MECHANICAL ENGINEERING | PHYSICS | PRESERVATION OF THE ARCHITECTURAL HERITAGE | SPATIAL PLANNING AND URBAN DEVELOPMENT | STRUCTURAL SEISMIC AND GEOTECHNICAL ENGINEERING | TECHNOLOGY AND DESIGN FOR ENVIRONMENT AND BUILDING | TERRITORIAL DESIGN AND GOVERNMENT | AEROSPACE ENGINEERING | ARCHITECTURAL AND URBAN DESIGN | ARCHITECTURAL COMPOSITION | ARCHITECTURE, URBAN DESIGN, CONSERVATION OF HOUSING AND LANDSCAPE | BIOENGINEERING | BUILDING ENGINEERING | DESIGN | DESIGN AND TECHNOLOGIES FOR CULTURAL HERITAGE | **ELECTRICAL ENGINEERING** | ENERGY AND NUCLEAR SCIENCE AND TECHNOLOGY | ENVIRONMENTAL AND INFRASTRUCTURES ENGINEERING | INDUSTRIAL CHEMISTRY AND CHEMICAL ENGINEERING | INFORMATION TECHNOLOGY | INTERIOR ARCHITECTURE AND EXHIBITION DESIGN | MANAGEMENT, ECONOMICS AND INDUSTRIAL ENGINEERING | MATERIALS ENGINEERING | MATHEMATICAL MODELS AND METHODS IN ENGINEERING

PhD Yearbook | 2016

DOCTORAL PROGRAM IN ELECTRICAL ENGINEERING

Chair:
Prof. Alberto Berizzi

The main objective of the PhD Program is to allow a direct, prompt and efficient involvement of PhDs in any research body such as an R&D department of a production or service 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 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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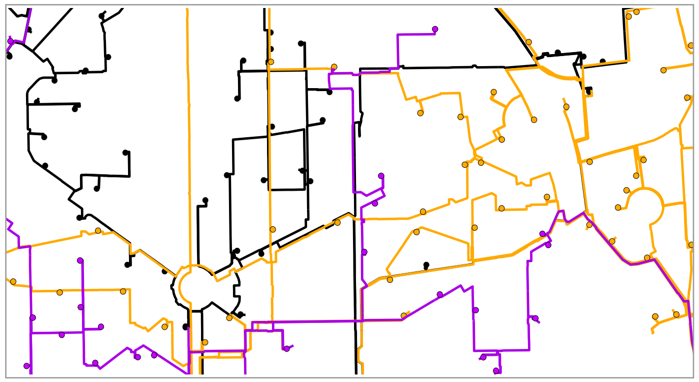
Companies currently providing scholarships:
- MCM Energy Lab
- A2A Reti Elettriche

