DOCTORAL PROGRAM IN ELECTRICAL ENGINEERING

Chair:
Prof. Alberto Berizzi

The main objective of the PhD Program is to allow a direct, prompt and productive involvement of PhDs in any research body such as an R&D department of a production or services company.
A PhD in Electrical Engineering has a solid basic knowledge of 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 circuits and electromagnetic fields as well as methods and applications in the main disciplines of Basic Electrotechnics, 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 presented in the PhD dissertation.

The main research areas are:

A) Circuits and Electromagnetics:

This field is intended to provide the basic knowledge of methods in electrical engineering for power applications. The 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 methods for 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 involves studies in the following subjects: Electrical energy production (e.g., frequency and voltage control, protection systems, renewable energy sources, dispersed generation and Smart Grids); Electrical energy transmission (e.g., power system analysis and dispatch, optimization of real and reactive power, security and stability, integration of renewables by probabilistic methods); Liberalized market issues (e.g., market models, ancillary service management, regulatory issues); Power quality and distribution systems (e.g., line current harmonic distortion, active filters, UPS, interruptions and voltage dips, direct current distribution); Optimization by innovative algorithms (Neural networks, Genetic algorithms, etc.).

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 structures of digital signal processing. Some of the main subjects of study are: measurement methodology as it relates to power systems, and both digital and analog signal processing. Methodologies and measurement systems associated with industrial automation and, in particular, microelectronic sensor applications, field bus based hierarchical and distributed structures, and advanced algorithms are studied in detail.

The PhD Course in Electrical Engineering is organized on a time horizon of three years. Each year, the PhD carries our both didactic and research activities and at the end of each year he is evaluated by the PhD Board.
During the first year, the students carry out a training activity thanks to courses specifically designed for the PhD (Main Courses). At the same time, the students must select, among the proposed dissertation subjects, the subject of their research, and must prepare a "Research project". The choice of the subject must be approved by the Supervisor and by the Board. Moreover, they have to deeply investigate the subjects related to the proposed area of research by means of a bibliographical research.
The second year is dedicated to complete the training through the basic PhD Courses, as well as to the acquisition of specialized skills necessary for the final dissertation that will be completed during the third year. Students are required to carry out a specific training for research through specialized seminars, conferences, and research activities closely associated with the topic of dissertation, and are encouraged to perform research activities in an international framework.
The third year is entirely dedicated to the PhD dissertation. Four months before the deadline to deliver the dissertation, each student is examined by the Board to verify the work done. If the research performed is evaluated as adequate, the student is allowed to write his dissertation, that will be evaluated by an international Commission.
After graduation, PhD are typically employed at:

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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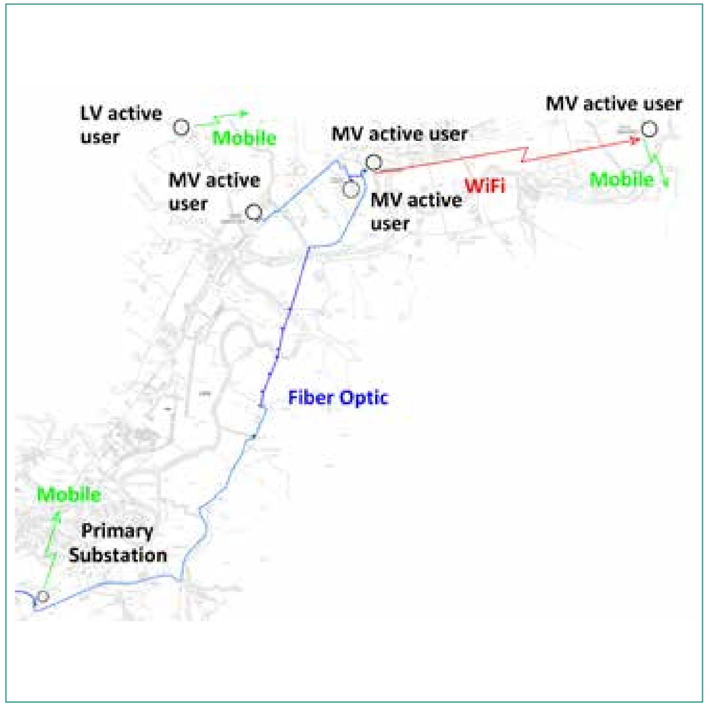
TECHNICAL AND REGULATORY ANALYSIS OF SMART GRIDS: A FOCUS ON NETWORK RECONFIGURATION AND ENERGY STORAGE

