MECHANICAL ENGINEERING | PHYSICS | PRESERVATION OF THE ARCHITECTURAL HERITAGE | STRUCTURAL, SEISMIC AND GEOTECHNICAL ENGINEERING | URBAN PLANNING, DESIGN AND POLICY | AEROSPACE ENGINEERING | ARCHITECTURAL COMPOSITION | ARCHITECTURE, BUILT ENVIRONMENT AND CONSTRUCTION ENGINEERING | ARCHITECTURAL, URBAN AND INTERIOR DESIGN | BIOENGINEERING | DESIGN | **ELECTRICAL ENGINEERING** | ENERGY AND NUCLEAR SCIENCE AND TECHNOLOGY | ENVIRONMENTAL AND INFRASTRUCTURE ENGINEERING | INDUSTRIAL CHEMISTRY AND CHEMICAL ENGINEERING | INFORMATION TECHNOLOGY | MANAGEMENT ENGINEERING | MATERIALS ENGINEERING | MATHEMATICAL MODELS AND METHODS IN ENGINEERING

PhD Yearbook | 2019

DOCTORAL PROGRAM IN ELECTRICAL ENGINEERING

Chair:
Prof. Gabriele D'Antona

The main objective of the PhD Program is to allow a direct, prompt and efficient involvement of PhD graduates in academic and non-academic research and development bodies. A PhD in Electrical Engineering has a solid basic knowledge of applied mathematics and physics. This is essential, particularly for handling and understanding advanced tools and methods as well as for proper modelling, analysis and design of electrical engineering applications, with particular regard to power applications.
A PhD in Electrical Engineering well knows methods and applications in the main disciplines of Basic Electric Circuits and Fields, Power Systems, Electrical and Electronic Measurements, Converters, Machines and Electrical Drives.
The most important part of the PhD program is the development of the research that will be the core of the PhD dissertation.
The main research areas are:
A) **Electric Circuits and Fields**: This area is intended to provide the basic knowledge of methods in electrical engineering for power applications. PhD students are specifically trained to develop critical ability and innovative approaches. The training method encourages the development of discussion and debate skills in a team environment.
The main research and training subjects are: Nonlinear networks and periodic time-variant networks; Analysis of three-phase and multiphase systems; Switching circuits; Electromagnetic field equations; Electromagnetic field numerical analysis; Electromagnetic compatibility; Design techniques devoted to electromagnetic compatibility
B) **Power Systems**: A PhD in the field of Power Systems deals with the following subjects: electrical energy production (e.g., frequency and voltage control, protections, renewable energy sources, Dispersed Generation, Microgrids); electrical energy transmission (e.g., power system analysis, real and reactive power optimization, security and stability, integration of renewables); electricity markets (e.g., models, ancillary services, regulations); power quality and Smart Grids (e.g., harmonic distortion, active filters, UPS, interruptions and voltage dips, DC distribution).
C) **Electric machines and drives**: This research field is strictly related to the rising demand for improved machine and converter performance, in terms of low price, efficiency, robustness, dynamic response and drive control. This need leads to device optimization and better design and testing criteria. Moreover, a system approach is required for accurate integration of technical and economic aspects for final application.
The main subjects in this field are: Use of new materials; Novel magnetic structures; Methodologies of model development for design and operating analysis; Optimization procedures; Use of finite elements code, simulation programs and environments for device study; Control system definition both on the device and system side.
D) **Measurements**: This research field concentrates on the fundamentals of metrology, particularly with respect to characterization of modern measurement systems based on complex digital signal processing structures. Some of the main subjects of study are: measurement methodology as it relates to power systems, including medium and high voltage systems and components, as well as both digital and analog signal processing. Methodologies and measurement systems associated with industrial automation and, in particular, microelectronic sensor applications, distributed structures and advanced methods and algorithms for maintenance-oriented diagnosis of complex systems are investigated in detail.

