DOCTORAL PROGRAM IN ELECTRICAL ENGINEERING

Chair:
Prof. Alberto Berizzi

The main objective of the PhD Program in Electrical Engineering is to allow PhD students to receive an educational level such that they can be effectively employed in any research body such as an R&D department of a production or services company.
A PhD in Electrical Engineering has a firm basic knowledge of mathematics and physics. This is essential, particularly for handling and understanding advanced tools and methods as well as for proper modeling, analysis and design of electrical engineering applications, with particular regard to power applications.
The main research areas are:

A) Circuit 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 should encourage the development of discussion and debate skills in a team environment. The main 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, Antennas and innovative communication systems.

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); Electrical energy transmission (e.g., Power system analysis and dispatch, Optimal Power Flow, Security and stability); Dispersed Generation and Smart Grids, including specifically designed communication systems; Liberalized markets (e.g., new generation patterns, ancillary service management, existing market models applied to the Italian system, regulatory issues, regulatory issues); Power quality in distribution systems (e.g., line current harmonic distortion, active filters, UPS, interruptions and voltage dips); Optimization by innovative algorithms (Neural networks, Genetic algorithms, etc.).

C) Power Electronics:
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; energy efficiency.

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.
At the beginning of the first year, the admitted students propose to the Board both the area in which they would like to develop their research and a supervisor.
During the first year, the students complete their knowledge by taking some Introductory courses chosen among the MSc Courses at Politecnico di Milano, and begin 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" where they explain the way they will develop it. The choice of the subject must be approved by the Supervisor. Moreover, they have to deeply investigate the subjects related to the proposed area of research by means of a bibliographical research. At the end of the first year, a first examination takes place, based on a report prepared by the students for the Board.
The second year is dedicated to the basic scientific and specialized skills necessary for the dissertation, which will be completed during the third year. Also, Main PhD Courses must be taken and students are also required to carry out a specific training for research through courses, specialized seminars, conferences, and research activities closely associated with the topic of dissertation. At the end of the second year, the second examination takes place. Here, the students present a second report to the Board.
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.

After graduation, PhD are typically employed at:
- Major research centres
- R&D departments
- Power transmission and distribution control centres
- Engineering consultant offices, in particular those involved with national and international security and environment regulations
- Metrology reference institutes and certification laboratories
- Process and transport automation areas

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UNIFIED CONTROL METHODS FOR POWER-CONVERTER-BASED SYSTEMS

Giuliano Angeli

Introduction and description of objectives

This thesis presents the analysis of some control methods for power converters, with a particular attention for those converters that are used in power systems to perform the AC/DC and DC/AC conversion. The focus is on the analysis of two quite common situations: *front-end converter* and *customer-end converter*. Besides the most typical configurations used in practice, also multiswitching converters are investigated. Power converter control problem is very complex as it is strictly related to the system under control. In particular two main aspects can be pointed out:

1. the control system, i.e. the method by which reference values of converter drivers are determined;
2. the modulation technique, i.e. the pulse generation methodology to realize the reference values.