Davide Falabretti - Supervisor: **Maurizio Delfanti**

Today, the fulfillment of global energy needs is becoming more and more challenging, driven by a sharp increase in prices of traditional energy sources and by the need to reduce greenhouse gas emissions. These global requirements led institutions to launch a series of economic initiatives to encourage the use of Renewable Energy Sources (RESs). However, the power plants converting RESs (such as solar radiation, wind, hydro, etc.) into electrical energy have generally a small size and are connected to the Medium Voltage (MV) and Low Voltage (LV) networks. Therefore, a great change in the power systems structure is occurring: the electricity production, traditionally performed by large power plants connected to the transmission system, is now involving increasingly distribution networks.
This new scenario, known as Dispersed Generation (DG), allows to increase the RESs exploitation, in the direction of a more sustainable future and, if properly faced, to achieve great benefits in the network operation (reduction of the energy flows along lines, losses decrease, investments deferral, etc.).
However, the DG penetration has also a number of impacts on power systems. At distribution level, the issues are mainly related to the new active behavior of networks, which have been designed and operated to date as passive systems. Significant drawbacks concern also the RESs unpredictability and variability, with negative effects on the need of dispatching resources and on the power systems security and efficiency (e.g. reduction of the number of plants able to provide the primary frequency regulation).
This thesis work investigates some solutions to face with the DG impact on power systems and to improve the grid efficiency and reliability, toward the evolution today commonly known as Smart Grid.
Among the many features provided by such novel systems, the research focuses initially on the network reconfiguration, as a useful tool to improve the performance of the distribution supply service. To this purpose, different objective functions are taken into account: continuity of service (number and cumulative duration of interruptions per MV/LV user, SAIDI and SAIFI, as stated by Resolution ARG/elt 198/11 of the Italian Regulating Authority), energy efficiency (losses over a whole year of operation) and hosting capacity for RESs (ability of the grid to accept new DG plants). An algorithm is proposed to optimize the MV networks configuration w.r.t. these performance indices, managing both the cases of static and dynamic network configuration (i.e. grid topology fixed or changing over time). The effectiveness of the approach is assessed on the model of a real MV distribution grid located in central Italy (A.S.SE.M. SpA).
A.S.SE.M. network is also involved in the Smart Grid pilot project incentivized by the Authority according to Resolution ARG/elt 39/10. The project includes the DSO's devices installed in primary substation and over the grid, five MV users and one LV user (Figure 1). The project management is in charge to the Politecnico di Milano – Department of Energy. The following innovative features are provided: increase of the reliability of active users loss of mains protections by transfer trip (to prevent unintentional island operation and nuisance tripping); logic selectivity among the protections; voltage control by DG; DG monitoring and control to improve RES dispatchability.
As further element of the Smart Grid architecture, Energy Storage Systems (ESSs) are studied. According to Resolution ARG/elt 199/11, Italian TSO (and DSOs) are allowed to install electrochemical ESSs (batteries) on their grids, on condition that these devices are included in experimental projects approved by the Authority. Some technical analyses have been performed as a base for a regulatory procedure put in force to incentivize the experimentation of ESSs in the Italian power system.
To this purpose, the thesis explains the rules and criteria, defined in collaboration with the commission of experts having in charge the selection process (composed by members of the Politecnico di Milano, Department of Energy, and RSE), to select the requests of incentive for the ESSs demonstration projects. On the transmission level, the selection process started with Resolution 288/12/R/eel (while on the distribution level a consultation process will follow).
The projects ranking is based on a performance index ("IM") assessed according to a semi-quantitative analysis. Among the many benefits which can be fulfilled through the ESSs on the transmission system, the key role is attributed to the solution of congestions on critical segments of the network made possible by ESSs. In this way, by shifting over time the wind energy which would exceed network capacity, ESSs prove to be useful to allow a better integration of RESs in the electric system. The ratio between the energy savings and the cost of investment defines the quantity "RBC", used as a base for the ranking.
To gain access to the selection procedure, each project proposal must refer to a well-defined portion of the transmission system affected by congestions. The grid must be equipped with control systems devoted to assess the network transit limits as a function of external conditions (dynamic thermal rating), thus maximizing the exploitation of the network ampacity. As mandatory features, the project has to provide, during all the operational conditions, primary frequency regulation within a bandwidth of ±5% of the ESS rated power for at least 15 minutes and to perform the reactive power flows regulation by the static converters equipping ESSs, with the purpose to adjust the voltage profile on the network.
The judgment of the commission of experts is also about the compliance of the proposals with further technical and optional features ("Qtec"; "Qopz"), such as the splitting of the overall storage capacity on more devices, different ESSs technologies adopted in the same project, advanced primary frequency regulation performances, RESs forecasting with collection of weather data.