After graduation, PhD are typically employed at:
- Major research centres;
- R&D departments;
- Power generation, transmission and distribution firms;
- Engineering consultant offices;
- Metrology reference institutes and certification laboratories;
- Process and transport automation areas.

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ADVANCED CONTROL STRATEGIES FOR POWER CONVERTERS IN AC MICROGRIDS

Alberto Bolzoni - Supervisor: prof. Roberto Perini

Introduction

The main topic of this thesis regards the development of control strategies for power converters in microgrid applications; the focus of the work has been mainly related to three-phase AC microgrids. The thesis is divided into two parts, each corresponding to a major control approach generally used for power converters: starting from the analysis of the state-of-the-art, those architectures are later extended in order to enhance the dynamical properties of the converter during the provision of regulation services to the microgrid. The goal of the thesis is to develop a set of robust analytical and numerical models able to interpret the regulation strategies at the light of the control architectures stability properties.

Part I: Enhanced-droop architecture

The first part of the thesis analyses the "droop control": this type of regulation allows the control of the voltage amplitude and frequency in a distributed way, guaranteeing equal load sharing between parallel connected units. Starting from the regulation scheme typically presented in literature, a new concept based on the combination of several sub-controls functions has been proposed, as in Fig.1 As a first stage, the dynamical properties of the internal voltage and current regulators have been taken into account. The active power sharing between parallel units is guaranteed by the droop regulation: a complete and rigorous model of the converter under this control architecture has been developed and tested (Fig.2). Furthermore, the introduction of the virtual impedance is analysed: this technique allows a fictitious emulation of a physical inductor in series with the converter output, enhancing the stability properties of the converter and enabling a balanced reactive power distribution between parallel connected units. A design procedure is identified and its stability conditions are validated experimentally both in grid-connected and island operations. The analysis reveals a strong dynamical sensitivity of the converter with respect to its external physical impedance. Thus, a procedure for the on-line identification of the converter interface impedance based on the system response to harmonic disturbances has been developed. Several algorithms are tested: they can be used as input for adaptive schemes inside the converter control.

Part II: Frequency-supporting PQ converter

In the second part of the thesis, the feasibility of transient frequency support by means of undispatchable units has been taken into account. This property typically goes under the name of "synthetic inertia": it consists of a fast-response active injection proportional to the system angular frequency derivative, thus emulating the natural damping effect of a physical inertia by means of an electronic converter. Starting from the PQ architecture typically used for renewable units, the control scheme has been extended to allow a controlled-inertia provision. The stability of the scheme is tested both analytically and by eigenvalues calculation. As the proposed approach requires a robust and fast extraction of the angular quantities from the available voltage measurement, a novel estimator (Second Order / Second Order Generalized Integrator with Negative sequence compensation, SOSOGI-N) has been developed and compared with other available techniques: this algorithm guarantees optimal performances, as illustrated in Fig.3. Two alternative inertia-provision schemes have been developed and tested, both in simulation and experimentally. The experimental set-up consists of a stand-alone small-scale microgrid exclusively supplied by electronic units. The results confirm the correctness of the dynamical model and the effectiveness of the proposed strategy in damping network frequency oscillations: this opens new scenarios for power system regulation.

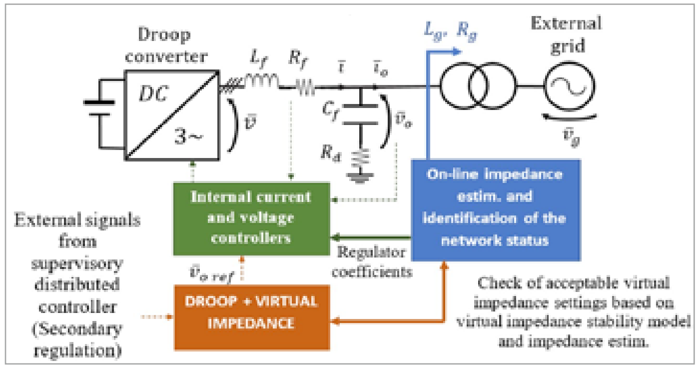

Fig. 1 - Enhanced-droop architecture: each sub-control is designed in order to guarantee the system stability. The dynamical effects of each sub-control in the converter stabilization both in grid-connected and island mode are analysed.