Methodology

Let's focus the attention on the first point: the control system. First of all, we have to be familiar with some basic concepts and the first one is the concept of *sliding mode control (SMC)*. Some of its most distinguishing characteristics are: simplicity of design, invariance to process dynamics and external perturbations, ability to decouple high dimensional problems into sub-tasks of lower dimensionality. Since this technique involves differential equations with discontinuous right-end side, the concept of solution needs to be redefined and alternative approaches to the classical ordinary differential equation theory needs to be developed. The basic concept of sliding mode control is that the control law commutes while crossing a particular surface called *switching surface*. That surface can be chosen in order to achieve the desired control requirement and in particular it has to be designed in such a way that all trajectories are directed toward the surface (regardless of which side of the surface they are). This condition is usually called *reaching condition*. Consequently, once it is reached, a new phenomenon appears: the trajectories are sliding along this surface. While sliding motion, the order of the system turns out to be decreased and the motion is the same if, instead of the discontinuous control, an *equivalent continuous control* had been used. This equivalent control can be considered as the mean value of the discontinuous control on the sliding surface. Yet, in sliding motion, the control switches with a high frequency and we usually refer to this phenomenon with the name of *chattering*. For what concerns commutation, we can say that the most widely used modulation techniques are organized in two main groups: the first one realizes a voltage reference signal (sine PWM and Space Vector Modulation for three phase systems); the second group of methods is based on a current reference signal to be realized. Among them the most common method is known as *hysteresis current modulation*. Thanks to its intrinsic simplicity, this method is widely used in a lot of fields with good results; the main drawback is the variable switching frequency. For this reason in this thesis the strategy known as *smart modulation* is taken in consideration. Smart modulation is based on unconventional current threshold set and its features are fixed switching frequency and pre-calculated commutation instants, allowing an accurate phase shift of the current ripple during parallel converter connection. Moreover it is characterized by the same features of hysteresis current control in terms of good dynamic performance, good accuracy and simple control technique. The method proposed here is very useful because it is general and it overcomes most of the specific problems usually occurring in applications. The steps that compose the method are the following:

1. primary reference signal on passive elements. Reference signals have to be the currents flowing through inductors and the voltages across capacitors. Theoretically, other reference signals are allowed, for example powers, energies…
2. control is designed by the mean of Sliding Mode Control. Sliding Functions are built and it is not mandatory that the number of Sliding Functions is equal to the number of primary references signals. The constraint to be respected is that controls must appear in the formulation of Sliding Functions derivatives in order to guarantee controllability. System appears as Multi Input Multi Output (MIMO), where the inputs are the switching controls (typically characterized by two levels) and the outputs are the Sliding Functions. It is useful to underline that the number of controls may be equal to the number of Sliding Functions or also exceed it.
3. System is reformulated as *n* decoupled systems Single Input Single Output (SISO). In order to get this result, it necessary to increase the number of Sliding Functions until it is equal to the number of controls, then making input-output matrix diagonal is mandatory to reach a direct correspondence between Sliding Functions and controls.
4. Each SISO element is then modulated by the mean of the current tracking modulation strategy called Smart Modulation.

Discussion of the results obtained

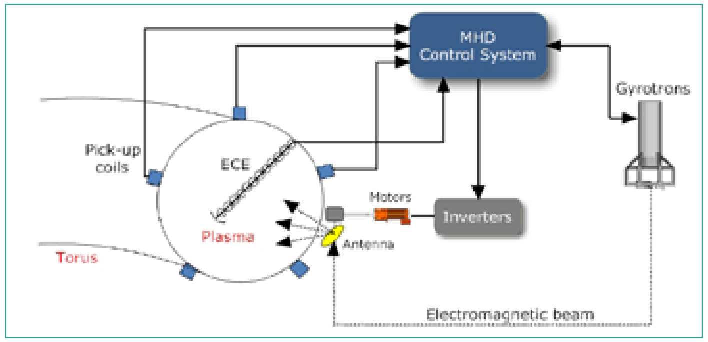
Control of Power-Converters-Based Systems is a very complex problem as it is strictly related to the system under control. Many strategies are available in literature: this thesis has been written in order to provide a "less conventional" road which is able to overcome the most typical drawbacks concerned with the conventional approaches. For what concerns the control strategy, this thesis has exploited the theory coming from Sliding Mode Control. After a brief recall about the basic notions of Sliding Mode Control, a short example of Sliding Mode applied to power converters has been shown. One of the most important problems to be faced during applications is called *chattering* and CHAPTER 5 gives an idea of what this problems means. The problem of chattering is related to the problem of commutation strategy and this correlation has given the opportunity to introduce two different approaches: the hysteresis control, that is more conventional, and the Smart Modulation, that is more innovative and allows an easier control of chattering. A general method for the control of power converters in power systems has been presented: this is the most innovative contribution of this thesis to the research field studied. This method is totally general, so it overcomes most of the specific problems usually occurring in applications. Three case study have been presented in order to show the use of the method proposed. First, a Front-End Converter as an harmonic damper has been proposed, than a Front-End Converter as interface between Utility and low voltage DC systems has been studied and finally Customer-End Converter has been controlled in order to feed final customers with the proper voltage imposed by the technical norms. Afterward, multiswitching converters have been taken into consideration. CHAPTER 8 has presented the general study of these devices and in particularly it has shown that the general method proposed is able to manage the multiswitching case by the mean of decoupling strategy: multiswitching systems are reformulated as the union of several decoupled systems, each of which modulated by Smart Modulation. In order to deeply clarify the notions expressed above, CHAPTER 9 presents two more case studies: the first consists in a study of the decoupled strategy applied to Current-Controlled Multiswitching Systems; the second takes into consideration an Innovative Universal Power Conditioner with UPS Function. These last two case studies had been already studied in the Electrical Engineering Department of Politecnico di Milano when I started my PhD program, nevertheless we have decided to show them in this thesis because they are still two of the clearest examples about what the general method proposed means.