1. A detail of the structure of the Smart Grid project

DEVELOPMENT OF MEASUREMENT METHODS FOR IMPULSE CURRENTS IN ELECTROMAGNETIC LAUNCHERS

Roberto Ferrero - Supervisor: **Roberto Ottoboni**

An electromagnetic launcher is a device in which a conversion from electrical energy to kinetic energy occurs, with the aim of accelerating a projectile. This energy conversion is carried out by means of the Lorentz force arising from the interaction between a magnetic field and a current flowing in a conductive armature of the projectile. Electromagnetic launchers find several applications, both military and civilian, and they are particularly attractive because of their theoretical possibility to reach very high launch velocities.
A possible electromagnetic launcher structure is the so-called rail launcher (or railgun), which is composed of a couple of parallel rails connected to a power source (e.g. a capacitor bank) at the breech end; the circuit is closed by an armature placed between the rails and electrically connected to them through a sliding contact.
Focusing on the case of solid armatures, the launcher efficiency and lifetime depend, among other factors, on the current distribution within the armature and at the rail-armature interface. An evaluation of this current distribution is in general too complex to be theoretically achieved (either analytically or via numerical simulation), because of the many involved phenomena with multiphysics aspects; for this reason the development of accurate measurement techniques is particularly important to better understand the physical processes defining the armature behavior and consequently to improve the launcher design.
This thesis reapproaches the problem of measuring the current distribution in multi-brush solid armatures, i.e. in armatures composed of several brushes connected in parallel between the rails, in different positions along the launch direction. In this case the current distribution within the armature is described in a first approximation by the knowledge of the current flowing in each brush. To measure these brush currents, a new method is developed, based on the use of external pick-up loops magnetically coupled to the launcher circuit, with suitable geometry and properly positioned on one side of the launcher; in more details, the loops are rectangular, their sides are much longer than the brush length and they are placed in perpendicular planes with respect to the launch direction.
The main characteristic of this method is its conceptual simplicity (concerning both its physical basis and the circuit geometry) that allows to formulate a simple but accurate analytical model of the mutual inductances between the loops and the launcher circuit, necessary to reconstruct the current distribution from the measured fluxes linked to the loops. The analytical model is derived using the partial inductance approach, which is particularly useful for circuits whose active sides are straight wires.
Having an analytical model at disposal, a parametric analysis of the proposed method is carried out, providing useful general results independent of the particular experimental setup. In more details, the method sensitivity and the model uncertainty are analytically evaluated, as well as the propagation of this uncertainty to the uncertainty of the current distribution reconstructed according to the model. This represents an intrinsic uncertainty contribution of the method itself, independent of the measurement uncertainties of all the measured physical quantities. The evaluation of this uncertainty allows in turn to identify in which conditions the method is more suitable to be applied and, on the other hand, in which conditions it is not able to provide meaningful results because of a lack of sensitivity.
Furthermore, the proposed method is compared on a theoretical basis to methods based on local magnetic field measurements; for this analysis, local field measurements are represented by small directional sensors, such as Hall or B-dot probes. The comparison reveals that the sensor position uncertainty becomes critical for local measurements when the sensors are very close to the currents to be measured, whereas this uncertainty is much less critical for integral flux measurements; in this case the advantage of big pick-up loops is maximally exploited. Another important advantage of the big loop size is represented by the lower induced voltages on the measurement circuits that connect the sensor to the signal acquisition system. Indeed, these induced voltages represent a critical issue for small sensors placed close to the launcher circuit, where the time-varying magnetic field is much higher.
The validity of the formulated analytical model for the mutual inductance calculation and the above hypotheses about the negligible effects of undesired induced voltages on the measurement circuit are verified by an experimental analysis carried out on a homemade launcher prototype, appositely built at the University of Pisa. The launcher is fed by a 765 μF capacitor bank with 38 kJ maximum energy, which can produce current pulses with peaks over 100 kA, reached in about 100 μs. As a case study, an armature with two brushes is employed and the pick-up loops used to reconstruct the brush currents are up to 16, covering the maximum expected acceleration path of the projectile. The total launcher current is measured by a homemade Rogowski coil, to provide additional information that can decrease the uncertainty of the brush current reconstruction provided by the pick-up loops.
The mutual inductance model and its uncertainty are verified in static conditions (i.e. with no armature movement), obtaining a very good agreement between model and experimental data. Then, first measurements of the current distribution between the two brushes are performed again in static conditions, in order to be able to validate the results by independent measurements provided by small Rogowski coils placed around each brush.
For what concerns measurements during launch, an additional issue that needs to be addressed is the measurement of the armature position during launch, which is needed for the mutual inductance model. At this stage of the work, this measurement is based on the mechanical interruption of electrical circuits passing through the barrel. Preliminary results of current distribution measurements are presented, but unsolved technical difficulties prevent from achieving high launch velocities, thus the path covered by the projectile is much shorter than what expected. Nevertheless, the measurement method is successfully validated in a benchmark condition (using only one brush) and this encourages further investigations.
Finally, a coaxial shunt with a double-cage structure is designed for the total launcher current measurement, as an alternative method to the use of the Rogowski coil. A fully analytical model of the shunt resistance and inductance is formulated, leading to a parametric description of the shunt response. The results obtained from this study reveal that also in this case the analytical model formulation leads to significant advantages; in particular, it allows to formulate an analytical optimization problem to identify the best design solution.
The validity of the model and its robustness with respect to uncertainties in the shunt geometry are verified on a homemade shunt prototype, obtaining a very good agreement between model and experimental data. The other important result arising from this analysis is that the simple shunt geometry and the analytical model allow also to study possible configurations of the measurement circuit to partially compensate the shunt inductance and extend its frequency bandwidth; moreover, the remaining inductive response can be compensated by suitable post-processing algorithms. With this approach, the shunt prototype can be successfully employed to measure the total current of the launcher employed in this work. The measurement results are validated by independent measurements obtained by the Rogowski coil.

DROOP CONTROL FOR INTERFACE INVERTERS OF HYBRID POWER PLANTS CONNECTED TO ISOLATED MINIGRIDS

Luisa Frosio - Supervisor: **Roberto Perini**

The present work concerns the development of control tools for the integration of renewable energy sources (RES) in small autonomous electrical systems (minigrids). The consolidation of the RES based minigrids is required to allow an increase of the RES penetration in the developed distribution networks, and to promote the use of renewable and local resources for the electrification of remote islanded areas.
The most critical aspects of RES generators are: the use of static converters for the connection to the minigrid, that may require the development of specific control technique to allow the minigrid regulation and stability, and the RES variable availability, that is compensated through the introduction of storage systems, both as independent units directly connected to the minigrid or as part of integrated generation and storage units (Hybrid Power Plants, HPPs).
In this thesis we investigate two main problems, related to the most critical features of the RES generators.

- the control issues concerning the parallel operation of static converters, to form an autonomous minigrid controlled even without the installation of a communication system;
- the optimization of the minigrid energy storage systems management, to improve their efficiency and their expected lifetime.