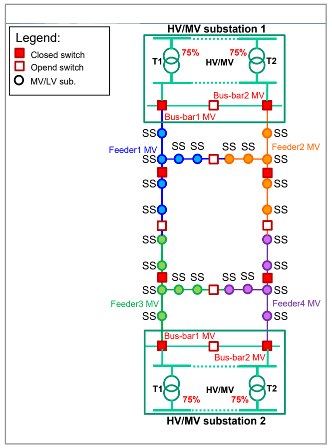
STRUCTURAL AND FUNCTIONAL OPTIMIZATION IN DISTRIBUTION GRID PLANNING

Alessandro Bosisio - Supervisor: Prof. Alberto Berizzi

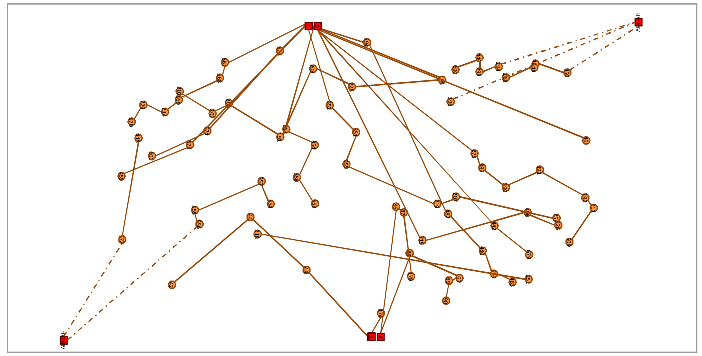
We consider the problem of planning an electric urban distribution network already in place, specifically the distribution network of Milano (Italy). Before the deregulation in 1999, in Milano there were two separate distribution networks, operated by two different companies, which grew up independently and without any coordination. Later, the two companies merged and today the main goal of the unique utility operator (A2A Reti Elettriche) is to optimally integrate the two distribution networks moving, at the same time, to a specific layout, called 2- step ladder configuration. The distribution network of Milano is supplied by 15 HV/MV substations, with almost 6000 MV/LV substations installed all over the city area, consisting of 4000 km of distribution feeders. In general, the topological optimization of this kind of systems involves a large number of continuous and integer decision variables and is formulated as a problem of Mixed-Integer Programming (MIP) and belong to a class of NP complete problems. The aim of the research is to solve a number of upgrade issues of an electric network already in place, to increase reliability related to the topology of the network. Figure 1 shows a part of the distribution network considered. Colors indicate feeders supplied from the same HV/MV substation. Different colors in the same area means the current network layout is not optimized and must be improved.
In figure 2 the 2-step ladder topology is shown with reference to the part of the grid between two HV/MV substations. The main advantage of the new proposed topology is to exploit line capacity during the normal operation (up to 75% of the thermal limit). In fact, this specific layout of the distribution network can meet load request also in case of any possible single fault of transformers, lines or equipments. Due to the aging of several feeder of the electric distribution network of Milano (some of them are very old), increasing of loads during the last decades and difficulties to build new feeders in an urban framework, this topology gives the possibility to exploit more the capacity of the existing lines, with the same, or even with a higher level of reliability. In order to model the 2-step ladder shape in an optimization problem, we consider a directed graph D = (V,A) containing all the nodes (corresponding to HV/MV and MV/LV substations) and all the edges of the existing network, determine a collection of additional edges to be activated so that the resulting network has 2-step ladder topology and a cost function is minimized. The objective function of the mathematical model developed consists of two terms: the new line installation cost, fixed term, and the cost of real losses, variable term. Several topological and electrical constraints are included in the formulation. The model has been tested over a real sub network composed of 78 nodes (74 MV/LV substations and 4 HV/MV substation bus bars). HV/MV and MV/LV substations locations and connections already in place are depicted in figure 3. Notice that dashed lines and related HV/MV squared substations are not in the input data being out of the clustered sub network. Figure 4 shows optimal paths layout considering the network already in place (see figure 3 for connections already installed). The algorithm keeps as many current lines as possible, optimizing, at the same time, feeders service areas in order to reduce losses. Analyzing output results shows that the model could reduce network extension by about 35%. Starting from an initial network extension of 15.49 km, the algorithm removes 9.73 km lines, it keeps 5.76 km lines and propose to install 4.30 km of new lines down to a new network extension of 10.06 km. Concluding, a model to optimal integrate two distribution network already in place has been developed. The main novelty is to enforce the resulting distribution network to be shaped with a specific layout, which we refer to as 2-step ladder topology, minimizing both installation cost and cost of distribution network losses. Thus, the method covers the choice of keeping, installing or removing cable routes, taking into account fixed and variable costs. It requires as input: HV/MV and MV/LV substations locations and their power; lines length (using Euclidean's, Manhattan or real metric) including connections already in place; lines data; customers data. The expected output is the optimal network layout which minimizes overall network planning cost. Using the optimization process, there might be a significant reduction of the distribution network extension, potentially increasing, at the same time, the reliability of the network.



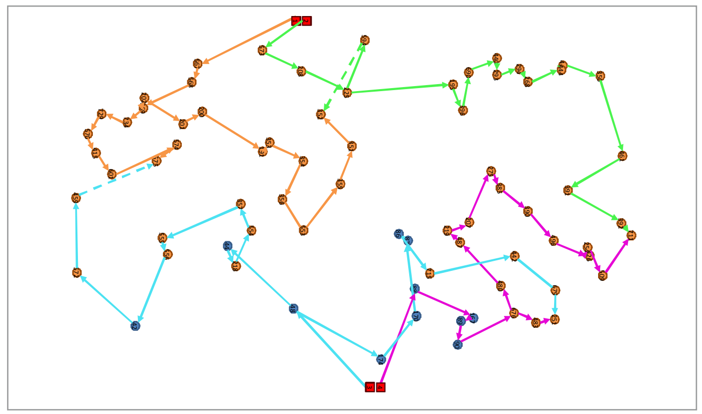
1. View of the Milano electric distribution network



