Convocatoria de ayudas de Proyectos de Investigación Fundamental no orientada

TECHNICAL ANNEX FOR TYPE A or B PROJECTS

1. SUMMARY OF THE PROPOSAL

PROJECT TITLE: “SMART POWER PROCESSING IN PV GENERATION” (FOTOPROINT)

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SUMMARY

The optimization of the processes for generating, distributing and consuming electrical power resulting from renewable energy sources requires novel concepts for designing electrical networks in which all the agents processing electrical energy should offer new performance and systems to guarantee the highest level of efficiency, power quality and security of service in the resulting power system. These electric networks of the future, internationally known as "Smart Networks", will be constituted by multiple distributed generators, with widespread presence of renewable energy sources, and based on the generalized usage of new applications involving power processors exploiting power electronic and the information and communications technologies (ICT).

As a particular case of the future distributed generation systems, the distributed photovoltaic (PV) power systems, should offer new advanced features that allow managing, in an intelligent way, any aspect related to the interaction with the electrical network, the efficiency in the power processing, and the exploitation of the PV resource. In this sense, this research project will aim to find new technical solutions devoted to facilitate the complete integration (and not the simple connection) of PV generators into the electrical power system with the objective of improving their reliability, security, efficiency and power quality.

The main objectives of this project can be summarized as follow:

1. Identify scenarios and operating settings for current and future PV generation systems
2. Develop simulation models representing characteristic scenarios and electrical networks, including the components and devices that constitute the electrical network as well as the PV generation systems to be integrated into it.
3. Analyze advanced topologies of power processors devoted to increase the efficiency, quality and robustness of the PV generation systems
4. Study of advanced control, monitoring and diagnosis/prognosis functionalities for intelligent PV generation systems which make possible both supporting the grid services for increasing its stability, reliability and power quality, and operating as an intentional island for warranting the supply to the loads.
5. Propose advanced power and control structures for the future smart PV generation systems, evaluating their performance by both simulation and experiments.

2. INTRODUCTION

ENERGY has played a decisive role in the economic, political and social reality of the World during the second half of the XX century. The high pollution levels and the worrying climatic change during the last decade demands an immediate reduction of CO2 emissions. Additionally, the emergent concern about the high dependence on the fossil fuels has encouraged politicians and investigators to look for alternatives exploring other Renewable Energy Sources (RES). A direct consequence of this new energy policy is the growth in the world-wide use of RES from 1995 to 2005. According to sources of the Earth Policy Institute [1], the wind (WIND) and photovoltaic (PV) energy have experienced the highest average annual growth in this decade, 28,6% and 26,2% respectively. In contrast, during the same period, the increase in the use of coal was 2,5%, 1,8% in nuclear energy, 2.5% in natural gas and 1.7% in petroleum.

In Spain, the political interest to activate the market of PV energy was latent in the RD 436/2004 decree-law (order in council in UK or bill in US), later substituted by the RD-L 7/2006. Both decrees established the feed-in tariffs for electrical power generated from PV systems, which were among the highest in Europe. The outstanding growth in PV power installation in Spain has given place to new directives which moderate the feed-in tariffs for solar PV-generated electricity (RD 661/2007 and a new legislative proposal that will affect to the PV facilities started up at the end of the 2008). The growth of the solar sector is boosted, even more, thanks to the new Technical Building Code (TBC), regulated by the RD 314/2006. In its basic requirement HE 5, this ordinance rules the minimum contribution of PV electrical power in the new buildings that, if it proceeds and according to each case, can oscillate between 6,25kWp and 62,5kWp.

