

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 | URBAN PLANNING,  
DESIGN AND POLICY | AEROSPACE ENGINEERING  
| ARCHITECTURAL AND URBAN DESIGN |  
ARCHITECTURAL COMPOSITION | ARCHITECTURE,  
BUILT ENVIRONMENT AND CONSTRUCTION  
ENGINEERING | ARCHITECTURE, URBAN DESIGN,  
CONSERVATION OF HOUSING AND LANDSCAPE |  
BIOENGINEERING | DESIGN | **ELECTRICAL  
ENGINEERING** | ENERGY AND NUCLEAR SCIENCE  
AND TECHNOLOGY | ENVIRONMENTAL  
AND INFRASTRUCTURE ENGINEERING  
| INDUSTRIAL CHEMISTRY AND CHEMICAL  
ENGINEERING | INFORMATION TECHNOLOGY  
| INTERIOR ARCHITECTURE AND DESIGN |  
MANAGEMENT ENGINEERING | MATERIALS  
ENGINEERING | MATHEMATICAL MODELS  
AND METHODS IN ENGINEERING



Chair:  
**Prof. Gabriele D'Antona**

## DOCTORAL PROGRAM IN ELECTRICAL ENGINEERING

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.

### THE STEERING COMMITTEE IS MADE BY

Surname	Name	Firm	Position
Canizares	Claudio	University of Waterloo, Waterloo Institute for Sustainable Energy, Canada	Associate Director
Carlini	Enrico Maria	Terna Rete Italia	Head of System and Transmission Control & Operation Central South Italy
Cherbaucich	Claudio	RSE - Ricerca sul Sistema Energetico	Vice Responsabile Sviluppo e Pianificazione
Ercoli	Sergio	Zeroemissioni Srl	Presidente del Consiglio di Amministrazione
Fasciolo	Enrico	A2A Reti Elettriche	
Ghezzi	Luca	ABB	R&D Principal Engineer
Godio	Andrea	Alstom Transport	Manager
Lo Schiavo	Luca	Autorità per l'energia elettrica e il gas AEEGSI	Manager
Mansoldo	Andrea	Eir Grid	Senior Power System Analyst
Monti	Antonello	The Institute for Automation of Complex Power Systems of E.ON Energy Research Center	Director
ZANNELLA	Sergio	Edison - Research, Development and Innovation	Scientific Network Manager

Companies currently providing scholarships:

- ABB S.p.A.
- De Lorenzo S.p.A.
- Fondazione Ing. Paolo Foresio
- MCM Energy Lab

# NOVEL METHODS IN CONTROL AND MONITORING OF PHOTOVOLTAIC SYSTEMS

Aghaei Mohammadreza – Supervisor: Prof. Sonia Leva

## Summary

Operation and maintenance is a crucial factor for Photovoltaic (PV) plants inspection and control activities which currently are quite hard to be performed due to manual and dispersive procedures. The current doctoral thesis proposes a novel, comprehensive and innovative approach to automating the entire steps of inspection and prognostic procedure using designing a control system to provide accurate and reliable information on operating conditions of PV plants. The system can perform PV systems' monitoring, diagnosis, defects and failures reconnaissance, data processing and to propose remedial actions. The proposed complex control system is integrated with separate systems including the Unmanned Aerial Vehicle (UAV), visual and Infrared IR cameras, monitoring cabinet, ground control station systems, programming and software, processing system, database and decision support system. Besides, each system contains various data acquisition system (DAS) and sensors to collect the data and signals. Moreover, the systems are connected to each other through network and Radio Frequency (RF) channel, and they are controlled by the central ground control station.

In the current research, various

experimental tests have been designed and performed to examine the quality, accuracy, robustness, reliability, validity, capability and flexibility for different parts of proposed automated and control system in real and large-scale PV plants. The preliminary results have proven that automated the procedure of PV plants inspection is very promising being practical, precise and much faster than traditional monitoring methods, cost effective. In addition, the finding of current research has indicated that the inspection procedure of PV plants can be performed by integrated various monitoring systems in a single innovative system package to provide entire accurate information requirements for each PV system in large-scale plants.

## Automated Control System for PV Fields Inspection and Remote Control

The proposed smart monitoring system is used to provide quality assurance service for PV power plant in a short time and explore the defects or failures on PV modules. Figure 1 illustrates two schematic view of the proposed system for the monitoring of the PV plants using UAV technology. The smart tracking system can propose an appropriate solution for each affected PV system. Besides,

the system can communicate with ground monitoring cabinet and data acquisition systems for analysis and evaluation PV systems electrical performance in power plants. Field monitoring cabinet controls the meteorological station.

Figure 1: Two schematic of the automated control monitoring system for PV power plants. In this concept, the control system is integrated with inspection, recognition of the problem, processing, and decision making. Therefore, all the requirements for operation and maintenance are associated with such a system. In Figure 1, the visual and thermography assessments are carried out by mounted infrared imaging sensor and visual camera on the UAV. Then, automatically the images captured are transferred to the Ground Control Station (GCS) by RF channel. Later on, the classified data are sent by the GCS to the database for the following processing. Subsequently, signal characteristics data (e.g. current, voltage, power, temperature, irradiation, etc) are acquired by monitoring cabinet or SCADA (Supervisory control and data acquisition). After software analysis of the received images, all the processed information is transferred to the decision support system for appropriate future actions to be taken. In this

TABLE 1: DETECTION OF PV MODULE DEFECTS BY AERIAL VISUAL INSPECTION IN DIFFERENT ALTITUDE AND GROUND RESOLUTION.

P V Component	Defects – Failures or Characteristic	Maximum Possible Flight Height for Visual Detection by automated system	GR [pixel/cm]
Module	Snail Trail	6-7 m	8-10
Module	Dirty	15 m	3-5
Module	White Spot	20 m	2-3
Module	Encapsulant discoloration (EVA)	20 m	2-3
Module	Different glasses	20 m	2-3
Cell	Day4 Technology	10 m	5
Cell	Number of Cell interconnect Ribbon (bus)	20 m	2-3

phase, the system evaluates the information in order to detect particular defect or failure on the PV systems in standard test conditions (STC) for the decision support system. The proposed software method by using digital image processing techniques focuses on the separating the hot and cold areas in IR images of the PV modules, and also it concentrates to determine degradation percentage of affected modules and as well classifying the particular defects or failures.