DIAGNOSIS AND CONTROL OF NEOCLASSICAL TEARING MODES BY ELECTRON CYCLOTRON HEATING IN TOKAMAKS

Mohsen Davoudi

The research for producing energy from fusion of light nuclei has led to significant advancements in the experiments based on the tokamak concept (TOroidalnaya KAmera v MAgnitnykh Katushkakh, Russian word for "toroidal magnetic confinement"). Magnetic confinement of high temperature plasma is a practical technique for a fusion reactor. A tokamak is a magnetic confinement system that produces toroidal and poloidal magnetic fields to confine the thermonuclear plasma in a vacuum chamber for achieving the conditions for nuclear fusion reactions. It is designed for achieving the controlled thermonuclear fusion power.
The control of unstable rotating Magnetic Hydro Dynamics (MHD) perturbations, associated with local distortions of the current density profile has been one of the important issues in thermonuclear plasma research. It has been the general objective of this research to develop some ideas and realize the tools and hardware needed for detection in real-time of magnetic islands and control of electron cyclotron heating and current drive (EC-H&CD) system in order to stabilize the MHD perturbations in particular neoclassical tearing modes (NTMs) to increase the performance of a fusion reactor. Generally, by injecting energy to the magnetic islands using microwave antennas, a specific magnetic surface layer will be resonance and the magnetic islands disappear. The MHD controller tracks the magnetic island movement along the minor radius of the plasma by controlling the angle of antennas which reflect the electron cyclotron (EC) microwave beam to the associated deposition surface (r_{DEP}) in the plasma. The performance of the MHD control system depends on how the system diagnoses the NTM position (r_{TARGET}) and the deposition minor radius (r_{DEP}). Since uncertainty and evidence of measurement are important issues in control strategy, the Bayesian theory based algorithm has been modified to be used for estimation of r_{DEP} and r_{TARGET} in FTU (Frascati Tokamak Upgrade, the tokamak in Frascati, Italy) using estimation theory and diagnostic methods.
In the research activity presented in this thesis, the control strategy and MHD control architecture for FTU have been defined and implemented.
An important part of the activity, in collaboration with IFP-CNR, was the hardware implementation of the estimators, observer, controller and model-predictive protection system for motors. A set of reliable, flexible and robust hardware structure and software tool which is capable of running estimator, observer and controller in real-time has been proposed to achieve the main goal of MHD instability suppression in order to be integrated in the FTU. The controller has been implemented on a set of FPGA and DSP modules which are mounted on PXI communication bus.