Our research is focused on the development of a droop controller, specifically designed for the interface inverters of hybrid power plants in DC bus configuration, to obtain a complete control of the minigrid with no need of a communication system between the generation units.
We propose a simple and effective droop control layout, composed of an external droop regulator, and an internal PD voltage regulator. We introduce a number of compensation terms to decouple the d and q axes regulators and to cancel the effect of terms seen as disturbances on the system. The sizing of the control components is performed considering the dynamic requirements of the inverter voltage control, and of the power flow control on the minigrid.
We develop a dynamic model of a study case minigrid and we implement it in Matlab code, to perform a stability analysis, based on the evaluation of the eigenvalues and of their participation factors in a calculated equilibrium point. We observe that the system components that most affect the minigrid stability are the droop control regulators and we individuate the stability domain for the active and reactive droop coefficients of the inverters connected to the minigrid.
We verify the effect of the inverter output impedance on the active and reactive power sharing between the droop controlled inverters: if the inverter output impedances are not purely inductive there is a coupling between the active and the reactive power regulations. To solve this problem adopt the solution proposed in the technical literature as the " virtual impedance" feedback function. The benefits of this solution are well documented in the technical literature, but still, a sizing procedure for the virtual impedance parameters, fully comprehensive of all the system requirements, has not been assessed yet. We study a sizing procedure for the virtual impedance parameters, based on the iterative numerical solution of the minigrid dynamic model. This sizing procedure takes into account the system stability, the inverter output voltage limits and the decoupling of the power regulations, measured through the evaluation of the active and reactive power sensitivities with respect to the control variables. Through the minigrid dynamic model we verify that the, so designed, virtual impedances allow to obtain an almost complete decoupling between the active and reactive power regulations in the study case minigrid.
In the second part of our work we study the optimization of the minigrid energy storage systems management, to improve their efficiency and their expected lifetime, in particular referring to the battery storage systems integrated in HPPs connected to the minigrid. We identify a crucial quantity for the reduction of the battery operating losses: the indirect power exchange between the storage systems, that is the total power globally flowing through the minigrid storage systems and not required to maintain the instantaneous power balance between the generations and the load. This unnecessary power flow is exchanged between the batteries and it increases the operating losses and the thermal operational stress on the batteries, thus reducing their efficiency and their expected lifetime.
We define a control technique that allows to reduce the operating losses and the stress on the battery storage systems, through the minimization of the indirect power exchange. The proposed control technique acts on the active droop coefficients of each hybrid power plant interface inverter and is based on the measurements of local quantities, with no communication between the generation units.
This optimizing regulator is a variable step incremental regulator, and it has a very low dynamic, thus it does not interfere with the internal droop control loop and it does not affect the system stability.
To evaluate the benefits of the proposed optimizing regulation we develop a simplified energetic model for a study case minigrid and we implement it on Matlab code. We verify that the proposed regulation tends to bring punctually to zero the indirect power exchange between the storage systems of the hybrid power plants.
The total amount of energy exchanged indirectly between the battery storages of the two hybrid power plants of the study case minigrid is reduced significantly (of about 70%), in a reference time period of a day.
The proposed optimizing regulation causes variations in the active droop curves of the power plants, with respect to the initial design values, and this could prevent all the inverters from reaching the maximum load condition together (for the same minigrid frequency). In high load demand conditions, the optimizing regulation could cause the disconnection of some interface inverters for the trip of their overload protections.
We define a "power limitation" mode, introduced in the droop controllers configuration, that allows all the inverters to reach their maximum loading condition, and avoids the consequential trip of their overload protections. This power limitation control does not affect the operation of the droop control, of the virtual impedance feedback function and of the droop coefficients regulation to reduce the battery losses.
Finally, we perform some experimental tests on a low voltage and low power islanded minigrid, composed of two parallel inverters, equipped with the proposed droop controller.
We verify the correspondence between the experimental and the analytical results concerning the stability domain of the active and reactive droop coefficients and the active and reactive power sharing between paralleled inverters, with and without the virtual impedance feedback function.
We verify the correct operation of the minigrid under some particular conditions: the parallel connection of an inverter to the minigrid, a load step, and the operation of one inverter in power limitation mode.
The results of the experimental tests show a good correspondence between the analytical and the experimental results and demonstrate that the proposed droop control system for parallel inverter satisfies the expected performances.
On the whole, the proposed droop controller takes into account not only the issues regarding the interface between the generation units and the minigrid, that is the voltage and frequency regulation and the power sharing on the minigrid, but also the issues regarding the management of the internal power flow of the HPP, that is the optimization of the battery storage systems management.

EQUILIBRIUM MODELS FOR ELECTRICITY MARKET

Majid Gholami - Supervisor: **Cristian Bovo**

The topic of this research is twofold; first, Generation Expansion Planning (GEP) models in a realistic framework and second, the islanding condition in presence of Renewable Energy Sources (RES).
The traditional structure of electric utility, which was vertically integrated in the past, has been deregulated in recent years. In particular, the competitive market paradigm is now adopted in many countries around the world. For instance during the last decade, competitions have been emerged in the European power industry according to the EU-electricity guidelines. Social welfare maximization in a perfect market and also the efficiency of the market were the main objectives of EU electricity market liberalization fulfilled by creating the EU internal electricity market. In presence of perfect competition, suppliers' pricing and operating decisions do not have significant effects on the market price. However, oligopoly is governing most of European electricity markets than perfect market competition where the profits of electric firms can be increased via strategic bidding, or through exercising market power in other words.In this context,the system regulator has to identify how electric firms could drive up the prices and accordingly erode the consumer's benefit of liberalization.On account of, economists have proposed models to represent the electricity market behaviour. Additionally, the introduction of the carbon market,the green certificate market and the strong investments in renewable energy sources are the most recent developments in the European electricity industry.
As the direct consequence of interactions of electricity markets, emission trading market, green certificate market and fuel markets, participants in EU electricity markets are confronting new challenges since the electricity industry is one of the major agents of these latest developments which necessitate the deployment of new models and adequate tools to cover these new challenges. In this context, developing electricity market models able to simulate the complex interaction of the electricity markets and above mentioned markets becomes an even more prominent challenge. In addition, the EU ETS came into effect in 2005 having significant impacts on electricity industry in Europe that covers several sectors such as power generation as the largest. The carbon "emission allowance" introduces a price on CO_2 emissions and consequently change the variable cost of fossil-fuelled power plants in the short run which not only affects the future investment decisions in the industry, but also changes the competitive price in the market. In the literature are discussed and proposed several Generation Expansion Planning (GEP) models in oligopolistic markets but generally they do not take into account environmental considerations such as CO_2 prices. In addition, transmission constraints can affect the GEP considerably, due to the zonal (or nodal) market price structure. Therefore, it also has considerable importance to include the transmission network representation in the GEP model. In fact, the generation expansion may add to or relieve transmission lines congestions and consequently affect the zonal prices. In this thesis, a new oligopolistic GEP model for analyzing generation investment decisions under different CO_2 reduction targets while considering the transmission system constraints is proposed. Furthermore, the Italian decree has been approved to set forth the terms for the financial incentive system for renewable energy sources.The key intent behind the RES financial incentives is to construct a stable legal environment to encourage the use of renewable sources. On account of, in our study the GEP model is improved to incorporate renewables power plants expansion to analyze the effect of different incentive plans for RES capacity development. Likewise, in the electricity market there are some power plants that have been installed many years ago but their investment costs have not been recouped yet. Recovering the investment cost of these power plants in the long run which, not only affects the generation mix, but also can change the future investment decisions. In this context, the GEP model has been developed to investigate the influence of already installed power plants in the generation mix.
Besides,the ability of the proposed procedures is demonstrated with reference to the Italian electricity market (taking into account the zonal structure) and EU ETS system. The numerical results show the possibility to apply the models to real system.
Regarding the activity for islanding in subtransmission grid,since modern power systems show an ever increasing amount of Renewable Energy Sources (RES) generation, especially wind and solar generation, that are characterized by intermittent and high variability in time and therefore many issues in what regards their integration into power systems result. Given the increasing size of such power plants, they are typically connected to the transmission and subtransmission grids. This situation leads to many problems that make the integration of such sources challenging, both on long-term and short-term. However, the availability of a significant amount of RES generation, in particular at the subtransmission level, can be seen as an opportunity to exploit new control resources, adopting for such networks the same approach used for the so-called microgrids at lower voltage levels: i.e., the possibility to exploit the generation plants to allow the islanded operation of the whole subtransmission grids or of a part of it.Therefore, an algorithm has been developed to check the possibility of islanding condition by means of renewable generation in a case that the certain region of subtransmission system is disconnected from the main system.