2. 2-Step ladder layout



3. 78 nodes network - grid already in place

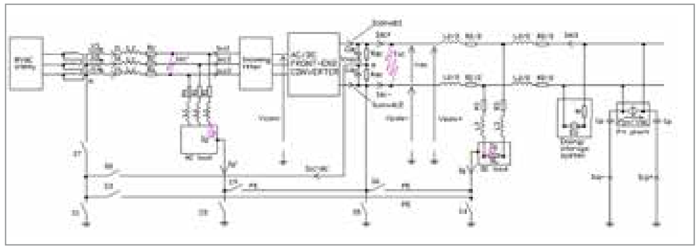


4. 78 nodes network - optimal layout

FAULT ANALYSIS AND PROTECTION IN LVDC MICROGRIDS WITH FRONT-END CONVERTERS

Marco Carminati - Supervisor and tutor: Prof. Enrico Tironi

The possibility to introduce DC distribution grid, equipped with energy storage systems and in presence of distributed generation and sensitive loads, is under consideration in order to replace the traditional AC systems. Nevertheless, the presence of converters affects the system behavior in particular during the fault condition, depending on the grounding system. Conventional wisdom is that converters limit currents in every situation. Although, it is true for some specific situations, there are others where converters are not able to limit fault currents. Hence, this work had the target to analyze the several faults that may occur in an LVDC microgrid in order to define suitable protection devices.
In particular, a deep analysis has been carried out on the system in Figure 1 including a MV/LV transformer, an AC load, and a general-purpose Front-End Converter (FEC), interfacing an LVDC active microgrid. The analysis has been done for different ground configurations of active and exposed conductive parts. First, by means of Simulink, the analysis during the normal operation has been carried out. Then, the analysis has moved to the short circuit and ground fault on DC side, the three-phase short circuit and single-phase ground fault on AC side. The system analysis has been done varying the fault resistance, also in presence of an Energy Storage System (ESS) and a PV plant. Moreover we have first neglected the presence of IGBT self-protection, called DESAT protection, which normally block the IGBTs. Such hypothesis has allowed current analysis in electronic components. Then, removing such hypothesis of DESAT protection absence, we have found out that the protection may be ineffective or it can interrupt only the fault contribution of the DC sources. As a result, suitable devices have to be used to interrupt the AC grid contribution, which passes through the freewheeling diodes, and to protect the electronic devices themselves.
The DC potential trends in the different configurations have been analyzed in case of normal operation. Moreover, we have investigated the effects produced by the high frequency variation of DC pole potentials towards ground in systems with the transformer neutral point grounded and in presence of PV module parasitic capacitances. We have found out that high leakage currents may appear that sum each other, flow through the transformer neutral and the AC phases. Resonance conditions may also occur with AC inductances, resulting in a dangerous and potentially harmful increase of both the DC pole voltages towards ground and the leakage currents.
The analysis of the short circuit on DC side has shown in particular that with low fault resistance, the converter behaves like a diode rectifier: fault current is only limited by the impedances of upstream network, MV/LV transformer, and the wirings, and by the diode voltage drops. Resulting values of fault current would likely bring to the destruction of semiconductors. Then, a deep analysis has been carried out during a ground fault on DC side with several ground configurations of the active and exposed conductive parts. More specifically, two distinct behaviors have been found if the fault resistance is "high", i.e., large enough so that normal operation of the FEC is not altered, and if it is "low" otherwise. The presence of the ESS and the PV plant does not improve the situation since, even maintaining the DC-Bus voltage at an higher value, the DC sources, for "low" fault resistance values, would however offer a reclosing path for the DC current from the FEC lower terminal, and they possibly forces a much higher current than the design values in the semiconductors. In particular, in system with the transformer neutral point grounded, depending on the fault resistance, the current waveform on AC side can remain always positive. As a result, the current can flow only in the freewheeling diodes of the cathodic star and in the IGBTs of the anodic star. Hence, the current goes out both from the upper and lower DC terminal of the FEC: it is an anomalous behavior, since in the normal one, the current flows into the lower terminal. In particular, for low values of the fault resistance, the FEC feeds only the fault, while the DC sources feed both the DC load and the fault. Subsequently, the DC-Bus voltage value for which the DC-Bus voltage value for which the DC sources start to feed the fault has been calculated.
The system behavior during an AC single-phase ground fault both per passive and active DC grid has been also studied. In particular, like for DC faults, the DC sources start to feed the fault when the DC-Bus voltage becomes lower than a particular value, which has been calculated and it is equal to that found for DC faults. Nevertheless, in dual manner respect to DC ground faults, now the DC sources start to feed the fault when the DC component of the upper terminal current is incoming rather then outcoming as in the normal operation.
In order to validate the model implemented by means of Simulink and the simulation results, a wide experimental test campaign has been carried out thanks to the RSE test facility. The experimental results have been concordant with the simulations. In particular, the FEC anomalous behavior has been verified during a ground fault with the current that comes out from both the FEC DC terminals and, for low ground fault resistance values, we have measured an AC current that remains always positive.
Moreover, an innovative FEC control methodology to limit the zero-sequence current has been studied. This methodology has been applied both in a numerical simulation with an active DC grid including two loads and a ground fault in one of them, and in experimental tests at RSE test facility, installing the innovative algorithm in the FEC control. The results have shown that, thanks to this new methodology, it is possible to protect the electronic components.
Other protection methodologies without zero-sequence current control have been studied. In particular, a protection method using a traditional circuit breakers has been studied and numerical simulated. In this case, the freewheeling diodes must be oversized in order to withstand the let-through energy during the circuit breaker tripping. Then, the possibility to implement a protective system by means of Solid-State Circuit Breakers (SSCBs) has been analyzed, first carrying out a deep bibliography research on the current technologies under consideration. Subsequently, a new SSCB bi-directional prototype with IGCT technology has been undergone to experimental tests at RSE test facility. The goals of the tests were in particular to measure the tripping time of the circuit breaker and to verify that the overvoltage during the opening operation was limited to a value close to the nominal value.
A coordination approach with SSCBs that was not the usual time-current or energetic selectivity (absence of electric arc) has been then studied. We have proposed the Logic Selectivity by means of optical fiber, transmitting a signal to interlock more circuit breakers. Moreover, the Directional Logic Selectivity has been proposed to recognize the short circuit location in presence of more DC sources. Thanks to such a coordination method, it is possible to distinguish whether the fault is upstream or downstream the DC source or FEC feeder. As a result, only the dedicated SSCB receives the tripping signal, guaranteeing the continuity of service of the other DC grid components.
Finally, based on the waveforms of the leakage and ground fault currents studied and starting from the RCD of type B already developed, I have submitted the patent demand for a new residual current detection methodology, able to distinguish between ground fault currents and leakage currents.