The modified r_{DEP} and r_{TARGET} estimation algorithms have been implemented on the I/O FPGA modules for performing fast front-end signal processing. The floating-point model of the r_{DEP} estimation algorithm has been simulated in MATLAB /Simulink and converted into fixed-point model to be implemented on the I/O FPGA modules. IIR filters, Integrators, and embedded MATLAB functions (m-files), which contain loops, multiplication and division operations are the parts of the r_{DEP} and r_{TARGET} estimation algorithm, which have been implemented on the I/O FPGA modules. The algorithms have been tested and simulated using off-line data collected from previous plasma shots of FTU.
A model predictive protection system for the safety of microwave antennas steering has been realized in an independent and reliable hardware. The system is going to predict in real-time the 2D rest



1. MHD control system layout

position of the antenna with its uncertainty. The protection will trip if the antenna position is going to run outside the physical boundaries. The independent protection system ensures that the EC-H&CD power is not conducted toward the chamber walls. A simplified algorithm of model-predictive protection has been implemented in a rugged industrial FPGA system using LabVIEW FPGA tool and tested successfully on the launcher to ensure the reliable functioning.
To realize the signal flow scheme, some signal conditioning and insulation circuits have been designed and realized on PCB considering electromagnetic compatibility and signal terminating issues. The PCBs deal with fast inverters encoder and ECE signals, slow digital 24V inverters I/O control signals, analog differential reference signals, serial communication signals and TTL motor brakes control signals. For data transferring among the processors, digital communication algorithms have been implemented in the FPGA and DSP modules from different providers. To increase speed of data transfer in the motor control loop, the problem of DSP port communication delay has been solved by driving the I/O channels to different ports.
The hardware and software of the MHD controller and protection system has been tested on the launcher mock-up and the final version of the launcher. Some tests have been performed for launcher model identification. Poloidal and toroidal movements of the antenna have been validated and the dead-bands of the launcher mechanical system has been detected. The tests performed on the final version of launcher system demonstrate that the system is capable to reach the dynamics of ≈1° poloidally at the antenna in 10 ms, required in the design phase. The motor control functioning has been validated in presence of high magnetic field as well.
The research on MHD instability suppression is an ongoing study in which many scientists and engineers from various fields are involved. It has been the general objective of this project to develop some ideas and realize the tools and hardware needed for detection and stabilization of the MHD perturbations which will be experimented and validated in FTU to be presented for ITER. The new launcher of the FTU makes it capable of performing higher level experiments to validate the stabilization methods developed for MHD perturbations. A part of the tests and experiments for validation of mechanical, electrical and control systems of the launcher will be performed when the launcher will be integrated in the FTU machine.

MVDC GRID WITH M2LC TRANSFORMERLESS WIND TURBINES FOR OFFSHORE WIND FARM

Daniele Rosati

In recent years, the interest in offshore wind farms has increased significantly. One of the reasons of this development is the less perceived environmental cost of an offshore wind farm with respect to an in-land one, especially for new installations where big turbines are preferred. However, they have also the advantage of an increased and more constant wind speed, leading to higher and more constant production of electrical power. For these kinds of wind farms a pure DC system could be an interesting and cost-effective solution. This thesis describes an innovative Medium Voltage Direct Current (MVDC) electrical grid system for wind farms, which is based on transformerless wind turbines.

The application of offshore wind energy and the problem of offshore Wind Farm (WF) connection to the onshore grid are receiving a lot of attention. Moreover the recent advances in power electronics components, together with the ones of HVDC (High Voltage Direct Current) technology, mainly related to Voltage Source Converters (VSC) use, have increased the interest in using DC instead of the more traditional AC transmission and distribution systems.

This is because DC solution provides several advantages, mainly related to the lower losses and voltage drops with respect to AC one. DC systems allow to transmit power over longer distances and to interconnect remote offshore WFs. Moreover, the problem of the more relevant costs of control and protection DC systems with respect to AC ones, which represented one of the most critical aspects. Among DC transmission and distribution systems, two possibilities are now under analysis: HVDC and MVDC (Medium Voltage Direct Current) ones. MVDC distribution system allows weight savings and higher efficiency with respect to AC one. MVDC distribution and transmission systems represent a promising solution for offshore WF characterized by short distance from the connection to the shore grid. However, the equipment necessary to realize a classical wind turbine (WT) operating with a MVDC system, can present many power conversion steps to reach MV level, with the effect of reducing the energy efficiency as well as increasing the electrical system costs.