AN INSULATION CAUSE OF FAILURE IN ELECTRICAL MACHINES AND DIAGNOSTIC TOOLS FOR A RAILWAY APPLICATION

Matteo Maria Maglio - Supervisor: **Francesco Castelli Dezza**

This doctoral dissertation is based on the work the author performed during the three years course spent in the XXV Doctoral programme in Electrical Engineering at Politecnico di Milano, Italy.
The research was supported by the "Dipartimento di Elettrotecnica" (Electrical Engineering Department), the "Dipartimento di Meccanica" (Mechanical Engineering Department), the "Dipartimento di Energia" (Energy Department), ITALCERTIFER, the certification authority for the Italian railway system and MCM Energy Lab, a spin-off of Politecnico di Milano University.
The title of the research is "An insulation cause of failure in electrical machines and diagnostic tools for a railway application".
Basing on this topic the author focused on two different aspects. The first is related to the electrical machine's diagnostic and the second is related to the development of diagnostic tools for monitoring a real important part of the train: the train axle.
The electrical machine diagnostic is a very wide topic and in the past years a lot of aspects have been faced. Very powerful tools have been produced to better analyze the machines and to deeply understand the fault causes. Nowadays state observers, precise sensors and estimation algorithms have been integrated resulting in more efficient and reliable tools for the electrical machine's diagnostic.
In the first chapter one of the fault causes in an electrical machine is analyzed. The analysis of the state of the art of the insulation systems for the electrical machines leads to the study of the electrical stress that the insulation stands when the voltage excitation is made of repetitive voltage steps with very steep fronts.
The state of the art of the acceptance and qualification tests is described together with the reference standards for designing an insulation system when the electrical machine is powered by repetitive voltage pulses that come from an electronic converter, as a PWM (Pulse Width Modulation) inverter or a controlled rectifier.
The main importance is given to the tests and qualifying process for an insulation system of an electrical machine fed by a power electronic converter. An inside look is given to the construction techniques and to the present regulations for designing and testing the insulation system.
The second chapter deals with the analysis of the overvoltage at the motor terminals when the voltage wave is made of repetitive square pulses due to the inverter feeding.
The combination of very fast switching voltage plus long cable can lead to overvoltage at the motor terminals as high as two times the DC-Bus voltage level. This phenomenon leads to high insulation stress in the first turns of the winding and proper countermeasures must be taken.
A new induction motor model is derived, which can simulate the low-to-high frequency effects like the motor terminals over-voltages and the voltage oscillations.
The extension of the classic induction motor model with the high frequency modeling components is based on the motor frequency response.
With the help of high frequency measurements made by the author on a 1.1kW induction motor, an accurate simulation with Matlab Simulink® is made.
The simulation results are validated through comparison with measured values in a wide frequency range and brings the simulation response to more realistic results. The reinforcement of the insulation in the first coil brings some disadvantages that are shown in the third chapter where also an analytical simplified machine's coil model is derived to investigate the voltage propagation along the coil.
The model can be useful to investigate the effect of the turn-to-turn and turn-to-ground capacitances on the voltage distribution and the prediction of the over-voltage propagation.
The second part of the thesis starts with chapter four and it comes from a research on the train axle diagnostic tools. The axle is a vital part of the train and its continuous monitoring can significantly improve the safety in the railway transportation system.
Strain supervision requires proper sensors and a reliable electrical power source to guarantee an effective measurement. The axle strain monitoring is an effective technique to prevent massive damage to the train. The measurement of the axle strain needs sensors, data acquisition units and data transmission units that lay on the rotating shaft and, most important, need to be electrically powered. Nowadays there are some commercially available devices for the strain measurement and all of them avoid slip rings and direct contact with the shaft.
The analysis of three different solutions is carried out along with some tests performed to validate the results and verify the effectiveness of these solutions. Each of them is associated with the analytical study of the system, where possible, or with the computation of the parameters of interest through a finite element analysis software.
The first solution is a high frequency induction power feeding system which involves a primary and a secondary winding in a coreless transformer. The system equations and the design parameters for the transferred power evaluation are derived considering series resonant windings for efficiency enhancement.
The second solution is a radio frequency transmission system. Thanks to patch and rectifying antennas, DC power can be collected from a radio transmitter. The evaluation of the transferred power is performed thanks to a 3D simulation of the antennas and of the train axle.
The third solution is based on the construction of a Permanent Magnets (PM) printed-winding machine mounted on a bearing structure around the axle. The rotating windings are printed on a circuit board while the magnets are fasten to the static bearing track. The machine works as a PM generator which transfers energy to the rotating windings and thus to the rotating telemetry system.
For all the solutions the main advantages and drawbacks are underlined. The performance results of each power feeding system show to the reader which technology can be more easily used for the next future axle monitoring system.