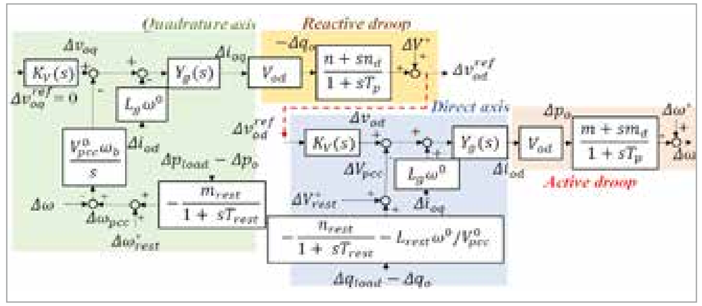

Fig. 2 - Dynamical model of the converter under droop regulation.

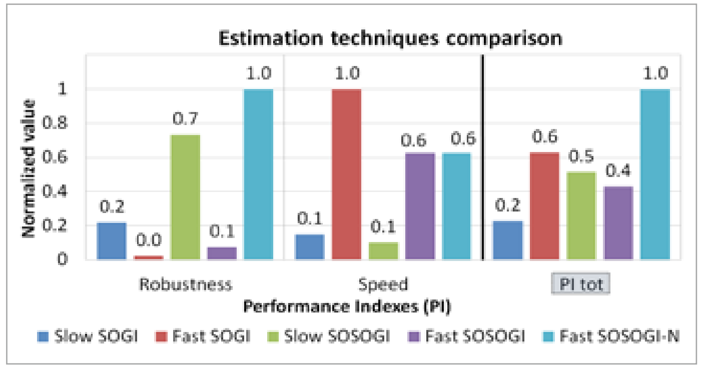

Fig. 3 - Normalized comparison of the angular quantities estimators in terms of robustness and fastness. A global combined normalized index is reported in PI tot.

EVOLVED FEATURES IN MVDC RAILWAYS AND HVDC NETWORKS BY ENERGY STORAGE SYSTEMS

Alessio Clerici - Tutor: Prof. Luigi Piegari

Relatore: Prof. Enrico Tironi

Since 1890, after the conclusion of the so-called "War Of Currents", Alternating Current (AC) became the actual standard for the most of electric system worldwide; the main reason for such choice was definitely practical: the transformer at first, the induction motor later on, made AC power the way to be transferred and used with low electrical losses and high mechanical efficiency, driving the Second Industrial Revolution in the last years of the 18th Century. Main disadvantages of Direct Current (DC) respect to AC were the impossibility of efficient voltage scaling by transformers, the difficulty in generating high voltages into the dynamos and high maintenance required by DC motors (both due to collectors wearing).

DC power, initially prominent respect to AC, was eventually confined in few fields of interest, usually in networks or grids specifically designed for specific purposes (e.g. rail traction or very long distances transmission lines). Such paradigm changed since the last decades of the 19th Century, for two main reasons:

Power electronics progresses: new solid-state based converters have been developed, by-passing both the problems of voltage scaling and defects of DC motors;

Spread of information technology and microelectronics (Third-Fourth Industrial Revolution): all Personal Computers (PCs), all portable devices, all modern electronic gadgets, smart-phones and so on are DC based, and they require a wide range of high quality supplies, also uninterruptible.

Due to previous reasons, great and growing interest is emerging about DC power all over the world. This huge revolution only touched marginally the mentioned pre-existing DC networks; many remarkable improvements have been got in such areas, especially regarding conversion efficiency and devices reliability, but the general layout of those systems is still the same: in 3 kV DC railway field, as example, power distribution is still mainly based on old-style diode rectifies, very robust, reliable, quite efficient, but not versatile, nor designed to adapt themselves to different energetic scenarios.