The proposed solution overcomes these limits adopting a Modular Multi-Level Converter (M2LC) to realize a WT with transformerless MVDC output drivetrain.

This PhD thesis presents an innovative electrical system configuration for wind farm that is based on an MVDC distribution grid with multi-MW wind turbines equipped with M2LC transformerless wind turbines, which have a DC output voltage at 23.6 kVdc.

The thesis is organized as follows: Chapter 1 describes the actual status of the wind energy and the European Union targets for 2020 concerning this renewable energy; Chapter 2 illustrates the state-of-the-art of the wind energy conversion systems; Chapter 3 presents the proposed MVDC grid and M2LC transformerless drivetrain structures and it underlines the main advantages and the technical problems of this solution; a comparison between the MVDC-M2LC solution and a traditional MVAC system is performed considering a wind farm offshore installation in the Mediterranean Sea (Gulf of Manfredonia, Puglia, Italy) and it is carried out in Chapter 4; Chapter 5 analyses the M2LC drivetrain through studies, models and simulations, while Chapter 6 reports the realization of a small scale prototype and validates the designed control system of the M2LC through experimental results.

UBIQUITOUS NEAR-ENERGY SERVICES IN EXTENDED ENTITIES AS OPPORTUNITY FOR ENERGY EFFICIENCY AND SECURITY

Mikhail Simonov

The research described in this thesis draws from the question about predictability of the energy flows exchanged between energy Producers and Consumers in Renewable Energy (RES) scenario. The saturation of the energy distribution networks due to the increased demand of the energy, coupled with the unpredictability of the energy coming from RES, requires the technology solution permitting to account the sustainability of the operational scenario and to keep it at the acceptable quality/safety levels. Author presents one solution making observable and manageable the real-time consumption dynamics in grids alimented from Renewable Energy Sources (RES) aiming at computational efficiency.
As a result, the Digital Energy (or e-Energy) proposed is an abstraction virtualising the physical electric energy. The proposed toolkit has a strong soft optimization potential thanks to its lower computational complexity, resulting in an important practical advantage in real-time dimension.
Prototyping accompanies the research implementing some Use Cases. Author describes some collateral issues: building grids with desired properties, solving information over-flood, new business models in M2M scenario. The described tools are published as public domain. The above described research becomes a manifold, bringing several contributes – shaped as correlated latters – in the subject area of the intelligent value added services offered in the electric energy domain.
The described research delivers one sophisticated load forecast and management tool to transform in inexpensive boxed software to handle the energy consumption dynamics. European electric power system is one of the largest technical systems in the world. It serves more than 400 million people, counts more than 200,000 km of transmission lines. Therefore, it has an enormous potential to exploit the Use Cases described in the Chapter eight.
This Ph.D. research analyses the real-time aspects improving the current load management and control schemes. Author discusses new tools to monitor in real time the energy production and consumption dynamics and the information flows traveling over the communication networks. Since the energy dynamics are caused by real life events, one contribute comes from the investigation on the nature of the above events and the cause-effect universal law, resulting in the useful heuristics which may reduce the computational complexity.
The proposed simplification of the mathematics brings the computational efficiency. Author solves another optimization problem replacing independent agents by one multi-agent ubiquitously distributed system, calling for the wider deployment of multi-agent artificial cognitive systems, notably smart metering devices with extended capabilities.
Author investigate on the main classes of real life events causing energy dynamics, discuss about the methods to capture them in real life conditions, about setting up the information processing. Conceptualizing elementary data as plans, patterns and other constructs, the rule-based reasoning and knowledge elicitation becomes applicable.
From technological viewpoint, author mixes smart metering and distributed architectures for multi-agent information processing of huge data volumes, touching the scalability problem, which becomes relevant because of the saturation of the grids.
The practical technological solution working in real time is tested through the early prototyping. Based on the business requirements, author builds the prototype and discuss about the implementation details and the sustainability of the operational scenarios.
The research outcome in the computational efficiency is the Digital Energy theory. Its applied research component is the DE toolkit described in details. The capability to monitor the causes of the energy dynamics relies on the semantics discovered at the intelligent nodes.
The energy digitization replaces the operations with the physical energy. Accounting the energy dynamics enables the real time knowledge mining and makes the control systems intelligent, evolving smart grids thanks to the Future Internet.
The prototype goes beyond the smart metering, offering a truly real time Digital Energy solution, raising Digital Energy events about the significant changes in the energy consumption dynamics, preserving the modest data volumes being exchanged.
It becomes the baseline for the "Near-energy" ancillary services being researched, discussed, and prototyped. The innovative and emerging ICT services for Energy are based on the energy distribution networks with broadband capabilities, exploiting SCADA networks and multi-sensorial devices, wired and/or wireless.
The resulting technical solution has been protected by one patent application.
Being evident the need to detect and classify the events happening in the power grids, the immediate effect was to propose the first theory of Digital Energy. Unlike PMUs, author abstracts the energy flows and replaces them by the digital events showing the rapid and important changes in the above dynamics. Author has identified the practical and commercial potential and has proposed an outcome to acquire, share, and manage the anticipatory knowledge form within the energy distribution networks delivering the anticipatory control features and dynamic partitioning of the smart grids.
In first chapter, author describes event spaces and related techniques. The second chapter is about the technologies used.
Third chapter presents the theory of Digital Energy managing energy consumption dynamics.
Fourth chapter is about optimisation methods to tune the toolkit. Fifth chapter describes the service based on the extended cooperation between renewable energy Consumers and Producers.
Sixth chapter explains how to build the grid topology manifesting desired properties.
Seventh chapter is about the security of smart grids. Eights chapter discusses new scenario enabled by M2M on the liberalised electricity market.