## Resolution Assessment

Resolution assessment of the aerial visual or IR sensors is a crucial task for the proposed monitoring system during PV plants inspection. In digital photography, the resolution of images is also imperative. In current doctoral dissertation, the following equations were proposed to describe the correlation between the resolution of aerial sensors and possible defect detection during PV plant monitoring. The ground distance can be evaluated in Equation 1.

$$GD = H \cdot \frac{PD}{f} \quad (1)$$

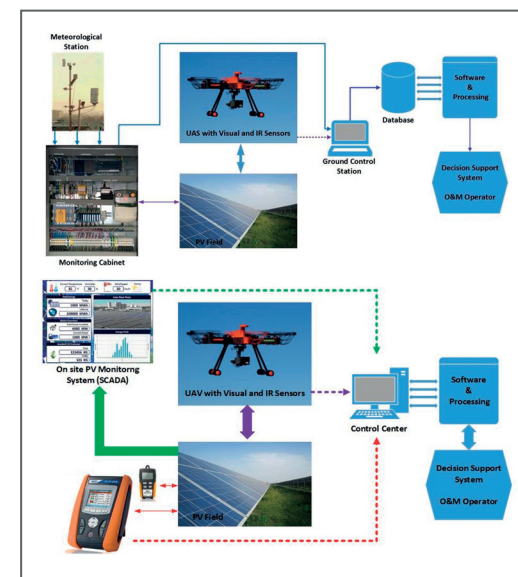
With this regards, the photo resolution (PR) and the corresponding grounding resolution (GR) can be defined in Equation 2.

$$GR = \frac{PR}{GD} = \frac{PR}{H} \cdot \frac{f}{PD} \quad (2)$$

According to many different experimental tests, Equation 2 was developed in order to estimate the correlation between altitude and resolution of aerial sensors and the specific defects identification on the PV modules. Furthermore, it is possible to correlate the features of

the camera (f, PD, PR) with the flying height of UAS (H) and the grounding resolution (GR). Table 1 summarizes visible defects on the aerial image photographs and ground resolution which have been captured by the camera mounted on the UAV. This can present an overview of correlation between identification of target defects and maximum flight height from the top of the modules during the aerial visual photography procedure performed using a Nikon-V1 camera.

## 1. Two schematic of the automated control monitoring system for PV power plants.



## INTRODUCTION OF DC AND STORAGE SYSTEMS IN SHIPBOARD ELECTRIC SYSTEMS

**Corti Matteo** – Supervisor: Prof. Enrico Tironi

The high penetration of natural commutated power electronics converter for electric propulsion systems, along with the requirements of high quality of service for some kinds of loads, has led to the study of the introduction of DC and storage systems in shipboard electric systems. This thesis aims to make evidence on how these technologies can improve power system's operation. It is worth noting that the majority of results is also valid for stationary applications.

After a general overview of power electronics converters and storage systems suitable to be used for shipboard applications, this work investigates shipboard distribution systems. A particular attention is paid to zonal electrical distribution systems with AC or DC primary feeders. Uninterruptible loads are installed inside DC zones and they can simultaneously be supplied by different feeders. This feature is achieved thanks to the proposed control strategies that are based on droop curves. The quality of supply is further increased by the installation of storage systems. Numerical simulation results are shown to validate theoretical analyses.

DC zones can also be used for isolating distorting loads from the AC network, thanks to DC

immunity to harmonics and the installation of forced commutated power electronics converters. Numerical simulations show how a hybrid system (AC with DC zones), together with both high-pass and single-tuned filters can improve the power quality of the AC part of the system, satisfying regulation requirements.

In addition to data communication line, power electronics converters play a crucial role to correctly operate an electric system.

For this reason, two multi-port converters have been developed. Their main features are port voltage decoupling, power flow management and fault clearance. Both pole-to-pole and pole-to-ground faults are investigated and several solutions are proposed to clear the latter. This thesis also proposes an algorithm for local stability verification for each multi-port converter. The behavior of the converters under several functioning conditions is validated by numerical simulations and experimental tests.

DC zones and storage systems can also be exploited for providing ancillary services to the AC part of the system. In particular, the management of an AC island by a FEC and the short-circuit power increasing are investigated.

For what concerns AC islanding, the originality of FEC control is

the emulation of a voltage source, instead of a current source. In this way, the converter is ready to supply AC loads after islanding way-in. Furthermore, transients are reduced during both islanding way-in and way-out. The proposed control strategy is tested by numerical simulations.

Shipboard short-circuit power is limited and circuit breakers may not trip after a fault. Consequently, a fault can result in safety and selectivity issues. Several solutions are proposed in this thesis. One of them is explained in literature by means of a theoretical treatise and numerical simulations. This thesis validates it by experimental tests for completeness and improvements.

# DESIGN AND DEVELOPMENT OF TECHNOLOGIES FOR THE MEASUREMENT OF BIOMECHANICAL PERFORMANCE IN ATHLETES PRACTICING JUDO

Frassinelli Stefano – Supervisor: Prof. Riccardo Zich

The training methodology is proposed as a science to manage, organise and plan the evolution of the athletes performance. Like other sciences, training methodology needs objective data to formulate his theories and laws. The sportsman study on the field, of sports training and of sport competition, is the best way to acquire the parameters characterizing the athletes performance. In this direction, the design and tools development that are able to investigate and measure the exercise biomechanic phenomena during real workouts and competitions, far from the reality of aseptic laboratory research, are the future sports analysis. Future whit great grow prospects. Judo is a fighting sport where the contact between the athletes, the friction and impact derived therefrom and the moisture linked to sweating, produce a lot of problems to wearing the measuring devices. Inertial Sensors designed and developed specifically, would allow reducing drastically the criticality of usage into unconventional experimental environment as the "tatami" (mat which hosts judo workouts). In addition right fit would allow athlete who wear it, to move without constraints or special care to preserve the equipment integrity.

The goal of the study is create a useful tool to collect specific data to measure athletic performance during workout and simulation of judo competitions. The issue has been analyzed and developed along three different path:

- an approach through the theory of movement
- a biomechanical approach
- an engineering approach

a) About specific examination of the factors that contribute to athletic performance in Judo, we considered only the movement aspect. All movement performance start from its technique. The movement technique and even more sport technique, are the ultimate means that the sporty performance uses to express itself. Analyze and measure sport technique means to collect useful data to improve the performance that it produces. The sport technique is strongly influenced by the athlete *motor abilities* and *capabilities*. The various *motor abilities* aren't precisely identifiable because they contribute in building up the movement itself and, with it, they make an only thing. During the development of the sports activities on the field, the *motor abilities* can be *observed* but *not measured*. Consequently the

taking charge and examination of *observable* parameters together with those *not measurable* involves a specific mathematical analysis. We propose two different but complementary mathematical matrices to quantify the *motor abilities* that are involved in sporting gestures: a Boolean matrix  $(A(i,j) = 0;1)$  and a Fuzzy matrix  $(\mu F(x) = \mu ; 0 \leq \mu \leq 1)$ . The first one allows us to discriminate motor abilities according to a global criterion, while the second one follows an analytical criterion. This allows a unitary quantification of the motor abilities. At the same time, it enables to quantify the weight and importance of capabilities (conditional and coordinative) that contribute to its formation and expression on the field.