Direct Current High Voltage (HVDC) transmission lines have been empowered a lot, because of necessity, in some cases, to overpass specific technical limits of AC: high inductive and capacitive effects, need of intermediate substations, infrastructure costs (pylons, cables, etc.); technology became much more efficient, but not fully integrated in the network: presently, multi-terminal HVDC grids are very rare, while they are common in AC.

In recent years, a new set of critical issues about power transmission and distribution is growing: high power loads can create problems of voltage stability and power quality, especially where network is weak; as example, modern trains on 3 kV DC railway are high power demanding, they cause voltage drops in acceleration and power waste during braking; low-carbon economic models generated the huge penetration of renewable not programmable energy sources; the result is a progressive dismiss of the traditional AC rotating generators, or their different way of utilization (cold stand-by); decentralized power production in AC network makes control and stability much more complex than in the past.

DC systems are maybe part of the problem but they can also offer a good way to mitigate some of the most dangerous effects; in particular, energy storage systems (ESS) technology is actually mature to provide a significant contribution in supporting DC and AC grids health.

This work aims to face above mentioned issues by introducing ESS in two of the most relevant power DC networks of today, 3 kV DC railway and HVDC transmission grids; because such fields are traditionally quite conservative, main focus of the project regards integration of new equipment with existing infrastructure; due to this, activity has been mostly organized as a feasibility study, in which some solutions (hardware and controls) have been implemented, sized and simulated in order to be included in actual or future installations; the main goal is a smooth transition to new and evolved features, giving tangible gains in terms of performance and/or functionalities.

Activity is structured as follows.

First part analyzes a 3 kV DC railway with high penetration of modern (high power demanding) trains; main technological challenges are: save energy and boost catenary voltage without oversizing the existing traction substations. After a preliminary analysis about recoverable energy, the problem is tackled by introducing DC wayside ESS to improve regenerative braking and catenary voltage stabilization; layouts and sizing results then are validated by simulations. Brief economic scenarios are also presented, in order to show a reasonable Cost-Benefit Analysis (CBA) of the solution.

Second part studies the most recent IGBT based HVDC grids, in order to stabilize AC frequency with synthetic inertia algorithms; main technological challenges are: implement an efficient inertial algorithm into the VSC converter control and avoid frequency fluctuations through different synchronous areas. After several studies and attempts by means of simulations, target is achieved by means of innovative synthetic inertia algorithm and with an oversizing of VSC converters DC filters.

In both chapters, approach is top-down, considering equipment as part of a plant, mainly focusing on functionalities; later on (also in appendixes), system structures are deepen considering in detail some aspects: design solutions are analyzed, control algorithms are explained and compared, presenting advantages and disadvantages.

RENEWABLE ENERGIES INTEGRATION ON DISTRIBUTION GRID

Mina Mirbagheri - Supervisor: Prof. Marco Merlo

The key point of international and European policies in order to reduce the greenhouse gas emissions is increasing the usage of Renewable Energy Sources (RES). Renewable energy technologies are divided into dispatchable (e.g. hydro and geothermal power) and non-dispatchable or variable (e.g. solar photovoltaic and wind power). The small size RES which is connected to distribution network and very close to demand side is called distributed power generation. This could be useful to reduce the need of high-voltage transmission network and centralized power generation.
However, the massive Distributed Generation (DG) connection and its uncontrolled and nonprogrammable power injections may cause power quality and reliability issues such as voltage profile and conductors ampacity problems, harmonics, unwanted islanding phenomena, due to neglecting the actual distribution grid power needs. Consequently, it may require new interventions on the grid to improve its ability to accept local generation without incurring the technical problems.
Hence, integration of such variable renewables to the distribution grid needs some grid transformation such as electric protection logics capable to properly manage bidirectional energy flow (top-down and bottom-up), demand management, energy storage, improve regional, national and international interconnection and introducing technologies and procedures to ensure proper grid operation stability and control (frequency regulation, reactive power regulation, active power reservation, congestion management, optimization of grid losses, network restoration) in the presence of significant share of variable renewables. Therefore, at operational level, efforts are made to turn the distribution grids into smart grids in order to achieve an optimal management of these resources.