NOVEL DISTRIBUTION NETWORK MANAGEMENT WITH DISPERSED GENERATION

Gabriele Monfredini - Supervisor: **Marco Merlo**

The PhD thesis is focused on the analysis of the Dispersed Generation (DG) impact on the electrical system. DG may affect the system safety and quality of service in existing networks. Increasing challenges shall be properly managed to ensure the transition from a centralized power production to a novel paradigm with a significant penetration of DG. DG units represent resources dispersed along the distribution network which have to be exploited in order to improve the network operation and management. This dissertation describes possible ancillary services offered by DG and its increased role in the active network management. Actually, most of the DG units are connected to the grid through inverter, therefore inverter technology and additional functionality in the power electronic equipment are a key element for driving the DG integration.

In the PhD work, first, the reactive power modulation service has been analyzed. DG injections at distribution level may affect the voltage quality of the supply system; possible over-voltages at the DG's Point of Common Coupling (PCC) may occur (i.e. violation of EN 50160 prescriptions). The goal of the research activity is to improve power quality by adopting a novel voltage regulation approach that involves GD units as regulation resources. The proposed approach is based on a modulation of reactive power injected/absorbed by the DG units.

The voltage control architecture proposed in the activity is based on a three level hierarchical structure: local control, coordinated control and centralized control.

The first layer of the control scheme is based on simple laws which modulate reactive power according to local measures of voltage or real power injected by DG. A parametric study based on load flow simulations is carried out with the aim to verify the impact of the voltage control on realistic Medium Voltage (MV) and Low Voltage (LV) distribution networks (based on real network data of the Italian system) in a multi-generator configuration. The results of the study highlight the response of the LV system to the voltage control: the reactive power flow along LV feeder has a low impact on the voltage profile because of the high resistance/reactance (R/X) ratio. The local voltage control is not able to completely limit the over-voltages and it could be necessary to adopt a real power limitation strategies. The DG real power limitation, combined with the reactive power modulation, allows to eliminate the voltage violations by increasing the Hosting Capacity (HC) of existing networks with only a small energy curtailment (a one year time window has been analysed). The effect of the reactive modulation depends on network features and it has an higher impact on the voltage profile of MV feeders (due to the lower R/X ratio). Simulation results show that on the MV system it is possible to increasing of the HC up to the structural network constraints (i.e. thermal limits of the lines), therefore, in the MV system, the voltage control obtained by modulating the reactive power is completely resolving for the slow voltage variations.

The local-corrective voltage control strategy is easy to implement without grid reinforcement and does not require a communication channel, therefore it is feasible in a short time period.

As evolution of the local control, in the thesis work different coordinated control strategies are proposed: this coordination could be introduced as a management of the DGs local laws (mainly based on thresholds). Proper analysis are carried in both MV and LV network models. The results show that a coordination between several resources is useful to improve the voltage regulation: each DG unit can be supported by other resources during critical voltage conditions. In particular, the proposed approach is based on a weak communication channel, i.e. a slow TLC apparatus able to exchange few bits between each DG units and the Primary Substation (PS). The results reported in thesis show that a coordinated control strategy can be also exploited to implement regulation functions useful for TSO needs. For example, the reactive capability of DG units can be managed to control the reactive power exchange between the PS and the transmission network and to enhance the overall power factor and self-production/consumption of the distribution network.

Finally, the centralized control is the most advanced voltage control structure; it is based on a state estimator and on Optimum Reactive Power Flow (ORPF) procedures, consequently it requires advanced metering apparatus and an adequate communication channel. The adoption of such advanced regulation allows a further improvement of the HC and the real power losses minimization, but it requires significant investment on the grid. During the PhD research an Ad Hoc procedure has been developed in order to compare the performances of each regulation structure proposed.

The second ancillary service discussed in the thesis is the real power modulation service. Actually, concerning the integration of renewable energy sources, the new issues are related to the intermittence of this generation typology. An high penetration of intermittent power plants will reduce the primary frequency reserve of the system and the system stability itself. In order to achieve a suitable network reliability, technological solutions which involve Energy Storage System (ESS) have to be considered. In this way, renewable energy sources can be exploited to provide ancillary services to the main grid. The primary frequency control represents one of the main grid applications: in case of frequency deviations from the nominal value the power injections are modulated according to a droop function. After a presentation of the effectiveness of the DG's participation to the reestablishment of the power balance among of the network, a dynamic model of a photovoltaic system coupled with an ESS has been developed with the aim to simulate its behaviour during frequency oscillations. The results obtained by dynamic simulations depict that this application has a relevant impact on the ESS life duration: with respect to a theoretical operation in the UCTE grid, about four complete charge and discharge cycles per day are necessary. This simulation outcomes have to be taken into account for economic and technical sizing of the ESS.

Finally, new issues related to the DG protection system are discussed. DG has to remain connected to the grid during faults, in order to support the system stability, and, at the same time, islanding operation of a portion of the distribution system has to be avoided. For these reasons a suitable Interface Protection System (IPS) has to be adopted in order to safely integrate DG into the present network.

In the thesis, a suitable procedure has been defined in order to evaluate the performances of various IPS schemes operating in local mode; in particular, a detailed analysis for the coordination of the voltage unlock relays of IPS based on double frequency settings (wide and narrow) is carried out by exploiting realistic network models. Dynamic short circuit events are considered in the High Voltage (HV), MV and LV network. Simulations depict that the combination of wide and narrow frequency settings introduces an improvement in the IPS local operation. A good coordination can be achieved even if, in local mode, a trade-off between reliability in case of islanding and selection of events is necessary. The analysis points out that only a communication based operation can overcome IPS's coordination issues.