b) The judo technique is analyzed according to biomechanical criteria and finds its basis in the Optimization principle and in the Minimum Action (MA) principle. The classification of throwing techniques, which are the fundamental technical movements of judo, is reduced to only two classes: techniques where Tori uses of a couple of forces for throwing Uke and techniques where Tori uses of physical lever for throwing Uke. Consequently, it also simplifies the classification

of all the movements that are performed in preparation for the execution of the technique. These movements are called the General Action Invariants (GAI) and Specific Action Invariants (SAI). We have identified for each analyzed movement:

Strength (= Mass x Acceleration) -  $[x \ 1\text{kg} \ 1 \text{ m} / \text{s}^2 = 1\text{N}]$   
 Work (= Force x Displacement) -  $[1\text{N} \times 1\text{m} = 1\text{J}]$   
 Power (= Work x Time) -  $[1\text{J} \times 1\text{s} = 1\text{W}]$

c) By commom inertial sensors currently on the market, it has been designed and developed a specific tool that was able to overcome the problems of an "unfriendly" experimental environment. The pair of athletes who struggle and throw themselves at each other on the mat, certainly presents an unconventional experimental reality. Most wireless inertial sensors are assembled with an accelerometer, a gyroscope, and a magnetometer. In our sensor there is only the accelerometer. This choice has been done with the aim to make the most compact instrument and improve its wearability. Two configurations in the dressing phase with the tools of the tested athletes have been choosen: the first one with seven devices, the second one with five devices. The acquisitions carried out involved lower limbs. The sensors were compared with a magnetic and inertial sensors system (TSDN121, ATR Promotions) and a gold standard, a markerless stereo-photogrammetric acquisition system based on synchronized digital cameras with a frame rate of 90 fps.

Traces analysis and their processing through the subsequent construction of the stick diagram, showed that:

- there are important differences between the throw techniques performed by low qualification athletes and high qualification athletes. The latter showing a much better performance.
- the athletes sizes have effects on the technical execution: the light weights express greater acceleration in relation to the mass comparated to medium weights and heavy.
- the genre, jointly to body weight, has influences on the technical execution.
- the techniques of the couple of forces are faster than those that use a physical lever for throwing the opponent. That is in accordance with the biomechanics principles.
- the acceleration and the angular velocities detected during the preparatory movements to the tecnical execution (GAI and SAI) don't present significant differences compared to those recorded in the execution of the true and proper throwing. The difference is given by the direction changes, which serve to break the opponent's symmetry and to put the same opponent in a situation of instability, thus facilitating the subsequent throwing.
- the principle of Minimum Action (MA) is not always respected in a more dynamic combat phases. During the analysis of dinamical situation to put as objective the function of the MA is a necessary condition but not sufficient. Actually it's appropriate

to integrate the principle of MA with the concept of Maximum Effectiveness (ME). The athletes, searching ME, are often forced to choose (instinctively) solutions which require a greater physical work (W). To enter the defense of an experienced opponent (putting him in a situation of instability, breaking its symmetry) means to make actions that are not biomechanically advantageous. This increased energy output is repaid by the ME of the final gesture. So, ME means not only MA as minimization of energy expenditure, but also the greater possible result in relation to the energy used.

At the end the wireless inertial sensors have showed to be an effective tool, useful to the purpose for which they were designed. The equipment with its good wearability allowed the athletes to express themselves freely, concentrating totally on their exercises, without any constraint and distraction. This research shows good flexibility of the evaluation system and opens an important window into the world of sporting evaluations carried out directly on the training field. There are many sports that already benefit from the scientific investigations that concern them, but many other are still waiting. They are those sports that take place in environments difficult to equip as laboratory or whose technical and sporting dynamics presenting a problem to be standardized. The instruments, object of this study, could certainly cover some of these gaps.

# ANALYSIS AND REALIZATION OF A NEW DEVICE FOR POWER QUALITY AND CUSTOM POWER IMPROVEMENT: OPEN UPQC

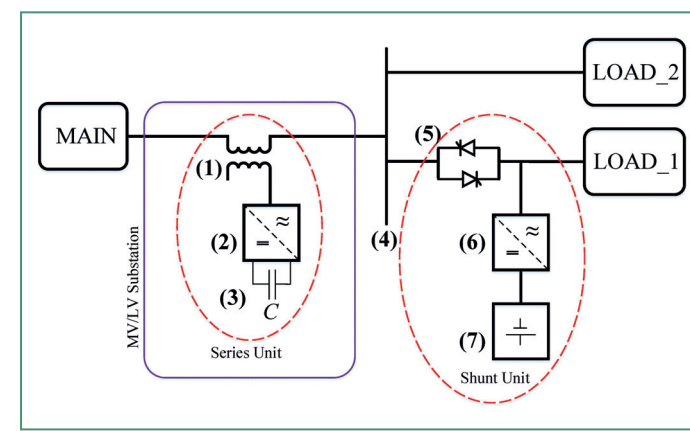
Hafezi Hossein – Supervisor: Prof. Roberto Sebastiano Faranda

Power Quality (PQ) in LV distribution networks is already a concern in many European Countries especially where there is a strong presence of renewable energy generation. Therefore there is a growing interest in new solutions able to improve power quality level of such a system providing regulated power to the end user within standard definition. In other hand for different reasons, customer may need or require customized power which may not fit into standard definition. PQ and Custom Power may follow the same patch or possibly those may contradict each other going in opposite directions. Therefore, it is not an easy task for Distribution System Operator (DSO) to respect both standard PQ definitions and custom power requirements.

Several solutions have been introduced by electrical power engineers in order to perform PQ compensation tasks and provide custom power requirements. Among those, Uninterruptible Power Supply (UPS) is the most interesting and prosperous solution which is able to provide both PQ and custom power requirements of one customer. However an UPS system is quite an expensive solution and several alternatives are proposed in order to decrease solution

expenses in the cost of reducing its functionality and flexibility. Series and Shunt conditioners with different topologies have been studied and those can furnish the grid with their voltage and current compensation capabilities however, a series or shunt conditioner alone, is an incomplete solution due to their compensation and service restrictions. To deal with series and shunt conditioners shortcomings, a combination of series and shunt conditioner is introduced by Akagi which is able to tackle both voltage and current impureness and it is called Unified Power Quality Conditioner (UPQC). Usually the UPQC is composed by two inverters which, one is connected in series with main through a coupling transformer and the other is connected in parallel to the load. In basic UPQC configuration, series converter and shunt converter are sharing common DC link where it is connected the storage system. An UPQC can be equipped with Static Switch in order to couple/decouple the device to/from the network. The UPQC looks a well-designed solution to manage PQ and custom power requirements but due to the increment of renewable energy (Distributed Generation) and storage integration into power system and specially at Low Voltage (LV) level, the

PQ conditioners paradigm has changed. By introducing bidirectional power flow in newly introduced Smart Grid system, DSOs started to look for system level and modular solutions which are able to operate within the Smart Grid system, communicating with other active participants. In these new systems a device needs flexibility and modularity in order to properly furnish the network. The Open Unified Power Quality Conditioner (Open UPQC) is a novel proposal and special design of original UPQC and it is a distributed solution which is able to provide high power quality to the installed area and provide custom power services to the end users and some auxiliary services to the DSO. The proposal is to split the UPQC series and shunt units, move the series unit to the Medium Voltage (MV)/LV substation, in order to support all the installed area, and to split the shunt unit into several units according to end user needs and install each shunt unit at front end of customer property, providing PQ and custom power improvements to the end user and different auxiliary services to the grid and DSO. The shunt and series units are able to communicate with each other within a generic Information and Communications Technology (ICT) system.