A wide literature review has been performed in order to properly point out and classify the problem; a schematic of renewable integration into power grids have been reported in Figure 1; process and technology statues, performance and costs, and potential and barriers are the main three frameworks for this subject. Process and technology statues cover the general terms of smart grid, micro grid and in general active distribution grid, therefore studies related to communication technologies, power electronics implementation for frequency control, system protection, energy storage, maximum renewable injection capacity and gathering the required information for these analyses are in this category. While, performance and costs framework in this schematic give people some ideas about the cost of implementation and increasing the share of renewable integration. Potential and barriers mainly focus on renewable integration policy and their liberalized market structures. Figure 2 represents the covered area in this thesis according to the overall schematic. Since a proper management of DGs is vital, strong research activities based on statistical, deterministic and heuristic approaches have been done in order to ensure with a given amount of DG connected to the distribution grid, the network is still working within the admitted operational ranges imposed by technical standards and regulatory agencies. Although grid regulations do not allow distribution system operators to refuse any request of DG connection, the goal of many research works is determining the optimal DG sizing and siting. However, these studies have a scarce applicability in real-life. In this regard, evaluation of the maximum generation that can be hosted by the distribution grid without violating the grid constraints is one of the main performance indicators that should be considered for planning and operation of the grid. This indicator is commonly known as Hosting Capacity. In the literature, this indicator could be implemented for several applications such as renewable energy sources integration, electric vehicle integration and voltage control; the main focus of this thesis is based on them. However, one of the main problems in the power system sector in some countries, especially developing and emerging countries for evaluating such an indicator is lack of public data and information about both transmission and distribution grids. Quite often, the only source is limited to the map of the network and general information on the voltage profile and power flows in the lines for a standard working point of the grid. Hence, it is currently hardly impossible to perform further network analysis. Hence, due to the aforementioned limitation, a procedure is required to be designed in order to estimate the hosting capacity of distribution grids even in case of uncertainties in grid parameters or lack of data. The proposed approach results particularly useful when it is not possible to collect all the necessary data for a classical load flow-based analysis, as in the case of studies relevant to emerging countries electrification processes, or when data gathering is difficult, for example when such data are considered sensitive. As the next step, evaluating the possible ways to increase the hosting capacity without reinforcement is a major concern in both DG and electrical vehicle planning. Therefore, the importance of voltage control as one of the main approaches to increase the hosting capacity is highlighted in many research papers. Traditionally, in passive distribution networks the voltage rise has been mitigated by network reinforcement.
Nowadays, local voltage control, coordinated voltage control and centralized voltage control have been discussed for active networks in research papers. Although all the approaches have been proven to solve the problem of voltage rise in distribution grids, using plenty of sensors to gather huge number of measurements could cause complexity and cost. Hence, a new procedure to set up a local voltage control law devoted to properly manage the voltage profile to increase the upper limit of total DG injection to the grid is required.All of the mentioned simulations in this thesis work are coded in MATLAB and then validated for a real-life case studies in Italy and Tanzania.