The PhD thesis investigates the effectiveness of a DG participation in providing ancillary services for the system; this analysis starts off with the three main primary regulations for the security of the electrical system: primary voltage regulation, primary real power regulation, protection systems for faults in both distribution and transmission networks. It can be concluded that the active network management realized by involving DG is fundamental to favor the penetration of renewable energy sources in the grid; it is a further step for the network evolution toward Smart Grid.

DEVICES DEVELOPMENT AND DATA MANAGEMENT FOR SMART-SENSOR NETWORKS: AN APPLICATION FOR PHOTOVOLTAIC SYSTEMS

Marco Rossi - Supervisor: **Loredana Cristaldi**

Nowadays it is possible to notice a growing diffusion of distributed measurement systems; this kind of architectures is based on the installation of sensing elements in areas which can be very vast. Each sensing element (which could include one or more sensors) can be associated to an electronic control unit and equipped with a communication interface able to dialog and to share measurement results with other sensing devices of the network. This apparatus represent the key element of distributed measurement systems and it is commonly defined as "smart-sensor".
A scenario where the exploitation of a this particular architecture is particularly effective, mainly for monitoring tasks but even for the optimization of the conversion efficiency, is represented by photovoltaic plants. For this reason the main goal of the research activity has been focused on the design of a device, heart of the monitoring system, able to exploit these functions. The smart-sensor has been developed in order to include, in addition to the section devoted to the measurement of electrical and environmental quantities, a control unit which implements the monitoring algorithms and a wireless communication interface. In particular, this kind of infrastructure has been selected for multiple reasons among which it is possible to recognize the reduced requirements in terms of hardware, the intrinsic galvanic insulation of the communication channel and the plug-and-play features. Furthermore, particular attention has been paid for the implementation of an hardware based on low-power-consumption, in order to do not significantly impact on the efficiency of each monitored panel.
One of the innovative aspects of this device is not only represented by the exploitation of monitoring and diagnostic algorithms but it also shows concrete control skills: in fact, by means of a built-in DC-DC converter, the developed smart-sensor has the possibility to decouple the panels from the input bus of the central inverter. In this manner, thanks to the proposed architecture, losses due to the mismatching of the photovoltaic modules are avoided. Furthermore, in addition to a simplified management and control of the plant, the distributed smart-sensors allow the installation of panels with different working profiles. Nevertheless, the introduction of a power converter determines additional losses which have to been carefully evaluated in order to do not discriminate the global efficiency of the plant. For this reason, the non-idealities of the employed converter and of its components have been deeply analyzed, and a new model of this device, which takes into account the losses and their effect on the electrical quantities, has been developed. Experimental results show that this model represents an accurate instrument for the simulation and the optimal design of the power converter.
In order to increase the performance of the diagnostic and control systems, the research activity has been focused on the definition of a mathematical tool which has the ability to simulate, in an easy but still accurate way, the electric behavior of a photovoltaic panel (or combinations of them). Thanks to a deep literature investigation, the so called "single diode model" has been selected as an optimal candidate for these applications. This model, despite its simplicity, requires complex and not immediate characterization procedures. For this reason, a consistent part of the work has been focused on the simplification of the tuning algorithms, until an innovative formulation of the model has been proposed. Despite it guarantees the same accuracy of the classical one, the characterization procedure results much easier. This tool, although a preliminary parameterization can be performed starting from the data provided by the manufacturers of the photovoltaic panels, can be tuned by means of simple experimental tests which can be performed in-field, without necessarily interrupt the power production.
This innovative model has been particularly useful for the definition of methods for the monitoring and control of the plant. In addition to the simplicity, the model can be inverted: in fact, despite is has been designed for the estimation of the electric behavior of a photovoltaic panel, this tool can be used even for the inverse procedure, or rather for the estimation of the solar radiation and temperature starting from the measurement of the electrical quantities.
This latter feature has been particularly useful for the development of applications which allow an optimization of the power production. It is well-known that the productivity of a photovoltaic plant does not only depend on the efficiency of the solar cells and of the power converters, but also on the performance of the maximum power point tracker (MPPT). In fact, photovoltaic modules have a single point on the electric characteristic curve in which the efficiency is the highest, and the tracking of its time evolution, has to be guaranteed. Different algorithms have been developed in the past and some of them are largely employed for their user-friendly skills. However they can show some stability and efficiency problems, especially for highly variable weather conditions. In these scenarios, the best performances are obtained by means of tracking techniques which are able to rapidly predict the electric behavior of the controlled photovoltaic panels. These algorithms are commonly called "Model-based MPPT" and, in addition to demonstrate a good accuracy, they are known for the intrinsic stability and fast response. These techniques are not commonly employed because of the necessity of a photovoltaic model (as stated before, classical models are not easily tunable) and of an expensive solar radiation sensor (which is required for the estimation of the maximum power point). However, these methods can be totally revaluated thanks to the exploitation of the proposed model. In fact, its characterization is simpler with respect to the one of classical formulations and, first of all, the model inversion allows an easy estimation of the solar light intensity, avoiding the installation of a dedicated sensor.
In addition to the optimization of the power production, the developed model has demonstrated noticeable features for the monitoring activity of photovoltaic plant. In particular, thanks to the possibility to predict the electric characteristic of each single panel, this tool is able to provide an estimation of the production and, by means of a comparison with the measured energy, it provides relevant information about the health status of each module. Thanks to the proposed distributed measurement system, a large amount of diagnostic information can be shared in real-time, and the localization of faults can be easily performed. Furthermore, the communication system connects the smart-sensors which can interact between them-selves and other networks, allowing the potential development of more advanced monitoring techniques.
Thanks to the proposed diagnostic algorithm, in case of fault or, more in general, a reduction of the power efficiency, it is possible to promptly detect the abnormal situation and the provided alarm can be used for the planning of the maintenance activities. In this case, since the presence of a fault does not necessarily interrupt the operation of the plant but, in most cases, it determines only a decreased efficiency, thanks to the exploitation of the model it is possible to develop tools which can be used for a more effective planning of the maintenance operations, reducing the inevitable missing production due to the reparation/replacement activities. In fact, the proposed model can be used to quantify the energy losses due to the detected fault and to evaluate, from an economical point of view, when and what operations have to be planned.