INNOVATIVE METHODS AND SENSORS FOR CURRENT MEASUREMENT IN LOW VOLTAGE CIRCUIT BREAKERS

Sergio Toscani

Circuit breakers are among the most important components in electrical power systems. Their main target is to provide adequate protection of the electrical equipment against potentially dangerous conditions. So, a key task is the detection of these unwanted situations; they can be very heterogeneous such as overcurrents due to overloads or short circuits, current unbalances, undervoltages, overvoltages, underspeeds of the synchronous generators, etc... In most part of the low voltage circuit breakers, the device devoted to the detection of these conditions is included into the circuit breaker: in this case it is called trip unit. Virtually every automatic circuit breaker contains at least an overcurrent trip device. Basically, there are two types of overcurrent trip units: electromechanical and electronics. The first ones exploit the mechanical actions due to the current flowing through the main conductor in order to detect the overcurrent and to release the breaker. In electronic overcurrent trip units the decision to release the breaker is taken through the measurement of the main circuit current and a proper signal processing of the measurement data; it is clear that they always require a current transducer. In the last years, the employment of electronic trip units in low voltage circuit breakers has increased significantly mainly because of their greater flexibility and their capability to implement advanced protection algorithms. However, electronic trip devices always require a power supply; when AC applications are considered,
the measurement electronics can be continuously fed employing a window type transformer. On the contrary, this is not possible when the trip unit is installed in a DC circuit breaker; in this case, the electronic trip device always requires an external power supply. However, for safety reasons it is mandatory that at least the instantaneous overcurrent protection is guaranteed even when there is no external power supply. So, the circuit breaker shall include another backup trip device able to perform the instantaneous overcurrent protection without requiring an external power supply.
Two approaches can be adopted; the first is the employment of a large, window type transformer which exploits the current transient to feed a low power consumption electronic trip unit and eventually to excite the trip coil. The other is the adoption of an electromechanical system enclosing the main conductor, comprising a winding and a movable part whose position affects the mutual coupling between the main circuit and the winding. The movable part is retained in an initial position which minimizes the magnetic coenergy of the system.
A sufficient main circuit current produces a mechanical action which brings the movable part in a position which maximizes the magnetic coenergy.
It may result in a change of the magnetic flux linked with the secondary winding, thus in an induced electromotive force which can be employed to excite the trip coil and release the breaker. This approach immediately appears to be simpler and thus more interesting. In literature it cannot be found a scientific, systematic analysis of this kind of electromagnetic trip unit (I call it reluctance converter trip unit) beside of a considerable interest of the industrial companies.
This is mainly due to two facts.