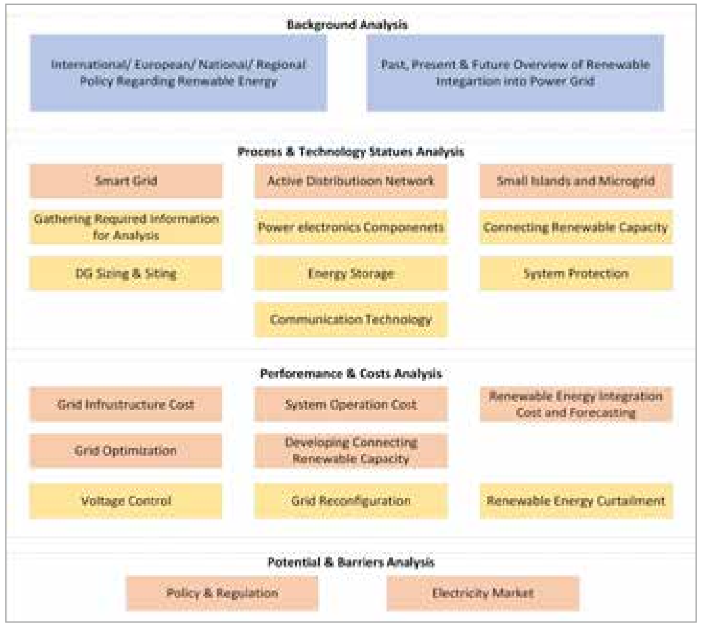

Fig. 1 - Overall schematic of renewable sources integration to the grid.

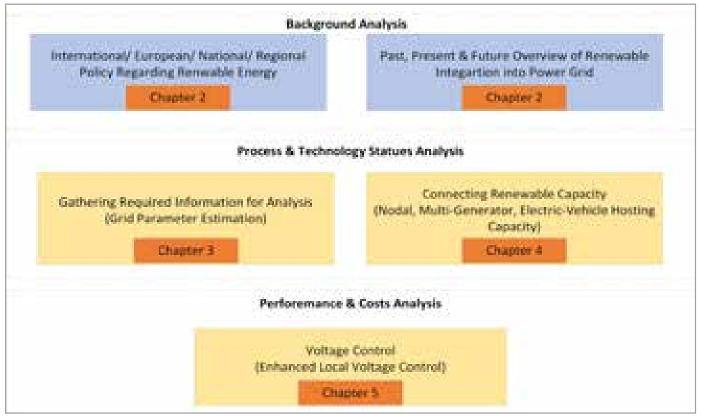

Fig. 2 - Adopted schematic.

MODELING INJECTION DEVICES FOR SUSCEPTIBILITY VERIFICATIONS AT UNIT LEVEL

Nicola Toscani - **Supervisor: Flavia Grassi**

The research activity documented in this thesis is motivated by the growing interest of the Electromagnetic Compatibility (EMC) community for the development of test procedures that can be valid alternatives to traditional radiated susceptibility tests. As a matter of fact, radiated susceptibility procedures are quite expensive and time consuming, since they involve anechoic or reverberating chambers and they are not suitable for pre-compliance verifications.
Some preliminary studies highlighted the possibility of exploiting conducted susceptibility procedures in spite of the radiated ones for suitable low frequency operation. Namely, correlation among alternative tests was theoretically set up in frequency ranges which are parts of the working intervals of the considered procedures.
Conducted susceptibility tests based on current injection through Bulk Current Injection probe and Tubular Wave Coupler are a valid alternative to the radiated susceptibility assessment. Moreover, they allow immunity verifications in complementary frequency intervals; in principle, a concerted employment of them can allow injection on an overall range from some kHz up to few GHz.