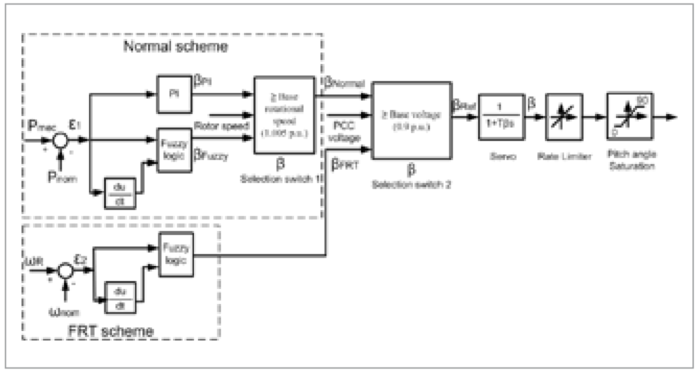


1. LVDC microgrid analyzed with the possible ground connections of the live parts and of the exposed conductive parts

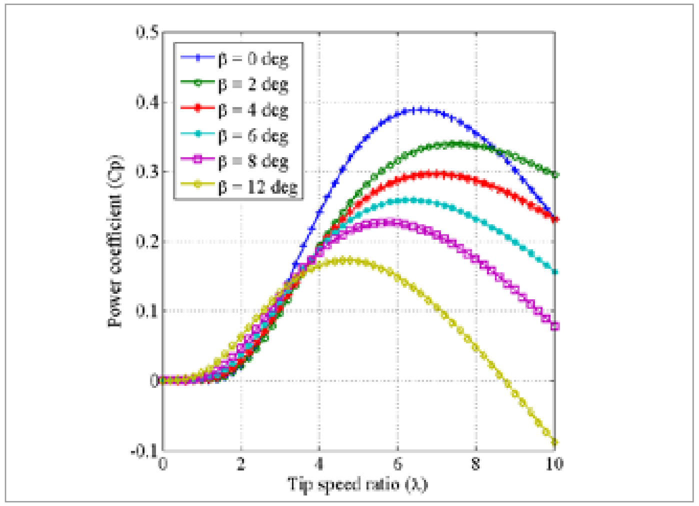
WIND POWER INTEGRATION: A STUDY ON WIND TURBINES MODELLING AND THEIR IMPACT ON POWER SYSTEMS

Minh Quan Duong - Supervisor: Prof. Marco Mussetta

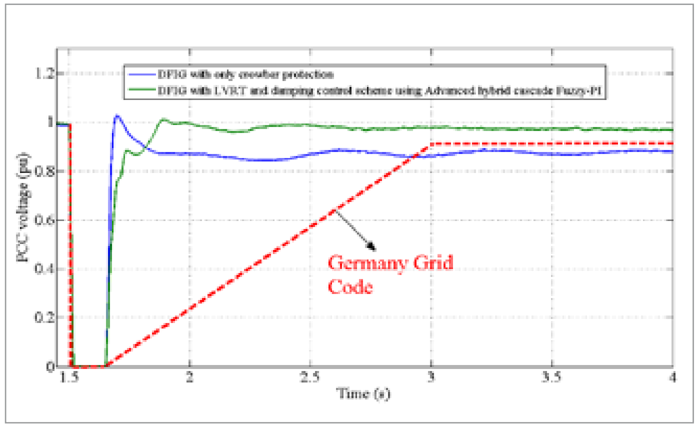
During the last decade the installed capacity of grid-connected renewable energy sources (RES) increased significantly. In particular, wind power is the world's fastest growing renewable source. This leads to large rapid changes in non-programmable sources, which can cause a significant reduction in power quality, reliability and stability. The question that needs to be raised is how new wind power sources will affect the power system. A part of the answer must be obtained from the modeling of wind turbines (WTs) connected to grid. This thesis firstly analyzes the performance of three different popular wind generators when connected to the power system. Based on this analysis a comparison was made for the three wind turbines studied: the squirrel-cage induction generator (SCIG), the doubly-fed induction generator (DFIG), and the permanent-magnet synchronous generator (PMSG). The fixed speed system is more simple and reliable, but severely limits the energy production of a wind turbine, its power quality and stability. In case of variable speed systems, comparisons shows that generator of similar rating can significantly enhance energy capture, power quality and stability. Moreover, performance of their output power leveling is here validated by a new numerical method in terms of maximum energy and leveling function.
Large SCIG wind plants have a significant influence on power system operation since they are related to unpredictability of the primary source. Thus SCIG WT must improve their production quality to ensure the stability and reliability of the power system as conventional power plants. In fact, wind energy is not constant and, since WT output is proportional to the cube of wind speed, this causes the power output of SCIG WT to fluctuate. In order to improve power quality and maintain the stable output generated from SCIG wind farm, this thesis presents also a hybrid controller (Fig. 1) based on proportional-integral (PI) and fuzzy logic controller (FLC) techniques for adjusting the pitch angle (Fig. 2), which is one of the most common methods for smoothing output power fluctuations.
Presently, Doubly-Fed Induction Generator (DFIG) Wind Turbines (WT) are used in almost 50% of the offshore and onshore wind power plants. Because of relative small rating of the power converters, WT based on DFIG are very sensitive to grid disturbances and require additional protection for the rotor side power electronic converter, such as crowbar protection. When the crowbar is triggered, the rotor is short circuited over the crowbar impedance, the rotor-side converter (RSC) is incapacitated and therefore the DFIG operates as a squirrel-cage induction generator (SCIG) that tends to drain large amount of reactive power from the grid during fault, potentially causing a voltage drop. A large disturbance of the stator voltage will cause high transient rotor currents which turn-on the crowbar protection for rotor-side converter (RSC). During crowbar activation, the RSC can no more control the active and reactive power, and the generator behaves as a SCIG. In these layouts of rotor crowbars, two main types are widely used. When this kind of crowbar is employed, the bypass resistor provides a bypass circuit to the rotor current during fault occurrences. This in order to attain the goal of limiting over-currents and protecting the rotor-side converter as well as rotor windings. In this segment, two layouts of rotor crowbars that have more merits will be compared.
Therefore, in this thesis the use of DFIG based Low-voltage-ride-through (LVRT) scheme is studied, including crowbar, RSC, GSC (Grid-side converter) and PSS (Power System Stabilizers) in order to enhance the transient stability and damping of the electro-mechanical oscillations of a grid-connected DFIG wind farm. An advanced hybrid cascade Fuzzy-PI based controlling technique is introduced to control the Insulated Gate Bipolar Transistor (IGBT) based frequency converter to enhance the transient stability. The performance of the presented control scheme is analyzed under a three phase fault condition on a single machine connected to weak grid. The transient operation of the system is investigated by comparing the performance of the DFIG system with and without LVRT and damping control scheme. The system validation is carried out in Simulink, according to PCC voltage (Fig. 3).
To improve the SCIG's low voltage ride through (LVRT) characteristics, this thesis presents recently developed control strategies for a variable-speed wind power generation DFIG (Doubly-fed Induction Generator) located closely to the SCIG-based wind system by utilizing the control capability of fuzzy logic technique.
The proposed control system regulates effectively reactive power output of the DFIG wind turbine by controlling both grid-side and rotor-side converters to compensate the reactive power absorbed by the SCIG-based wind turbine.



