, the accuracy, the robustness, the information content, the limited computational complexity, and the possibility of exploiting its properties in real-time. Indeed, the Dynamic Mode Decomposition takes advantage of different mode amplitudes, enabling real-time tracking of the most significant electromechanical modes. The estimated electromechanical modes are characterized by higher energy values, whereas the numerically transient modes are simply discarded. The performance is validated using the presented results and analyses. The adopted indices, threshold set, and overall monitoring system are demonstrated to be reliable and robust under different operating conditions, as reported.