1. Generic schema of Open UPQC

Figure 1 shows generic schema of Open UPQC. It consists of a coupling transformer (1), series unit inverter (2) and a set of capacitor bank as series unit DC bus (3). The series unit fundamental task is to regulate PCC (4) voltage. The shunt unit is installed close to the end user. Figure 1 shows one shunt unit connected to the LOAD\_1 which is representative of controlled loads. Shunt unit consists of a Static Switch (5), AC-DC converter (6) and it is equipped with storage battery system (7). LOAD\_2 represents uncontrolled loads and in Figure 1 those are shown in integrated form and are directly connected to PCC without shunt unit. This thesis discusses about working principle, hardware and

controller design of the Open UPQC. Working philosophy of Open UPQC is explained in detail and series and shunt units responsibilities are addressed. Series unit is meant to work with pure non-active power compensation strategy in order to reduce system losses and its realization cost. This non-active power working concept, will impose operation limits on series unit. Series unit operation limits is analyzed in deep, considering possible contribution that shunt units can have to improve series unit performance and this led to the co-operation idea between series and shunt units as happens in the UPQC. Series and shunt units should be able to work independently

so, both units controller should be fast enough in order to deal with transient events. Series unit is designed to work as self-supported Dynamic Voltage Restorer (DVR) system in order to compensate both fast and slow voltage variation of the grid. In other hand shunt unit's function is like a line interactive UPS system which is able to give some ancillary services to the grid. Beside series and shunt unit local controller, ICT based controller is also described in order to enable co-operation between series and shunt units. The performance of the designed Open UPQC is verified by MATLAB based simulation and Laboratory experimental tests prior to the real field tests. The whole Open UPQC has been realized as a part of Smart Domo Grid (SDG) project and it has been installed and tested in a real LV distribution network in the city of Brescia, north of Italy.

## RELIABILITY ASSESSMENT OF PHOTOVOLTAIC PLANTS

**Khalil Mohamed Mahmoud Abdel Fattah – Supervisor: Prof. Loredana Cristaldi**

Failures of Photovoltaic (PV) systems started to reflect a dramatic effect on the economics of power generation and risk of power interruptions. Recent surveys and reports manifest the delusion of PV systems being reliable systems based on the recorded failures of the system components and the associated degradation of PV output power. The thesis presents a complete reliability assessment on the functional failures associated with grid connected PV systems. This objective is achieved by a root cause analysis of failures through the widely used reliability technique “Failure Mode Effect Criticality Analysis (FMECA)”, which is developed in this work and a new approach is introduced. The new approach is introduced because the traditional FMECA approach is not recognized during the operation phase in all the current FMECA standards, except TM-5-698-4 standard that states the possibility to implement FMECA in the operation phase. However, TM-5-698-4 standard does not state any details on the steps to implement FMECA in the operation phase. Since the traditional FMECA is limited to the design phase, the traditional FMECA considers only failure modes and no considerations are given to the mechanisms of

these failure modes. Moreover, traditional FMECA is not up-to-dated with maintenance activities. The novelty of the new FMECA approach stems from the possibility to apply a strong FMECA technique during the operation phase through a strong dynamic reliability modelling, using Markov Process based on functionality analysis with multistate modelling, and a proper condition monitoring. In this work, the drawbacks and standards controversies of the traditional FMECA are discussed and a new approach is introduced. This new approach is applied on PV systems during the design and operation phases. During the design phase, the root failure causes of PV systems are studied in details through FMEA approach and criticality analysis. A detailed failure cause root analysis is conducted for each possible failure mode of PV systems. This is associated with a prioritization for each failure mode using quantitative methods, for PV inverter, and a qualitative approach, for PV module and Balance of System (BoS). During the operation phase of PV systems, Markov process modelling and condition monitoring are applied on the different failure modes of PV

systems. In Markov modelling, a functional analysis based on possible failure modes are conducted using Markov process through another route of analysis based on failure modes which is different than most of Markov structural analysis, carried out in literature, of the traditional two levels of performance. Since, it might be practically hard to track the reliability of a complex system that has large numbers of failure modes. Each subsystem is analysed separately by Markov process in order to evaluate its probability of success, reliability, then these subsystems are connected together according to their functional relationship. Finally, the overall reliability is evaluated based on the reliability functions of the traditional Reliability Block Diagram (RBD). This multistate system Markov modelling overcomes the commonly adopted assumptions of binary one, provides more realistic representation of engineering systems and guarantees a proper maintenance policy based on all possible scenarios of the system conditions. This gives a strong tool to evaluate and predict the probability of failures. Meanwhile, the proposed condition monitoring is based on sensor measurements, which

are processed and analysed in order to detect any drop in PV performance. This drop can detect the potential failure mode in the field considering the proposed detection strategies. The main objective of the new FMECA approach is to improve the design of systems in order to limit or prevent any potential failures in the future operation. In addition, it helps in avoiding and reducing the failure modes that might occur during the operation phase itself.

## DESIGNING HOTEL FOR ALL FROM INTEGRATION TO SOCIAL INCLUSION

**Lei Ting – Supervisor: Prof. Roberto Ottoboni**

This Ph.D. yearbook is based on a three-year Ph.D. program in Electrical Engineering under the instruction of Prof. Roberto Ottoboni, carried out at Politecnico di Milano, Milan, Italy from 2013.