1. Hybrid FLC for normal and FRT operation.



2. Power coefficient curves for different pitch angles.

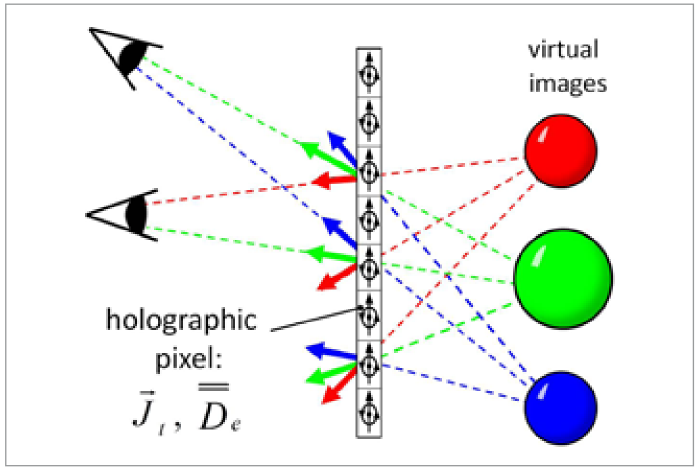


3. Resulting voltage at generator PCC.

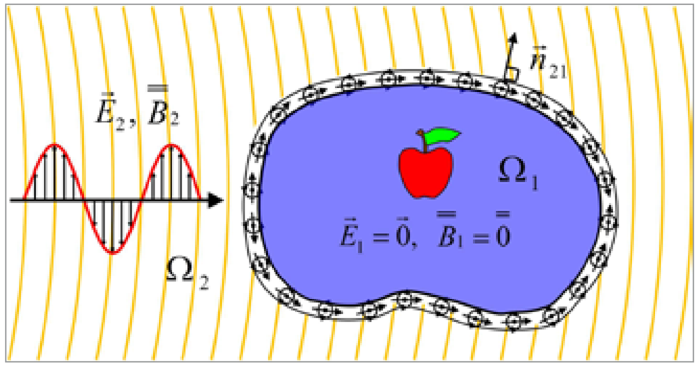
A PERSPECTIVE ON METASURFACES, CIRCUITS, HOLOGRAMS AND INVISIBILITY

Carlo Andrea Gonano - **Supervisor:** Riccardo Enrico Zich

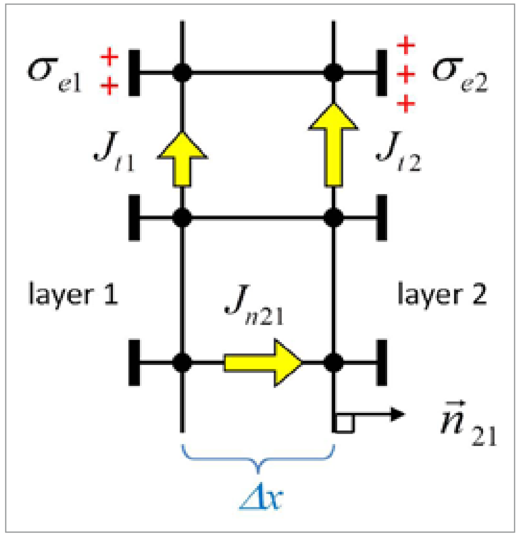
Metamaterials are artificial materials, made by microscopic unit cells and projected to exhibit specific macroscopic properties, e.g. they can be designed in order to show a negative refractive index or a superluminal wave propagation. During the last decade, the interest in electromagnetic metamaterials has been grown because of their possible applications, such as for antennas, transmission lines, lenses, cloaking devices etcetera. In this work we deal specially with metasurfaces, i.e. thin artificial screens or "2D metamaterials" . In particular, we analyze how to express the Huygens' Principle and the Boundary Conditions using the ElectroMagnetic Potentials, also considering the relativistic case. Starting from the Boundary Conditions we derive a circuit model for the project of a screen whose permittivity ε and permeability μ are assigned. In the last chapters we wonder about the possibility of using metasurfaces in order to realize a holographic television or a hypothetical invisibility cloak.