In such framework, this thesis focuses on modeling Bulk Current Injection probe and Tubular Wave Coupler so to enforce correlation between the interference induced by field illumination and by current injection. Initially, behavioral black box models based on measurements were developed to preliminary investigate the undergoing coupling phenomena between the generator circuits and the victim conductors. Then, circuit models were developed for either single- and multi-conductor setups. Thus, explicit formulations of the networks adopted for the interpretation of the black box representations were obtained through analytical formulas and transmission line theory. Then, some efforts were spent for implementing a robust circuit model in SPICE for the Bulk Current Injection probe suitable for time domain simulations, even in the presence of nonlinear devices (e.g., diodes). Moreover, 3D electromagnetic models were developed as well by realizing accurate virtual reproductions of the considered devices in terms either of geometrical dimensions and materials. These virtual devices allow the simulation of test setups that may be difficult to realize in practice. Consequently, calibration structures for both the injection devices were studied and modeled. In this way, it is possible to simulate all stages of a real test for conducted susceptibility assessment; that is, the objective is to have a virtual laboratory at disposal for fast pre-compliance checks.
Based on these models, modal analysis was carried out to assess the nature of injection of the two devices on multi-wire bundles in terms of common and differential modes. With this aim, equivalent modal circuits were proposed for predicting the physical interference due to the Bulk Current Injection probe.
Some of the models proposed in this thesis were applied to susceptibility test cases of interest for the automotive sector, in the framework of a collaboration with BOSCH (USA) and CST.

Fig. 1 - Bulk current injection probe, model FCC F-130A.

Fig. 2 - Tubular wave coupler made by Amplifier Research.

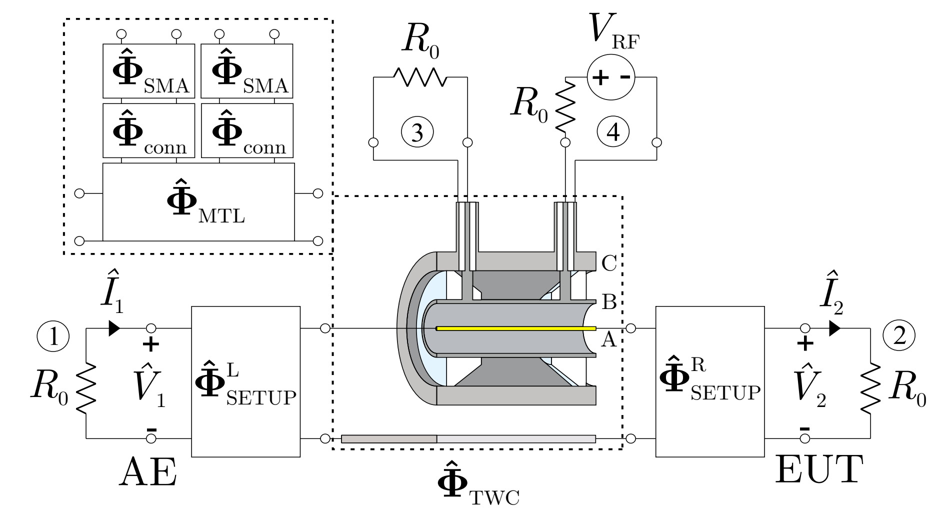

Fig. 3 - Distributed-parameter model of the TWC mounted on the CF. The TWC model is detailed in the up-left panel.