The aim of my research activity carried out in the last three years is to contribute to the subject of characterizing the behavior of instrument transformer under distorted input condition or real working condition, in particular, focusing on the aspect related to the harmonic measurement. The justification of doing this research is described following. As more and more nonlinear loads and renewable energy sources have been connected to the grid, the topic of monitoring harmonics in the power system attracts more attention; furthermore, an accurate measurement of power system harmonics using the already installed instrument transformer (IT) is needed. However, most researches and standards in the past proposed to characterize an IT only considering its behavior at the fundamental frequency or, in the advanced cases, treating the IT as a linear device and adopting the frequency sweep as the method for IT characterization over frequency. Nevertheless, if we consider the transformer

behavior, when harmonics are present in the input signal, the transformer study based only on the fundamental frequency is not sufficient to describe its behavior at higher frequencies as well as, being the transformer a nonlinear device, its behavior cannot be fully interpreted by the sinusoidal frequency response. In fact, the harmonic measurement is very useful, which can help to improve the power quality since its measurement result provides useful information for harmonic elimination approaches like the active power filter. There are two groups of instrument transformer applied to the grid, namely the conventional instrument transformer (CIT) and the non-conventional instrument transformer (NCIT). And, the conventional instrument transformer has a long history and due to the robust and the economic reason, the conventional instrument transformer (CIT) is still the most widely used instrument transformer in the grid and we mainly discuss the property of CIT in the following sections. Its working principle is that, according to Faraday's law of induction, if a varying voltage is applied to the primary winding of the transformer, this varying voltage will create a varying magnetic flux

in the transformer core, which creates a varying magnetic flux at the secondary and induces a varying electromotive force (EMF) or voltage in the secondary winding. If the transformer is ideal, it means that the voltage signal measured at the secondary permits to infer the primary voltage without error. From the practical point of view, there are many aspects, which cannot be neglected in a real transformer, namely core losses or magnetizing current losses, Joule losses due to the resistances in the primary and secondary winding, and leakage flux. The eddy current and hysteresis effect are responsible for the core losses, also known as iron losses, and its magnitude is related to the core flux and the operating frequency. The magnetizing reactance is responsible for providing the mutual flux in the core. However, the core magnetization characteristic that makes the shape of magnetizing current so different with respect to the primary current is the primary source of transformer nonlinearity. This nonlinearity would cause the spectrum difference collected at the transformer two sides and the elimination of the nonlinear effect is also the major task in this research.

In this respect and considering, in particular, the voltage measurement transformer (VT). The main goal of this work is the proposal of an accurate transformer model capable of describing the device in terms of its linear and nonlinearity behaviors. The original contribution of this work relates to the definition of a simplified Volterra model in the frequency domain, which is specially designed for transformers. Comparing to the complex GFRF or the original form of the Volterra series in the frequency domain, this model does not require knowing of many high-order frequency response coefficients and it permits to reduce the model complexity, without limiting its accuracy, thus opening the way to practical applications. Since this truncated model has retained completely the linear response components and reserved some significant higher order response coefficients for describing the system nonlinearity, it can be treated as a reinforcement or replacement to the classical transformer characterization method, i.e. the traditional frequency response approach. In the meantime, a measurement setup, arbitrary medium voltage generator (AMVG), has been developed and a simple approach for compensating the nonlinearity of the step-up transformer in the AMVG developed in the laboratory of the Politecnico di Milano in order to enhance the performance of the AMVG. The corresponding test results show that, with this simple approach, the harmonics have been noticeably reduced.

Thanks to its software-based controller, this setup is able to test the transformer under the distorted condition, process the experiment data automatically. Then, using this developed AMVG, we test the several transformers under both the sinusoidal and distorted conditions. Comparing the test results obtained under the aforementioned different conditions, we find out that, there is always a difference between the sinusoidal and distorted condition in terms of the ratio and phase errors of harmonics for all the transformers under test. This difference clearly points out that, when the input signal is distorted, the transformer nonlinearity plays an important role and has a significant effect on the harmonic measurement. Finally, the proposed model has been validated on different transformers through experiments, where several possible applications of applying this model have also been discussed. In the validation process, we have applied three different signals to test the transformer under test (TUT). The first signal is designed for the estimation of the model coefficients of the proposed simplified model, while the other two signals are used for verifying the reliability or robust of the model under different input conditions. The test results demonstrate clearly that the proposed model fits the transformer behavior very well and the accuracy of the model is acceptable. In addition, the proposed model has been applied for three different applications,

namely the measurement of harmonics, the identification of the inner-turn fault, and the measurement of the DC-bias in the transformer. The aim of these tests is to prove its effectiveness and to discuss its advantages with respect to the traditional frequency response method. The first application of the model is the most important in all three application, where the transformer output has been used for predict or reproduce the transformer input. The result shows that, with the new model, the error of estimating the harmonics can be largely reduced with respect to the linear approach which does not consider the nonlinear effect. Certainly, there are still some open issues that need to be studied in the future, such as, any truncation to a nonlinear model can cause a corresponding error and this error is considered as a part of the model uncertainty, which is normally proven by mathematic derivation. Unfortunately, for the proposed model, this relevant and important aspect is still left open. Another issue that needs further discussion is that, in our model, to further investigate the possibility of eliminating some model coefficients using the symmetrical feature of the model. In addition, we have to study more applications suitable for using this model. Last but not least, all the research now is carried out on the voltage transformer and the behavior of the current transformer has not been considered. These issues will be discussed, hopefully, in future developments of this work.



# MODELS AND OPTIMIZATION OF ISLANDED MICRO-GRIDS INCLUDING RENEWABLE ENERGY SOURCES AND BATTERY ENERGY STORAGE SYSTEMS

Magistrati Giulia – Supervisor: Prof. Alberto Dolara

Islanded micro-grids are commonly settled in remote rural areas, which have small population size and do not have large industrial plants. These areas are not connected to the electric grid because of the high connection, maintenance and operating costs. Nowadays, Diesel Generators (DGs) power the majority of the islanded microgrids: despite their many advantages like portability and flexibility, they do not represent a profitable solution from the economic point of view. For this reason, the integration of renewable energy systems within the DG micro-grids is a valid alternative for a more convenient management. This is possible since renewable energies, like solar and wind, can be locally available and these technologies are, currently, a low cost solution. Moreover, the electrification of remote areas and the improvement in power quality and energy cost in existing power plants is a very potential market, especially in Africa.

The introduction of non-programmable renewable energy generators dramatically changes the management of the power flows into the microgrid. To ensure the grid stability, the variability of the renewable source requires an increase of

the spinning reserve of the whole power plant. Since the spinning reserve will be covered by the DGs, the benefits due to the installation of Renewable Energy Systems (RESs) will reduce until they will become vain. For this purpose, it is recommended to include other type of regulating generators like storage systems provided by inverters with droop control, so that they can act as rotating generators and perform spinning reserve. Regulating generators performing primary and secondary regulation guarantee the power balance of the micro-grid, sharing the load power among the generating unit and restoring voltage and frequency levels after primary regulation intervention. The tertiary regulation controls the power flows to pursue power quality and economic benefits; usually a daily scheduling defines generators to be working and their generation curve in terms of hourly average values. This work developed two optimization models to set up a longterm schedule for tertiary regulation. The first one aims to maximize the energy harvesting from renewable energy sources, thus minimizing the energy production from DGs; it is based on Linear Programming method. The second one aims

to minimize the operating costs, and it is based on Mixed Integer Programming. Both models have been applied, as case study, to an islanded micro-grid composed of DGs, photovoltaic systems and Battery Energy Storage System (BESS) operating in Somalia since November 2015.