1. Holographic screen. Each pixel can exhibit a different color depending on the viewpoint.



2. Invisibility cloak. Outside the EM fields E2, B2 are unperturbed and are equal to the incident ones. Inside E1 and B1 are zero. From the Boundary Conditions it is possible to calculate the surface current distributions Jt and De.



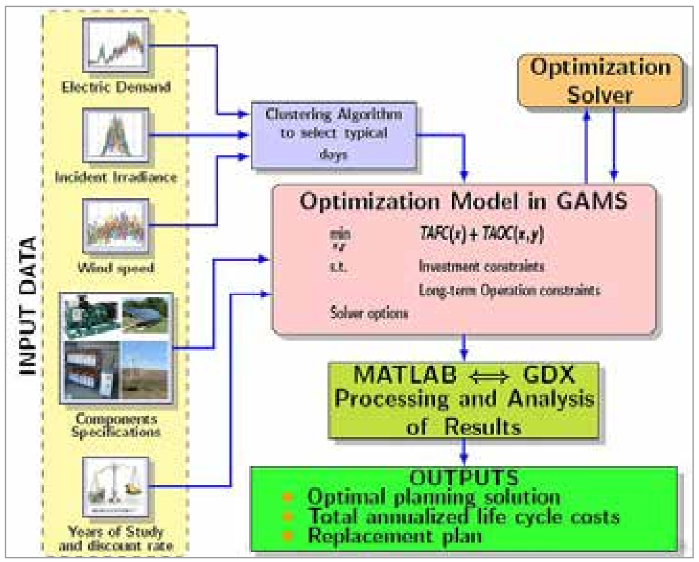
3. Basic circuit model for a 2-layer metasurface.

OPTIMAL PLANNING OF HYBRID MICROGRIDS

Godfrey Gladson Moshi - Supervisor: Prof. Alberto Berizzi

This thesis applies mathematical programming and optimization approach in planning of hybrid microgrid considering long-term operational constraints. The aim is to obtain the optimal capacities, combination, and number of components to install in a microgrid in order to ensure reliable and continuous supply of its electricity demand at minimum cost. A novel Mixed Integer Linear Programming (MILP) deterministic model for microgrid planning is proposed and solved. The overall microgrid long-term operation is integrated in the proposed MILP planning model. A technique called Clustered Unit Commitment (CUC) is applied in order to reduce the number of discrete variables required to model operation of Diesel Generators (DGs). In order to make the model computationally tractable, a modified K-medoids clustering algorithm is applied to select typical representative days. Each typical representative day has 24 hours profiles of solar irradiance, wind speed and electricity demand data as inputs to the planning model. Piecewise Linear Approximation (PWLA) of the nonlinear characteristics of Distributed Energy Sources (DERs) considered in planning is carried out. This allows the use of powerful solvers such as CPLEX and GUROBI which are available in General Algebraic Modelling System (GAMS). A block diagram of microgrid planning approach adopted in this research is shown in Figure 1.

The deterministic planning problem is reformulated in order to incorporate uncertainty in the main input data (i.e. hourly solar irradiance, wind speed, and electricity demand) in the microgrid planning model. Two MILP models for microgrid planning problem under uncertainty are developed. The first model adopts a Two-Stage Stochastic Integer Programming (2SSIP) formulation, whereas the second model adopts a Robust Optimization (RO) formulation. For the 2SSIP model, uncertainty are modelled by using discrete scenarios, whereas the for the RO model, uncertainty are modelled by using polyhedral uncertainty sets. The 2SSIP model determines the optimal planning decision variables which minimize the total annualized life cycle cost (LCC) computed over a number of suitable selected scenarios. On the other hand, the RO model determines optimal planning decision variables which ensure operational feasibility for all realizations of parameters within the uncertainty sets and minimize the total annualized LCC for the worst case realization of uncertain parameters. Applicability of the proposed 2SSIP and RO models are demonstrated through case studies for planning of new microgrids in un-electrified villages. Table 1 summarizes optimal number of components to install in the microgrid as obtained by the 2SSIP model with different number of scenarios, and RO with different budgets of uncertainty.



1. Block diagram of microgrid planning [TAFC: Total Annualized Fixed Cost, TAOC: Total Annualized Operation Cost]

Evaluation of the results obtained by the 2SSIP and RO model is summarized in Figure 2.