NONLINEAR FREQUENCY-DOMAIN MODELLING OF POWER SYSTEM DEVICES

Michele Zanoni- Supervisor: Prof. Sergio Toscani

Nowadays, the diffusion of nonlinear devices such as those based on power electronics is continuously growing. The reason is on the one hand the impressive advancement of high-power semiconductor devices and the reduction of their cost, on the other one the increasing penetration of photovoltaic generation. However, such nonlinear devices are responsible for significant harmonic distortion levels in ac distribution systems, as well as for the related power quality issues.
It becomes clear that studying and predicting the impact of nonlinear devices on the harmonic pollution of the grid is extremely important. However, it requires proper models able to capture the nonlinear behavior of the devices. Furthermore, monitoring voltage harmonics in electrical grids represents a vital task, but this demands for adequate instrument transformers. In particular, when measuring small harmonic components, transducer output may be significantly affected by nonlinear effects, which are seldom taken into account. Innovative tests based on a nonlinear model of the instrument transformer would allow an accurate characterization of their measurement performance, permitting to qualify and quantify the impact of nonlinearities.
These considerations show that nonlinear modeling of power system components represents a vital tool when dealing with harmonic pollution. This thesis investigates different frequency-domain modelling approaches, suitable to represent the steady-state output due to a periodic input. All of them can be derived starting from the well-known Volterra series framework by exploiting, in different ways, the peculiar spectral content of electrical signals in ac power systems.
The Volterra series comes out as the most straightforward extension of the well-known linear time invariant systems theory to the nonlinear case. The approach has been presented and deeply discussed, focusing in particular on its frequency domain representation. However, frequency-domain Volterra models are generally employed up to the third degree (or nonlinearity order) since the number of coefficients required to represent their behavior grows more than exponentially with the number of input harmonics and the with the nonlinearity order.
When focusing on ac power systems applications, the spectral content of the input signal, supposed to be an electric quantity, typically consists of a largely prevailing fundamental component which is superimposed to harmonics which are considerably weaker in comparison. By exploiting this peculiarity, different nonlinear models specifically devoted for power systems applications have been derived and presented.
First, the best linear approximation approach has been introduced as the optimal method to represent nonlinear time invariant systems with a frequency response function. The most important feature is that it allows quantifying nonlinear effects. A frequency-domain Volterra model can be dramatically simplified by using the a priori knowledge about the input signal, which in power system applications consists of a strong fundamental component superimposed to harmonics which are considerably smaller. Neglecting interactions between input harmonics leads to quasi sinusoidal Volterra models. A further simplification is considering only the nonlinear effect which is purely due to the large fundamental, thus leading to harmonic distortion models. For both the models, a procedure allows an easy practical implementation is provided for the first time. Other nonlinear frequency domain models already proposed in the literature can be derived as spectral linearization of the frequency domain Volterra models under different assumptions. In particular, Frequency Transfer Matrixes (FTMs) have been employed to consider nonlinearities in power systems for a long time, and they represent the most commonly employed approach. These models are based on a frequency domain linearization around a reference input of each output spectral component with respect to the whole input spectrum. Another possibility is adopting polyharmonic distortion models, representing a specific case of the spectral linearization approximation which is employed to compute X-parameters in radiofrequency applications.
The idea which polyharmonic distortion models are based on is pretty similar to that exploited to define FTMs. However, in this case the input signal spectrum is split into large and small components. Linearization is performed only with respect to small signal components; parameters resulting from linearization are considered as nonlinear functions of the large components.
All of these approaches have been tested using numerical simulations by considering two significant yet very different case studies: representing the behavior of an inductive voltage transformer and modeling the current-voltage relationship of a bridge rectifier feeding an ohmic-capacitive load. Firstly, the proposed approaches have been applied by means of numerical simulations to represent the relationship between primary and secondary voltage harmonics of an inductive voltage transformer. Moreover, results have been compared for the first time to those achieved by using FTM and X-parameters approaches. Finally, the proposed modeling approaches have been implemented and validated through an experimental activity on a MV VT; results are compared with those obtained from simulations. Results show that the measurement performance of voltage transformers are significantly affected by nonlinearity, especially as far as low-order harmonics are considered.
Then a bridge rectifier has been considered: the proposed models have been applied by means of numerical simulations to represent the relationship between current and voltage. Firstly, the BLA has been estimated: this permits to quantify the large impact of odd nonlinearities. Moving to nonlinear models allows achieving considerably improvements. Harmonic Distortion models permit to increase accuracy up to the ninth order current harmonic, while the proposed simplified Volterra models permit further improvement at low-order harmonics. The FTM approach results in good performance, albeit worse than that obtained by the simplified Volterra approach (having similar number of coefficients). On the other hand, the X-parameters approach permits high accuracy for all the considered components, but the amount of coefficients to be identified is fairly large
Finally, the simplified Volterra and Harmonic Distortion models have been experimentally validated by considering an actual BR. Results have confirmed what expected from numerical simulations.