The main function of the BESS is the improvement of the stability of the power plant, with the aim of increasing the exploitation of RES, thereby leading to a substantial fuel economy compared to the solution with only DGs. The plant is designed to supply the city of Garowe through three overhead distribution lines, operating in medium voltage. Since the micro-grid is located in a rural area of Africa, the load is mainly domestic and related to lighting, thus concentrated in the evening hours.

The micro-grid is controlled through a system based on Programmable Logic Controllers (PLCs). Normally, it is automatically managed through control logics based on power flows measurements, operational constraints and settings. The actual control logics regulate the power generated by the DGs and the PV and the power generated or absorbed by the BESS. Normally, in order to take the maximum advantage from the

solar energy, PV plant is managed with the Maximum Power Point Tracking (MPPT) algorithm. In case the power production, both from PV and DGs, exceeds load demand and BESS is not available to store energy, PV is regulated by reducing the power with the algorithm of Regulated Power Point Tracking (RPPT). Anyway, DGs are regulated in order to guarantee an adequate spinning reserve.

The control logics are currently organized in a hierarchical order, based on the relevance and time of implementation of the actions. Functions with the maximum priority are related to safety operations, like prevention on anti-motoring of DG or rapid curtailment of generation. Then functions with medium priority manage the power flows to determine the stability of the micro-grid. In the end, functions with the lowest priority deal with the preservation of the main components, for instance by handling the number of start and stop of DGs to exploit them in the same way.

The actual control logics do not lead to the best mix of power that allow to take the maximum advantage from the RES. For that reason, this work aims to verify if an additional level of control, based on forecasting

and optimization method, will be useful to increase the amount of energy produced by RES. In this perspective, the optimization model would be inserted at the bottom of the control logics, as medium-time control.

A typical sunny day and a typical cloudy day have been selected as a sample days to highlight the limits of the actual control logic. Optimization models allow to improve the actual management, by minimizing PV curtailment or operating costs, namely fuel consumption. The optimization model developed using LP has been formulated in order to minimize the DGs' energy produced during the day. The LP model imposes the DGs to operate in the range between zero and the minimum operating power, thus with an extremely low efficiency, for several hours per day, resulting in an increase of the fuel consumption. The optimization model developed using MIP has been formulated to overcome this problem, setting the objective function as the minimization of the operating costs.

MIP model is a more complex and more complete model with respect to the LP model, able to represent real operating management scenarios of the micro-grid without any limitations.

In particular, the modeling of the start and stop of DGs and their independent management is crucial in defining power flows that minimize the use of fossil fuels. Moreover, MIP model allows to point out the weak decisions of the actual control logics of the case study microgrid.

In addition to this, the results of the optimization models, both for LP and MP, have been presented for the case study and then, assuming that the actual battery bank has been substituted by other type of batteries, comparative models have been implemented. The battery technologies that have been considered are Lithium Titanate Oxide and Sodium-Nickel-Chloride. Moreover, it has been carried out further models with different values for spinning reserve margins, in order to investigate the possible improvement on micro-grid performance.

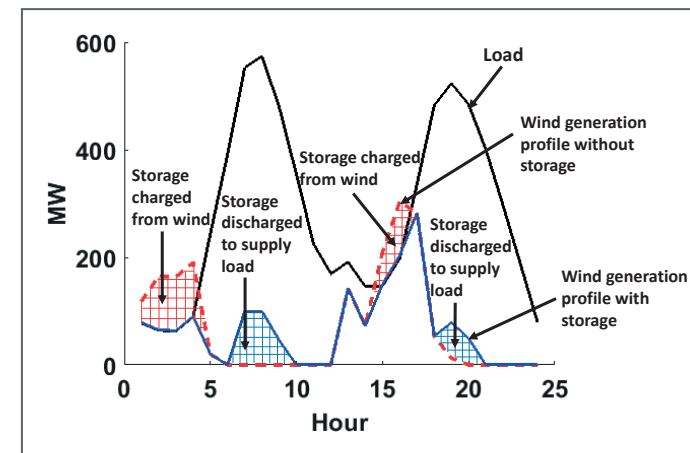
## OPTIMAL PLANNING OF ENERGY STORAGE SYSTEMS CONSIDERING UNCERTAINTY

Nguyen Nhi Thi Ai – Supervisor: Prof. Alberto Berizzi

Renewable energy has been increasingly integrated into power systems as a result of the effort to reduce CO<sub>2</sub> emissions and build a future power grid economically feasible and environmentally sustainable. Particularly, according to the Blue Map scenario for power supply, electricity generation from renewable energy provides a share of 22% of global electricity generation in 2050, which grows almost threefold compared to the Baseline scenario. Along with this growing share of renewable technologies, greater interest has been attracted to the use of Energy Storage Systems (ESSs) due to the variable nature of most renewable energy sources. ESSs can accommodate renewable generation in time-shifting its energy to match demand and avoid power curtailment. They can also be used to mitigate transmission congestion and hedge forecast errors, etc. As the use of ESSs for wind penetration increases, decision on their sizes and locations becomes important for both security of operation and economy of the system. The goal is to place a minimum capacity of ESSs at appropriate sites where their applications will be most exploited. The addition of ESSs introduces time correlation characteristic into the planning problem, which is a major

difference between ESS planning and conventional system planning. Moreover, the integration of wind generation resource into power systems creates challenges for system planning, concerning the high uncertainty in wind power production. Deterministic approaches can not explicitly capture the stochastic nature of wind and hence can not help to make the right decision. Consequently, it is crucial to develop probabilistic techniques for solving the uncertainty issue associated with wind generation. In this work, the planning problem of ESSs under uncertainty is investigated. A multi-period deterministic AC Optimal Power Flow (OPF) model is formulated to incorporate ESSs and wind generation. The ESSs are employed for time-shifting wind generation (see Fig. 1), thus increases the value of wind energy and reduces wind curtailment. This multi-period formulation allows to take into account inter-temporal constraints of the ESSs. In addition, the AC OPF formulation can capture realistic physical power flows of the system better than the DC one. It is also much more accurate and reliable when issues such as congestion and voltage constraints are concerned. Two approaches are proposed for optimal planning of