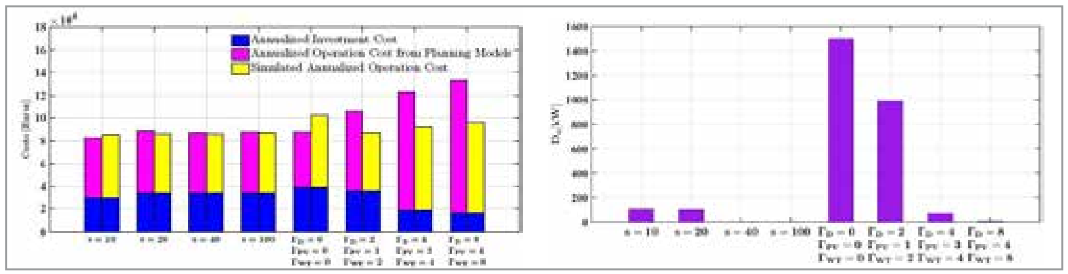
It can be seen in Table 1 that the computing time for the 2SSIP model grows rapidly as the number of scenarios increases. However, in this case, increasing the number of scenarios does not change results obtained by the 2SSIP model. This indicates that a relatively small number of scenarios is sufficient to obtain accurate solution for this case study. On the contrary, computational time for the RO model varies slightly with the size of uncertainty sets. The 2SSIP model, even with a small number of scenarios, yields a solution that accurately approximates the operational cost and which has lower quantity of unmet demand. When uncertainty budgets are set to zero, the RO model installs more renewable energy sources (RESs). This is due to the extremely low generation costs for RESs. However, solution obtained with zero uncertainty budgets underestimates the operational cost and has significant quantity of unmet demand. Increasing the uncertainty budgets for the RO model gives solutions with less uncertain sources, in this case wind turbines (WTs) and more reliable sources, i.e. DGs. Moreover, the RO solution becomes more robust with less quantity of unmet demand but with higher operational cost. Results from both 2SSIP and RO models show that storage plays a crucial role as energy buffer against uncertainty. The RO model selects the maximum number of storage batteries (15 units) in all cases with nonzero budgets of uncertainty.

This thesis has presented three models for planning hybrid microgrids: determinist MILP model, 2SSIP model, and the RO model. The proposed models combine long-term operation of the overall microgrid in its planning model. The models adopt discrete planning and operational decision variables which reflect real-world application and enable more realistic and accurate approximation of the long-term operation costs. It is found that these models complement each other by revealing different information to the planner. The RO model gives valuable planning results with regards to reliability of the solution. For feasibility studies, the RO model is arguably better complement to the deterministic MILP model.

Components			Number of Installed Components							
			2SSIP Model				RO model			
Name	Type	Capacity	s = 10	s = 20	s = 40	s = 100	$\Gamma_D = 0$, $\Gamma_{PV} = 0$, $\Gamma_{WT} = 0$	$\Gamma_D = 2$, $\Gamma_{PV} = 1$, $\Gamma_{WT} = 2$	$\Gamma_D = 4$, $\Gamma_{PV} = 3$, $\Gamma_{WT} = 4$	$\Gamma_D = 8$, $\Gamma_{PV} = 4$, $\Gamma_{WT} = 8$
DG	DG1	16.0 kW	3	3	3	3	3	3	4	4
	DG1	7.2 kW	2	2	3	3	0	1	0	1
PV	PV1	1.0 kW	20	30	30	30	30	30	10	20
WT	WT1	10.0 kW	4	4	4	4	4	4	2	0
	WT2	3.0 kW	0	0	0	0	4	1	0	0
SB	SB1	4.92 kWh	15	15	12	12	4	15	15	15
BC	BC1	10.0 kW	4	4	4	4	2	5	2	2
CPU Time [s]			22.75	473.68	5024.85	172366	2.9	249.2	106.3	73.9

DG: Diesel Generator, PV: Photovoltaic array, WT: Wind Turbine, SB: Storage Battery, BC: Bidirectional Converter

Table 1: Number of installed components obtained by 2SSIP and RO Model



2. Planning results obtained by 2SSIP and RO model: total annualized investment and operation cost (left), and annual unmet demand (right)

NOVEL METHODS FOR PV ENERGY FORECASTING OF THE DAY-AHEAD HOURLY POWER CURVE

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Nowadays stochastic models are widely used in the forecasting activity and it is easy to find software and applications to employ them, but the great problem is to find in literature a well-defined method for the setting-up of these models in order to get the most accurate results. The main goal of this work is to set up a well-defined method that could be applicable to any Photo-Voltaic (PV) plant to identify the best Artificial Neural Network (ANN) in terms of number of neurons, number of layers and training set size to perform the day-ahead energy production forecast. This is the hourly PV power output curve given 24 hours in advance. Therefore, my PhD thesis has been addressed to set up a new hybrid method (PHANN – Physic Hybrid Artificial Neural Network) – see the scheme in Figure 1 - in order to enhance the energy day-ahead forecast combining both the deterministic Clear Sky Solar Radiation Algorithm (CSRM) and the stochastic ANN method. The CSRM has been used both as a "validation mask" of the other parameters provided to the ANN and as an input.