In 2006, the rate of growth in the installed PV power in the most representative countries of the world remained stable in an impressive 36%, more than 1,5GW of PV power were installed and the total cumulative installed power reached 5,7GW [2]. More than the 89% of the installed PV power was connected to the grid. It is worth to point out that approximately 80% of these 5,7GW belongs to Germany (2.863MW) and Japan (1.708MW). According to 2006's data, below these two countries in the world PV ranking, but still far away, there were United States (624MW), Spain (118MW) and Australia (70MW). Spain is one of the countries with highest expectations in the rate of growth in the installed PV power during the next decade. The growth rate of installed power was of 104,8% in 2006. The "Spanish Plan for Renewable Energies 2005-2010" [3] set as a target to have 400MW of cumulative PV power installed in Spain in 2010. The RD 661/2007, currently in force, makes reference to a limit of 371MW of installed PV power for maintaining current feed-in tariffs for PV-generated electricity. According to data from the Association of Photovoltaic Industry (ASIF) of Spain, the growth of the installed PV power in Spain during 2007 was higher to 500%. According to official data from the National Commission of the Energy (CNE) of Spain [4], 91% of the limit of 371MW had been reached in August of 2007. Nowadays, this limit has been already overcome. Recently, the Ministry of Industry, Tourism and Commerce of Spain has remitted to the CNE a new decree-law proposal in which the new feed-in tariffs for PV power are set intending a strategic target of 1200MW of cumulative PV power installed in 2010 –such amount of power is already considered insufficient by several associations of the PV industry. The PV generators will be broadly spread in the current distribution grids, either in the form of PV plants or small PV facilities, and they will have a remarkable presence in the residential and commercial sectors –contrary to what happens with the wind turbines. 200MW of the 1200MW to be installed in 2010 are exclusively planned to on-roof PV systems.

2.1. Precedents / Problem description

The intensive research performed during the last decade has allowed great advances in high quality PV cells and PV wafers production systems, achieving a higher efficiency and reducing the manufacturing costs. Progresses in power electronics based power processors have been also remarkable, mainly in terms of efficiency and robustness. However, all the ambitious political objectives for expanding the RES expansion, and particularly for the PV energy, might be radically reduced due to the problems that these distributed generators can cause when they are integrated in the current electric system.

When outlining the massive integration of PV generators, it is interesting to take into account the lessons learned from earlier experiences on WIND energy integration into electrical networks. In 2006, Spain satisfied the 8,8% of the electricity demand by means of WIND energy [5]. That same figure was equal to 20% and 5,7% for Denmark and Germany, respectively. It has been demonstrated in these countries that the lack of technical planning in the installation of distributed generation can eventually slow down its integration and even threaten the stability of the electrical system. In Spain, the amount of WIND power installed in the last years has experienced a gradual reduction (1587MW in 2006, 1730MW in 2005, 2361MW in 2004), what contrasts with the trend in other countries like Germany (2233MW in 2006, 1785MW in 2005 and 2037MW in 2004) or USA (2454MW in 2006, 2424MW in 2005 and 372MW in 2004) [6]. According to the Spanish WIND industry, this decrease was mainly due to a slowness imposed by the Spanish grid operator, Red Eléctrica Española (REE), for giving the grid connection licenses of the WIND turbines [6]. On the other hand, REE claims that this cautious attitude in closing the grid connection administrative technical contracts for WIND turbines is mainly justified by its concern to maintain the stability of the electrical power system when the penetration index of distributed generators based on WIND turbines is high. A common characteristic in all of the countries where there is high penetration of distributed generators is the existence of grid

connection codes that establish the requirements imposed in the grid connection of WIND generators to achieve a stable operation of the power system and to guarantee a high enough reliability level [7].