The first is that we are experiencing a growing interest towards renewable power sources and distributed generation. Most part of the generation from renewable sources is intrinsically DC; even when rotating machines are employed, in general their speed has to be decoupled from the AC mains frequency by means of AC/DC and DC/AC converters. Furthermore, even great part of the loads includes an electronic AC/DC converter. Because of this, a DC connection between distributed generation and local loads, thus forming a so called DC micro grid appears to be a cost effective solution. On the other side, DC distribution is widely employed in marine applications and nowadays appears to be a cost effective solution for the electric systems not directly connected to the AC power grid.

The second is reason is the growing importance of the cost and size reduction of the devices employed in the circuit breaker. Both of them can be achieved through a rational, systematic design of the components.

So, the core of this dissertation is to provide a systematic analysis of reluctance converter trip devices and to explain the basic guidelines to be followed in order to optimize their design. Chapter 1 is essentially an introduction to the trip units; state of the art electromechanical and electronic trip devices are presented. In Chapter 2 the proposed approach to the design of reluctance converter trip units is explained. After an introduction to the dynamic modeling of electromechanical systems, the design guidelines are exposed. The design has been decoupled into two tasks. The first is to guarantee that, when the current threshold value is exceeded, the trip unit detects the event and extract a sufficient amount of energy from the main circuit. At the same time this energy (which is that necessary to excite the trip unit) has to be quickly available. The second is to make the operation of the trip unit as insensitive as possible to the rate of change of the primary current. The proposed approach has been applied to two case studies. First of all, a trip unit optimized to operate with relatively low current thresholds has been designed. In particular, the threshold can be adjusted from 400 A to 1000 A. It comprises a simple magnetic circuit, an induced winding providing the excitation of the trip coil and a moving element. It is kept in a non-minimum reluctance position by a proper retaining system; the threshold current can be set by changing the force due to the retaining system. The first part of the design process assumes that the main circuit current remains constant. The geometry and the design parameters have been chosen in order to maximize the efficiency of the energy transfer between primary circuit and induced winding. A simplified magnetic circuit has been employed in order to compute the flux-current relationships and the electromagnetic forces. Then, these parameters have been integrated in a dynamic model of the system. In order to verify the results obtained employing the simplified magnetic circuit, the flux current relationships and the mechanical actions due to the magnetic field have been re-computed through a finite element modeling software. The results of the dynamic simulations which employ the parameters obtained from FEM simulations are very close to those computed starting from the solution of the magnetic circuit. Finally, the effects due to the derivative of the main circuit current have been investigated. It has been shown that the rate of change of the main circuit current may introduce a significant time delay in the release of the breaker; a remedy to this problem has been proposed.

The threshold current of the designed trip unit is limited in the upper range because otherwise the force of the retaining system becomes excessively high. If higher current threshold are required, a different trip device have to be employed. So, another trip unit having a threshold current ranging from 800 A and 7200 A has been designed. It employs a magnetic shunt branch in order to limit the force of the retaining system for a given primary current. The design process started from simple, intuitive considerations and has been carried out through the conjunct employment of a simplified magnetic circuit, a finite element magnetostatic model and a dynamic model. Furthermore, it can be shown that with few adjustments, the current threshold range can be easily extended to over than 15000 A.