OPTIMIZED ANTENNA FOR LOW UHF BAND WIRELESS POWER TRANSFER (WPT)

Houriyeh Shadmehr - Supervisor: **R. E. Zich**

Delivering power/energy without requiring wire is an advance in transferring power technology; and it is named Wireless Power Transfer (WPT). Wireless power/ energy transfer makes possible to overcome drawback of conventional power transfer with wires, due to the wire resistance, wire routing, and so on; re-charging cell phones, game controllers, laptop, mobile robots, and electrical vehicles without being plugged in; making more reliable industrial systems and medical devices by eliminating trouble prone wiring and replaceable batteries; transmitting energy/power in safe mode for human body and animals; providing continuous and instantaneous power transfer; and to miniaturize electrical systems and devices. Such advantages promote the interest of scientists, engineers, and researchers in studying and using wireless power/energy transfer.

At present, energy/power has been delivered wirelessly employing such diverse physical mechanisms like: Radio Frequency (RF), and Resonance Inductive Coupling.

Radio Frequency: Recently, the availability of wireless standards for huge number of applications, from mobile phones, smart phones, to always-on WLAN devices shifted the attention on the extraction of energy from EM fields in the RF band. For this purpose, Energy Harvesting Technology is employed.

Energy Harvesting Technology (EHT) allows to scavenge small amount of energy/ power from human activities or environment heat, light, vibration or Electromagnetic Field (EF). Hence, among of several techniques which are available for EH, we are interested in RF Energy Harvesting. Extraction energy/ power from electromagnetic waves to power devices is called Radio Frequency (RF) energy harvesting and it has the resulting benefit to product design (e.g. miniaturizing biomedical implanted devices and power supply), transfer power/energy wirelessly over distance (e.g. Solar Power Satellite), in self-powering, where requires continuously available power source with lifespan (e.g. Wireless Sensor Network), and so on. Furthermore, RF Energy Harvesting provides the possibility of recycling EM radiation in the air and using it as an alternative supply source in order to reduce of the EM field pollution, and can allow reducing the size of the harvesting system with respect to energy harvesting system based on the other energy sources (e.g. large size of a photovoltaic).

One of the most important components in RF energy/power harvesting system is called rectenna which is composed of a received antenna and rectifier. The received antenna plays a critical role in RF energy/power harvesting system, since it must extract the power radiated by electromagnetic waves.

Resonance Inductive Coupling: in this mechanism, resonance is used to deliver power wirelessly by tuning transmitter and receiver at mutual EM frequency; and coupling transmitter and receiver in resonant way has two main profits: exchange power efficiency without much leakage (minimizing energy leakage causes the maximization in the transferred energy to the receiver), and improve power efficiency over distances. Inductive coupling techniques have been reported to have high power transfer efficiencies (on the order of 90%) for very short lengths (1-3cm). Although, the power efficiency of such technique decreases for longer distance drastically.

Therefore, the biggest challenge in the design of RF power system (rectenna) and wireless power transmitting systems is the maximization of the transferred energy to the receiver in order to increase their performance. This is possible by suitably redesigning the transmitting and receiving devices, reducing of the size, trying to find the correct shape that allows on rising in performance, and tuning the transmitter and receiver at EM frequency to decrease leakage, and transmitting power in safe mode for human body and animals.

In this work, an approach based on a novel evolutionary technique is proposed for the design of an optimized loop wire antenna configuration, with the aim to increase the transfer efficiency, the robustness of the coupling, and to minimize the average power loss.

The new hybrid approach here proposed, called Genetical Swarm Optimization (GSO), and consists in a strong co-operation of Genetic Algorithm (GA) and Particle Swarm Optimization (PSO). In particular, a key feature of the algorithm is that it maintains the integration of GA and PSO for the entire run. In each iteration, the set of solutions is divided into two parts and it is evolved with two techniques respectively. It is then recombined in the updated population for the next iteration; after that it is again divided randomly into two parts in the next run, in order to take advantage of both genetic and particle swarm operators. The population update concept can be easily understood thinking that a part of the individuals has been substituted by new generated ones by means of GA, while the remaining are the same of the previous generation but have been moved on the solution space by PSO. This kind of updating results in a more "natural" evolution, where individuals not only improve their score for natural selection of the fitness, or for good-knowledge sharing, but for both of them at the same time.

A driving parameter is introduced for the GSO algorithm, called Hybridization Coefficient (HC); it expresses the percentages of population that in each iteration is evolved with GA: so HC=0 means the procedure is a pure PSO (the whole population is processed according to PSO operators), HC=1 means pure GA(the whole population is optimized according to GA operators), where 0<HC<1 means that the corresponding percentage of the population is developed by GA, while the rest with PSO technique.

The output of the evolutionary optimization method or in other words, the candidate design is simulated at frequency range 450MHz- 600MHzby Matlab simulation in order to investigate the properties of the candidate design. Rao-Wilton_Glisson basis function and delta-gap feed model have been used to create a system of moment equations (Method of Moment) in home-built Matlab simulation tool. A wire is represented with the use of a thin strip model having one RWG edge element per strip width. The strip width should be four times of the wire radius. As the last step, the results obtained by Matlab are compared with the obtained results by FEKO Lite (commercial software) to check and verify the reliability of the optimized antenna.

In this study, a novel antenna with optimized loop wire base on fractal variation has been proposed for application in WPT devices and rectenna component. The presented optimization approach is based on a recently developed evolutionary method. The design procedure is well suited in order to increase the transfer efficiency and the robustness of the coupling, with the aim of minimizing the average power loss.

Numerical results simulated with home-mode MoM Matlab code have been verified by comparison with full-wave commercial simulator and the power efficiency calculated for optimal antennas showed the impact of optimized antenna design.