Regarding PV power penetration in Spain, the current lack of coherence between the performance of the PV generators, the inherent needs of the electrical grid and the requirements imposed by the grid operator, together to the frantic rhythm in installing PV power (the growth rate was around 500% in the last year), make possible to foresee a future scenario of distributed PV power characterized by numerous and small PV generators (spread among the low voltage distribution system and with a notable presence in residential and industrial areas), with variable production (depending on the available solar radiation), not controlled by the grid operator (an official WAN for controlling and supervising PV distributed generators doesn't exist) and without any capability to support the grid services (there is not support to the grid voltage and frequency stability and supply restoring). Obviously, it is simple to demonstrate that the stability of such a power system would be really poor. The current grid codes regulating the grid connection of PV systems consider them as "slaves". They should stop feeding the grid when certain faults occur or when they are intentionally disconnected (operations and repairs), avoiding, in this way the existence of "islands" fed by PV systems. Equivalent procedure codes were in force in the first times of the WIND turbines connection to electrical networks. These rules intends to avoid accidents/malfunctions in those areas not fed by the grid operator, at the same time that it makes easier the restoration of the grid services once the operating conditions are re-established. However, this policy is incongruous with the effort invested in designing high-efficiency and high-performance PV panels and power processors, since they will not be able to continue feeding to their local loads as a consequence of grid shortcomings which they have nothing to do with. The experience in WIND turbines, with a higher penetration index, has demonstrated that those standards should be radically modified when the presence of distributed generators is significant. Additionally, only exist incipient databases that collect consolidated experiences (>25 years) in reference to the performance, efficiency and reliability of PV generators, something that makes even more difficult to design long term policies concerning to the connection and operation of such systems.

Precedents of the research activities proposed in this project can be found in the 6th Framework Program of the EU, which promotes the research activities for integrating RES, implying more actors and favouring the creation of the "Technology Platform for the Future Electric Networks" in 2005. According to a European Commission report at end of 2005 [8], the learned lessons of these experiences reveal, among other things that:

- It is critical to change the mentality for 'integrating' RES (instead of 'connecting') in the general operation of the electric system.
- The future electric grids will use, massively, electronic power processors (EPP) and information and communications technologies (ICT).
- The complete integration of RES will report benefits like the increment of transmission and distribution capacity and a reliability increase.
- The most important requirements associated with the high scale integration of RES are the reliability, the security and the power quality.

In this line of work, the Photovoltaic Technology Platform (PVTP) (www.eupvplatform.org), also funded under the 6th FP of the EU, is an initiative which aims at realising the European Strategic Research Agenda for PV for the next decade(s) and give recommendations for implementation; ensuring that Europe maintains industrial leadership. One of the main contributions of this Platform is the report called "A Strategic Research Agenda for Photovoltaic Solar Energy Technology" [9], published on March 2007. In this document, European research priorities for short, medium and long terms are described. At the component level, "highest priority is given to the development of inverters, storage devices and new designs for specific applications". One of the main objectives is to "develop control and monitoring strategies to maximise system performance, whilst retaining simplicity of operation". This is directly related with:

- Using functionality built-in to the inverter to improve the quality of grid electricity, by controlling reactive power or filtering harmonics, therefore adding value to the electricity produced.
- Looking at concepts of storage in grid-connected systems using inverters that are able to operate in island mode to increase the reliability of supply in case of disturbances on the main grid.

In the longer term, PV systems will become key components in low-voltage sub-grids (or micro grids), and thus, a detailed assessment of the value of PV electricity in various grid configurations both with and without storage is very important. Consequently, techniques to manage island micro grids with a high share of PV generators, as well as components and system designs for island PV and PV-hybrid systems, must be developed.

Summarizing, the main research objectives identified by the Platform are:

- New concepts for stability and control of electrical grids at high PV penetrations.
- Development of power electronics and control strategies for improving the quality of grid electricity at high PV penetrations.
- Analysis of intelligent inverter functions and PV system interaction with other distributed generation technologies.
- Techniques to manage island micro grids with a high share of PV generators, as well as components and system designs for island PV and PV-hybrid systems.

- New storage technologies for small and large applications and the management and control systems required for their efficient and reliable operation.
- Finding concepts for stability and control of electrical grids at high PV penetration levels.

The 7th European Framework Program persists on the necessity of reformulating the current electric systems and identifies an investigation area referred as 'Smart Energy Networks'. This area intends to increase the efficiency, security and reliability of the systems and the electricity and gas networks, and also to eliminate the technical obstacles that nowadays still hinder the development and the effective integration of renewable sources and distributed energy.