ESSs considering wind and load uncertainties, i.e., combined GA and cumulant-based Probabilistic OPF (POPF) approach and two-stage stochastic programming approach. A methodology to define candidate buses for ESS installation is also proposed. A sensitivity analysis is then carried out to assess the impacts of ESS locations on system operation. The AC OPF problem with ESSs and wind integration is formulated into single-period model and operation of the ESSs in both models, single-period and multi-period, are compared. Theoretically, multi-period model is a more suitable approach to deal with storage devices. From the tests carried out, multi-period model is shown to provide more economically optimal solution over single-period one in terms of production cost and amount of wind curtailment. Moreover, in single-period model, ESSs are only operated based on variations of wind power while in multi-period model, it is operated based on both wind and Locational Marginal Pricing (LMP) variations. Therefore, the multi-period formulation is applied for planning problems with ESSs in this research. Two approaches, namely combined Genetic Algorithm (GA) and cumulant-based probabilistic approach and two-stage stochastic



1. Time-shifting application of the ESSs

approach, for incorporating wind and load uncertainties into ESS planning problems are proposed. In the first approach, optimal placement and sizing of ESSs is implemented in two steps: in the first step, optimal ESS location and the expected value of ESS capacities are determined by GA and deterministic multi-period AC OPF with the goal of minimizing ESS investment cost and total expected generation cost while maximizing the generation of wind and storage; in the second step, probabilistic assessment is carried out on the obtained ESS locations and capacities. Probability distributions of ESS power and energy capacities are obtained, which can be used by decision makers to finally choose the size of ESSs to be installed. This approach, specifically the cumulant-based POPF approach, represents uncertain system inputs with probability distributions, but it retains the deterministic formulation of the OPF. Thus, the expected value of control variables is not

influenced by the randomness of uncertain system inputs, but only the probability distributions of control variables are determined by them. The other approach, i.e., two-stage stochastic programming, is developed for optimal sizing of ESSs. Wind and load scenarios as input of the problem are clustered and reduced into smaller sets of wind and load scenarios by adopting PCA-guided search for K-means clustering technique. This approach not only treats system inputs as random variables but also establishes stochastic formulation for the problem. Therefore, the uncertainty of random parameter inputs directly influences the optimization result. Test results show that this approach can explicitly incorporate wind and load uncertainties in the optimal sizing of ESSs. A methodology to define the best candidate buses for ESS installation is also proposed in this research. The identification of candidate buses is performed based on the Lagrangian multiplier, which represents the

variation of total production cost with respect to the variation of real injected power at a bus. A sensitivity analysis is performed, using this methodology, to assess the impacts of ESS locations on system operation. Two different applications of the ESSs are investigated, including time-shifting wind generation to meet demand and mitigating transmission congestion to avoid wind curtailment and allow an efficient utilization of transmission capacity. Installing ESSs at the best candidate buses allows the maximum benefit for power systems from several points of view: the minimum overall cost, the minimum curtailment of wind power (that could also lead to minimum CO<sub>2</sub> emissions), the maximum mitigation of congestions, and the maximum benefit, in terms of energy process. A final procedure for optimal siting and sizing of ESSs under uncertainty is then proposed. The first and necessary step in this procedure is preliminarily identifying candidate ESS locations. This helps reduce system size and make the planning problems tractable. Then, either the combined GA and POPF approach or two-stage stochastic programming approach can be adopted for optimal planning of the ESSs considering wind and load uncertainties. Applicability of this procedure is demonstrated with a case study and a complete comparison on solutions of the combined GA and cumulant-based POPF approach and the two-stage stochastic programming approach is provided.

## DIAGNOSTIC METHODS FOR ELECTRIC ARC PLASMA IN LOW VOLTAGE CIRCUIT BREAKERS: MODELING AND COMPUTATIONAL ASPECTS

**Rigamonti Francesco** – Supervisor: Prof. Gabriele D'Antona

Low voltage circuit breakers are protection devices in use in order to prevent faulty and dangerous conditions in civil and industrial electric networks. A key aspect in circuit breaker engineering is the capability to timely switch the electric arc plasma occurring when the electric current flow is interrupted by breaking the circuit. The modeling and simulation of electric arc plasma, under the conditions which are met in low voltage circuit breakers, is a complex and not completely dominated issue.

The aim of this research project is to develop an effective diagnostic method and the underlying know-how to monitor the complex and fast behavior of the electric arc plasma during the transient opening phase of a low voltage circuit breaker.

The final deliverable is a signal processing algorithm returning a space-time map of a characteristic physical quantity associated to the arc plasma, in this case, its current density distribution. The processed quantities are the external magnetic flux densities measured by the Hall effect sensor array specifically designed for this project, placed along breaker sidewall.

Such technique would be a significant improvement over and supplement to state of the

art diagnostics, currently limited to electric measures of purely macroscopic electric quantities or optical methods affected by problems of practical nature. The establishment of the correlation between plasma location and macroscopic measurement will help the modeling of partially understood arc plasma physics, as well as designers and engineers working in the R&D of protection devices. Nowadays the design for those devices is based on a phenomenological and semi-empirical approach, or the analysis of multi-physical simulation and lab measurements.

The developed approach is based on lumped parameter model of the arc, where the ferromagnetic nonlinearities are also evaluated and modeled. The solution is reached by minimizing a nonlinear goal function. An ad hoc, novel regularization technique was developed to improve the resolution without impacting the robustness of the regularization scheme.

Numerical simulation methods are nowadays possible, based on computational magnetohydrodynamics and rich of fine modeling. Thanks to these tools, realistic synthetic data are generated, and the developed identification procedure was tested and validated, by comparison with

a reference solution. The main goal of this work was accomplished with an experimental arc identification in a real breaker, during standard short circuit tests. Inversion results are in agreement with present interpretation and knowledge of arc behavior, and add useful information regarding arc evolution in low voltage circuit breaker.

# EXPERIMENTAL PERFORMANCE EVALUATION OF MPPT ALGORITHMS FOR PHOTOVOLTAIC SYSTEMS

Soulatiantork Payam – Supervisor: Prof. Marco Faifer

In last decades, photovoltaic (PV) systems in the generation section are increasing rapidly and this growth is expected to be continuous. So on one hand, the number of new developmental PV components and devices are increasing and coming on to the PV market. On the other hand, the real peak power of the installed PV plants is one of the crucial parameters for the energy harvesting specifically in places with low solar radiation during the daytime. To address the problem of finding the maximum power point (MPP), many testing systems and maximum power point tracking (MPPT) algorithms have been developed in the PV industry. The testing system is not intended to be only for system development but also can be used to validate the quality of the PV products in the market. In addition, it would be interesting to evaluate the performances of the employed Maximum Power Point Tracking (MPPT) algorithms for a given PV panel or array in the same working conditions. Indeed, in recent literature, many MPPT algorithms have been proposed. However, a rigorous method to compare their performances is still missing. The typical problem related to the evaluation of the number of the PV system performances and MPPT algorithm

comparison is the guarantee of the repeatability of the testing conditions (e.g. temperature and radiation), which is very difficult to do it. It is also well known that the PV cell performance is strongly dependent on the solar radiation and the panel temperature. The definition of current-voltage (I-V) and power-voltage (P-V) in different environmental conditions characterize completely a solar cell, module or array. Unfortunately, the knowledge of these curves is not sufficient to estimate the actual generated power of the panels in working condition. In fact, as well known, it is also necessary to recognize the employed MPPT tracker. For these reasons, a testing system for PV applications has been developed and characterized. The system has been designed according to the following constraints:

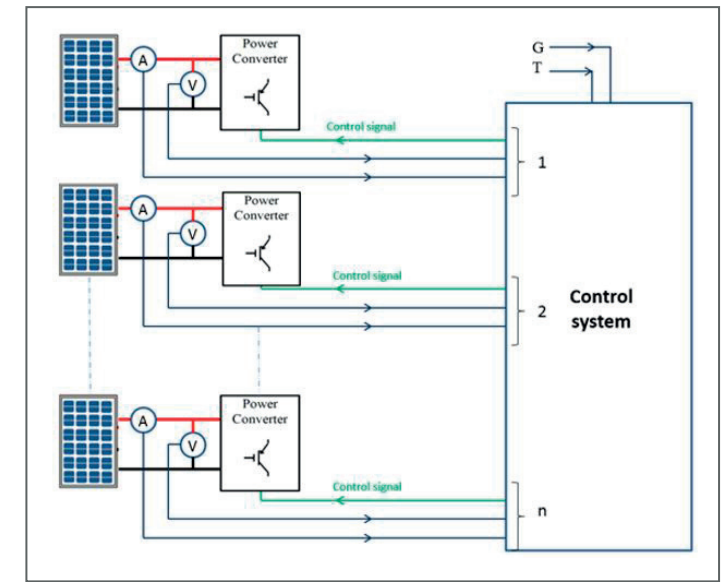
- 1) Flexibility, ease of use and low cost.
- 2) Capability to evaluate the characteristic curves of more than one PV panel simultaneously (same environmental conditions) (i.e. I-V and P-V).
- 3) Capability of algorithms simulation.
- 4) Capability of tracking MPP on the base of different MPPT algorithms.

Previous researchers focus more on characterizing and harvesting a possible Photovoltaic systems power that draws many attentions as a clean sustainable energy amongst the other renewable energies. In the literature, many developments for the MPPT algorithms comparison have been done. However, just a few works compare different algorithms or different PV panels at the same environmental conditions based on simulations only, without experimental evaluation. The difficulties stem from the experimental comparison, it is hard to duplicate the environmental conditions. Therefore, an experimental testing system is necessary and must be developed to have the capability of reproducibility in environmental conditions for comparing these algorithms and characterizing them by the ease of use. A possible solution is to present a testing system with the proposed architecture shown in Figure 1. The system is based on a board for control and measurement management from Simulink environment. The system gives the possibility to measure the characteristics curve of four different panels in the same environmental condition, as well as the radiation and their temperature parameters.

Moreover, it is possible through the system to implement directly the simulated MPPT algorithms in the simulated environment and comparing their performance in real-time.

With the availability of a graphical object-oriented package (Control Desk software), a dSPACE system provides the capability to develop user-friendly control panels for online monitoring and supervision. A dSPACE rti1104 system is quite popular in controlling platform and widely used in automation systems and car manufacturing industries. As an alternative application area, the dSPACE system is used as a control platform for PV application. In this thesis, the test is carried out in Simulink/MATLAB environment with the SimPower/MATLAB toolbox and dSPACE RTI1104 (Real-Time Interface) block set libraries. Figure shows the proposed strategy to achieve the abovementioned objectives. As can be seen, voltage and current of each PV panel are measured and sent to the control system, in which the algorithms are embedded. The output of each algorithm sends a control signal to control the duty cycle of the related power converter to force the system to track maximum power point. The hypothesis of the research has addressed the main gap of the MPPT algorithm real-time implementation and comparison. The research objectives outcome consists of following results:

- 1) Review of the state of the art in the photovoltaic testing system;



1. Block diagram of the testing system

- 2) The design procedure and realization of the proposed hardware DC-DC converter topology components are discussed in details. Furthermore, the optimum switching frequency is verified by means of analytical calculations and evaluated by the numerical model.
- 3) The design of the testbed hardware and software for the measuring the real-time parameters, with the aiming of repeatability and reproducibility in the same environmental condition.
- 4) A literature review on different methods of MPP trackers is presented, the MPPT algorithms parameters are optimized, and then the

systems amongst different PV testing systems, which enable the capability of the characterizing the PV module and tracking the MPP.

5) The different comparison tests have been performed according to the dynamic and steady state behaviour of the energy generation. Furthermore, the algorithms also have been compared in real-time operating condition. In addition, namely identical PV panels energy productions have been compared in the same environmental condition.

## DIAGNOSTIC METHODS FOR ELECTRIC ARC PLASMA IN LOW VOLTAGE CIRCUIT BREAKERS: MEASURING AND APPARATUS DESIGN

**Taccola Marco** – Supervisor: Prof. Gabriele D'Antona

The aim of this research project is to develop an effective diagnostic method and underlying know-how to monitor the complex and fast behavior of the electric arc plasma during the transient opening phase of a low voltage circuit breaker.

Our idea relies on adopting inverse methods based on magnetic measurements to be recorded by an apparatus which, owing to the many demanding requirements, would inevitably have to be fast, accurate, compact and located in a hostile environment.

The final deliverable is an experimental setup returning a space-time map of the magnetic flux density close to the circuit breaker side wall associated to the unknown arc plasma current density distribution.

Such technique would be a significant improvement over and supplement to state of the art diagnostics, currently limited to electric measures of purely macroscopic electric quantities or optical methods (e.g. IR and high speed cameras, optical fibres) affected by problems of practical nature.

The complexity and time behavior of the phenomena under study requires sampling the magnetic flux density at a large number of locations at high sampling rate. This work has led to the design

of a magnetic sensor array, based on Hall effect sensors, and a data acquisition system meeting the following requirements:

- Dynamic range:  $\pm 100$  mT
- Accuracy: 1 mT
- Bandwidth (3 dB): 20 kHz
- Size: 35x35 mm
- Number of sensors: 8x8

The diagnostic methods to develop strongly rely on high quality and massive magnetic and electric measures. Particularly, owing to the strong sensitivity of inverse methods to signal noise, accurate sensor signal conditioning and calibration is required. This is a difficult challenge due to the reduced space available to locate sensors and the rapid dynamics and high intensities of the spurious electric and magnetic fields around the current breaker during the short circuit event.

Laboratory tests have proven the ability of the developed system to reconstruct the arc current density distribution under real experimental conditions.