During the setting up, several starting problems came to light. Most of these problems are related to the quality of the historical data which are assembled from different sources: the weather forecast providers and the PV plant monitoring systems. In fact several gaps, time-mismatching and fault-events heavily affect raw data. Hence, a careful data validation and pre-processing are always needed. This hybrid method has been tested on different PV plants in Italy by means of some evaluation indexes:

- NMAE normalized mean absolute error
- nRMSE normalized root mean square error
- WMAE weighted mean absolute error

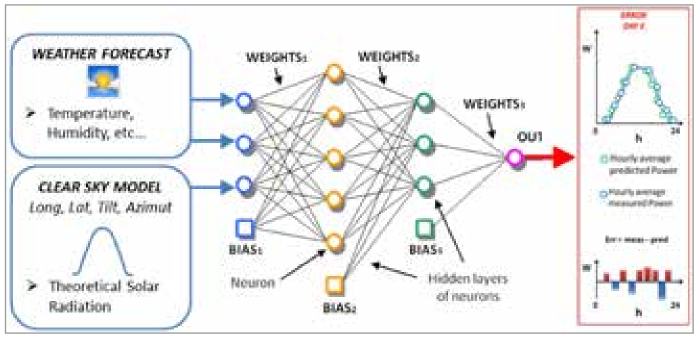
assessing the following:

- the role of the training set with different size and also in terms of data composition (typology of the day in the training set, classified by their clearness index k_t),
- the number of trials to be included in the "ensemble forecast".

Then different strategies have been analyzed and adopted to overcome the main problems related to this task. Finally, different weather conditions have been taken into account to test the robustness of the algorithm as well as the effects of particular events on the forecasting output.

Some further conclusions can be outlined. As regards the setting up of the method and the day-ahead forecast accuracy it can generally be inferred that:

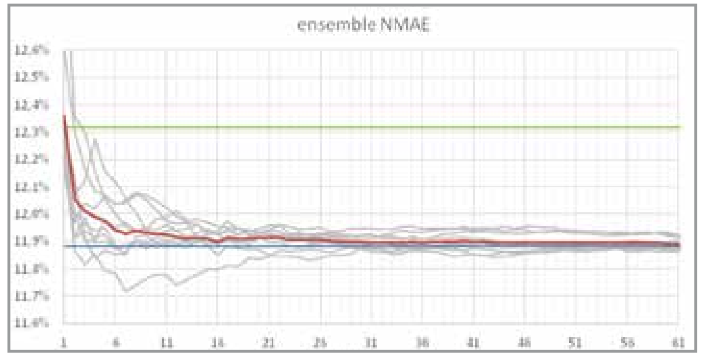
- to properly train a big network, a large dataset is needed and this is more time consuming,
- the error committed by dual layer networks is slightly lower than the one obtained by the single layer networks,
- the hybrid method (PHANN) better performs the day-ahead forecast if compared to pure stochastic models (ANN),
- large networks provide better results with large training,
- in the case of a sunny day, both large and small networks provide comparable results, while a large properly trained network gives better results in the case of cloudy days,
- "ensemble forecast" better performs, if compared to the single trials. After a certain number of trials the reducing rate of the error is not valuable (as it is shown in Figure 2),
- increasing the number of neurons and the number of training days, the errors are lowered (as it is shown in Figure 3),
- with the same small amount of available days in the training, two differently sized networks provide comparable results.



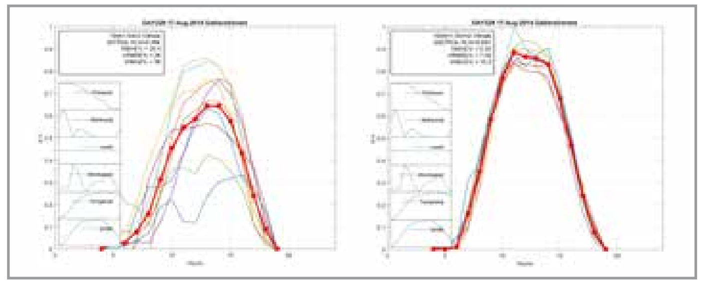
1. PHANN scheme.

A properly trained network is able to provide a day-ahead ensemble PV power output curve, which is the result of less scattered forecasts. Nevertheless these forecasts are strongly affected by the weather historical data accuracy used to train them, therefore it is possible that a properly trained network could still provide a very inaccurate profile due to the weather forecasts inaccuracy.

Finally, in the view of the electricity market, a tolerance threshold is included in the error assessment of the forecast and a corrective factor has been applied to the output of the model in order to minimize the error. From this analysis it is evident that there is not a single corrective factor value which minimizes the absolute errors in each PV plant. Therefore the corrective factor should be tuned on a suitable value among all the optimum values, if the forecast of a PV plants group is performed. Otherwise the best solution should be investigated for each particular PV plant.



2. NMAE of ten random ensembles (grey lines) as a function of the size of the ensemble basin (number of trials). The ANN has 120 neurons and the Levenberg-Marquardt training algorithm. The mean NMAE of the ensemble forecasts is in red, the mean NMAE of one thousands forecasts is the upper constant green line and the ensemble NMAE of one thousands trials is the lower constant blue line.



3. (Left) Ensemble forecasts performed with 30 training days by a 10-5 neurons ANN - red thick solid line - and (Right) by a 100-50 neurons ANN - red thick solid line – with 350 days of training for PV plant 1.