2.2. Proposed solution / Project target

This project, SMART POWER PROCESSING IN PV GENERATION (FOTOPROINT), proposes hardware and control solutions that *i)* will increase the efficiency and quality in processing the energy collected form the PV resource, and that *ii)* will boost the integration of PV generators in the electrical grid by a smarter power processing based on new management and control functions. From the expected improvements in PV generators, this project intends increasing the security, the efficiency, the flexibility and the overall quality of the resulting distributed generation system (DGS). Contributions resulting from this project will contribute to the development of the future smart electric power grids, since the improvements introduced in the power processor of the PV generators will allow locally controlling the quality and security in the operation of the power processor, the interaction with the grid at its coupling point, the operation in island mode, and the optimal management of energy collected from the PV panels. Moreover, the communication functionalities implemented in the PV generator will allow distributing and processing information about their operating state and its contour variables, which will increase the overall controllability of the DGS and will generate useful knowledge for the other agents of the power system.

The two main axes of this coordinated project are defined by two subprojects defined in the following.

SUBPROJECT I: “ADVANCED CONTROL TECHNIQUES OF PHOTOVOLTAIC DISTRIBUTED GENERATION SYSTEMS FOR IMPROVING THEIR INTEGRATION INTO ELECTRICAL NETWORKS” (FOTOINTEGRA)

This project deals with distributed generation systems (DGS) with widespread usage of PV power generators. The interaction between the PV generator and the electric network will be studied in this project with the aim of designing advanced control techniques that allow improving the overall stability and reliability of the PV distributed generation systems (PV-DGS). These advanced control techniques will increase the quality and stability in the electrical supply, which eventually will contribute to a better integration of PV generators into the existing electric networks. This project will cover the following issues:

- Evaluation of grid connection requirements for PV generators. The national and international grid connection codes estate certain conditions under which the PV generators should remain connected/disconnected to/from the electrical network. Designing of simulation models, with different detail degrees and work domains, will allow conducting a exhaustive technical evaluation of the requirements imposed by the grid codes, studying those not considered scenarios and outlining new recommendations for the grid connection of PV generators.

- Grid services support and power quality improvement. Implementation of advanced control functions in the PV generators will allow that these generators can contribute to increase the voltage and frequency stability in LV distribution networks, something of vital importance in DGS. Likewise, PV generators are also able to act as active conditioners which allow cancelling out conducted disturbances, such as harmonics or flicker, balancing voltages and currents, and compensating the power factor, which eventually improves the power quality of the network in which they are connected to. This project will face the study of control solutions to improve the behaviour of electrical networks by implementing grid support functions in the distributed PV generators.

- Intentional-island operation mode. According to the evolution of more developed DGS, like those based on WT, it is expected that operation of PV systems as intentional islands will be considered in the future grid connection codes. This project will study different solutions for setting the voltage and frequency of the island (micro-grid) from the collaborative operation of different PV generators, which will increase the security and reliability of the supply. Solutions based on either implementing ‘droop-control’ algorithms in the PV generators or designing an intelligent connection agent, which acts as a ‘master’ of the grid, will be studied.

- Monitoring of the PV generator. The operating conditions of a PV inverter should be continually monitored to guarantee that it is operating in range. A monitoring system with low computational load, based on synchronization techniques stemming from adaptive filters, will be designed in this project to supervise the value of the grid voltage and frequency, the grid parameters, the grid voltage quality, the injected current quality, the earth leakage current, the energy delivered, the potential of the PV resource, and other parameters related to productivity, security and reliability. Generic grid scenarios will be considered in the design of the monitoring algorithms and all those cases prone to be discussed in the grid codes will be studied. The information resulting from the monitoring process will

be available to higher hierarchical level computational systems by means of the communication functions implemented in the PV generator controller.

- Diagnosis and prognosis of PV generators, clusters and plants. The production of a PV plant varies throughout its operative life as consequence of the degradation of its components and the variability of the environmental conditions. This project aims to develop an expert system, based on mathematical simulation models, on the information received from actual PV generators by using ICTs, and on the environmental conditions on the PV plant location. Results from the simulation model will be correlated with the actual data received from the PV plant in order to progressively refine the parameters of simulation model. An expert system based on precise simulation models will allow diagnosing the origin of faults in the PV power plant and will predict future incidences by means of stochastic analysis. This prognosis functions will make possible to plan predictive maintenance tasks on the PV generators and plants, which will contribute to extend the operative life of these generation systems.

SUBPROJECT II: "ADVANCED PHOTOVOLTAIC POWER PROCESSING TOPOLOGIES WITH HIGH POWER QUALITY AND EFFICIENCY PERFORMANCES". (FOTOPROCES)

This project deals with the improvement of the electronic power processor of PV generators with the aim of increasing its efficiency and robustness. This project intends to find new PV inverter topologies, modulated by specific techniques and governed by low level controllers which allow maximizing the efficiency in the power conversion, the quality of the wave supplied to the grid and the use of the PV resource. This project will cover the following aspects:

- Single-phase transformerless topologies for PV power processors. Well known transformerless PV inverter topologies, as H5 or HERIC, present the drawback of generating common mode voltage which gives rise to leakage current flowing from the PV system to ground. This current can cause problems related to personal safety, interferences, resonances and PV panels degradation (e.g. in the case of thin-films). For this reason the leakage current to ground use to be limited by the grid codes. This project will evaluate new single-phase topologies, variants from the previous ones, which using a proper modulation technique are able to cancel out the common mode voltage at the same time that they maintain a high efficiency as the original topologies.

- Three-phase transformerless topologies for PV power processors. Most of the existing three-phase transformerless inverter topologies are not optimized for PV applications. This is because they are usually based on conventional topologies and modulation techniques, which generates common mode voltage. This project will evaluate two new transformerless topologies for three-phase PV inverters, which are an extension of the aforementioned single-phase topologies, characterized by a high efficiency and low common mode voltage.

- Robust control of the injected current by using advanced digital techniques. The control of the injected current is of great importance in PV systems, where it is also necessary to take care of the power quality delivered to the grid. The use of advanced direct current control techniques for delivering power to the grid through LCL filter, with low switching rate, reduced harmonic content and supported by an advanced digital control, will give rise to a robust grid connection, like in the hysteresis controllers, at the same time that respectful with the power quality requirements.

- Multi-stage (multilevel) power processor for the DC side of the PV power processor. Designing of a power processing stage having a multi-source (multilevel) DC bus would permit establishing different optimal operating points depending on the PV matrix area, something interesting since the solar reception is equal for all the panels. This project will cover this issue together the design of optimal MPPT techniques suitable for the proposed DC multi-stage power processor.

- Optimal control of the PV matrix. The efficiency of the PV systems in front of situations like partial shading or irregular ageing depends on both the MPPT algorithm and the connection topology used in the PV matrix. In this project, such situations of irregular irradiation will be reproduced in the lab by using simulators of PV modules, which will permit to evaluate the performance of different MPPT techniques as a function of the PV matrix connections layout and to eventually selecting the one that performs the best response.

- Storage systems. The intermittency in power generation is one of the main drawbacks of the generation systems based on RES. This limitation both makes difficult the grid management and operation, and complicates the usage of this kind of generators in those applications in which the power flow pattern is directly set by the loads, e.g. as in the case of micro grids. Several storage technologies will be studied in this project, e.g. batteries and ultracapacitors, and their performance will be analyzed regarding their application to FV-DGS.

2.3. National and international groups working on the project field or on related areas

At national level, the research activity in Spain about PV energy is relatively moderate if compared with the ambitious Spanish national plans regarding the large scale installation of this kind of technology in short term. The research group supporting this project proposal has collaborated for years with several national research centres. Some research groups and projects related to PV energy are detailed in the following:

- Centro Nacional de Energías Renovables (CENER)
- Instituto de Energía Solar (IES) of the UPM
- Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas del MCYT (CIEMAT)
- Instituto para la Diversificación y el Ahorro de Energía (IDAE)
- Instituto de Tecnología Eléctrica (ITE)
- Electrical Engineering Department. Universidad Carlos III
- Plataforma Fotovoltaica (PTFV) (Consejo gestor: ASIF, CENER, CIEMAT, IES, ISOFOTON)
- GENEDIS projects (CIDAE, IKERLAN, LABEIN, UPV, Universidad de Mondragón, ROBOTIKER, CIDETEC)

The international research activity on PV energy is very important. The research group supporting this project has collaborated with some of the most prestigious research centres of Europe and United States. The centres and most important international programs are:

- Institut für Solare Energieversorgungstechnik. Kassel University (Germany)
- Institute of Energy Technology. Aalborg University, Aalborg (Denmark)
- Photovoltaic Power Systems Programme, International Energy Agency
- Riso National Laboratory. Solar Energy Department, Roskilde (Denmark)
- Energy research Centre of the Netherlands (ECN). Petten (Netherlands)
- Department of Electric Power Engineering. Chalmers University of Technology, Göteburg (Sweden)
- Energy Conversion Group (ENO), Norwegian University Of Science And Technology (NTNU), Trondheim (Norway)
- DELFT University of Technology Wind Energy Section (Netherlands)
- National Research Energy Lab, U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, Golden, CO (USA)
- Center for Power Electronics Systems, VA (USA)
- Power Electronics and Clean Power Research Laboratory. Texas A&M University, College Station, TX (USA)
- Centre for Renewable Energy & Sustainable Technologies Australia (CRESTA).
- Curtin University of Technology, Perth, WA (Australia)

The research group of the UPC keeps a close relationship with the Institute of Energy Technology (IET) at Aalborg University. Currently, there is a very active collaboration in different projects with the IET research group, whose thematic is closely related to the one proposed here. These projects are:

- "Smart PV Power Generators for DPGS", Danish Research Agency. Jan. 2007 - Dec. 2009
- "Monitoring and control of PV power clusters for DPGS", Danish Research Agency. Jan. 2007 - Dec. 2009.
- “Vestas Power Programme 2007-2012”, Vestas and Aalborg University.

Other already concluded projects in which the UPC group collaborated with IET are:

- "Monitoring and Advanced Control of Three-Phase Distributed Power Generation System" (AAU, Risø, Eltra)
- "Reliable Grid Condition Detection and Control of Single-phase DGPS" (AAU, STVF)

The research group of the UPC maintains a close collaboration with the Energy Conversion Group (ENO), Norwegian University of Science and Technology (NTNU) as well. In the NTNU, where the professor Marta Molinas is co-supervising the work of Gerardo Vázquez, a PhD student participating in this project. This student comes from the center CENIDET of Mexico and he has a research scholarship inside the CONACYT framework for a PhD project entitle "Smart PV Grid-connected Power Converters". (Ref. 180016/229630).

Likewise, the group of the UPC acts as the leader in an inter-university cooperation project granted by the Ministry of Science and Technology of Spain (MCYT) entitled "Advanced concepts in grid connected power converters to increase the penetration of distributed generators based on renewable energy (PHB2006-0074)". This project, developed in collaboration with the University of Alcalá of Henares, the Federal University of Rio of Janeiro and the Federal University of Pernambuco, intends increase the knowledge for installing generators based on renewable energies in Brazil according to the government project PROINFA. Nowadays, the following stays in the UPC for Brazilian PhD students and postdocs are planned:

- "Wind turbines based on double fed induction generator (DFIG) under low voltage ride through (LVRT) conditions", February 2008 - February 2009
- "Power converters for PV applications with advanced functionalities for grid active conditioning”, March 2008 - March 2009.
- "Control of distributed power generation systems" (Postdoc) February 2008 - February 2009.

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