DERri
Distributed Energy Resources
Research Infrastructures

TEMPLATE FOR PROPOSAL UNDER DERRI

User-Project Proposal:

User-Project Acronym	PV-APLC
User-Project Title	Design and Implementation of a Photovoltaic Active Power Line Conditioner
Main-scientific field	Electrical Engineering
Specific-Discipline	Photovoltaic energy systems

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Activity type and legal status* of Organization	1
Position in Organization	FPU (Formacion Profesorado Universitario) Scholarship, student of PhD by Ministerio de Educación of Spain.

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Activity type and legal status* of Organization	1
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Activity type and legal status* of Organization	1
Position in Organization	Research Professor

* Higher Education Institution (1) – Public research organization (2) – Private not-for-profit research organization (3) – Small or Medium size private enterprise (4) – Large private enterprise (5) – other (specify)

(Repeat for all Users)

Date of submission	25th of June
Re-submission	YES_______ NO____X___
Proposed Host TA Facility	*Option 1: University of Strathclyde.* *Option 2: Austrian Institute of Technology, Österreichisches Forschungs- und Prüfzentrum Arsenal Ges.m.b.H.*
Starting date (proposed)	From October on

Summary of proposed research (about ½ page)

This project proposes a Photovoltaic Active Power Line Conditioner, a device designed to extract the maximum power of a Photovoltaic (PV) system and to compensate the non-linear and unbalanced loads of the electrical power systems. Nowadays, the electrical networks present a distributed generation because renewable energy sources are used in addition to conventional energy sources. The grid-connected PV systems require DC-DC and DC-AC power converters to maximize the generated PV power and to inject an AC current to the network. In this work, a neuro-fuzzy system is proposed to achieve the Maximum Power Point (MPP) and a fuzzy logic control loop of this PV system has been designed with two main objectives. On the one hand, the DC-DC power converter control assures the Maximum Power Point Tracking (MPPT) of the PV system connected at DC side using an algorithm by means of a fuzzy logic control. On the other one, the DC-AC power converter control strategy includes an active compensation of the non-linear and unbalanced loads connected to the electrical system. The performance of the PV conditioner with the neuro-fuzzy control designed has been analyzed in radial power systems through a simulation platform by means of a variety of loads.

This way, we would like to test our model in the Distributed Energy Resources Research Infrastructures in order to check the simulation results. We need to prove that the MPP is reached under all environmental conditions using the proposed control methods and to check that the inverter can work as an active power filter, so it can inject the reactive power and active power to the load connected to the electrical network as well as to compensate the harmonics of the AC loads.

State-of-the-Art (about 1 ½ page)

Photovoltaic energy systems are very extended renewable sources. A grid-connected PV power system consists of an array of solar modules, a DC-DC power converter, a DC-AC power inverter and a control system.
The PV modules convert the solar energy to electrical energy and they inject it to the electrical power system, [1]. The generated power depends on the temperature and the solar irradiation which are environment conditions. There is only one operating point with a Maximum Power Point (MPP) under particular conditions by each PV module. Therefore, this point can be tracked through different algorithms (Maximum Power Point Tracking, MPPT) that control the switching

converter in order to achieve the maximum power point under all conditions [2-8]. Most of them are based on the principle of perturb and observe using a DC-DC power converter [4]. With this method, the output power gets the equilibrium point but it has an oscillatory behavior. Moreover, that equilibrium point is not always achieved because of a local maximum is reached instead of a global maximum. The artificial neuronal network method has a better performance but presents an involved structure. In this project, the proposed MPPT algorithm has been developed using a fuzzy logic control, that it is easier than the previous one and the adequate performance can be achieved. A neuro-fuzzy system is also used in order to obtain the operation point and that makes the control faster. This system has to adjust the duty cycle of the DC-DC power converter to track the MPP by measuring the current and the voltage at the input of the converter.

In addition, the control of the DC-AC power inverter of the PV system has been designed to compensate the harmonics, the reactive power and unbalanced loads of the electrical system using a strategy based on the modified vectorial theory, [9-12]. So, the global control makes possible to extract the maximum power of the PV system, to compensate the non-linear and unbalanced loads of the electrical system and to regulate the input voltage of the DC-AC power inverter. This way, the Power Quality (PQ) of the electrical network is improved, [13-14]. In order to get it, a system called PV active conditioner has been used.

References

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Detailed Description of proposed project : Objectives – Expected Outcome – Fundamental Scientific and Technical value and interest (2-3 pages)

- Electrical Power System modelling

A grid-connected PV power system consists of an array of solar modules, a DC-DC power converter, a DC-AC power inverter and a control system. The complete scheme of the electrical system, including other electrical source and a load, are presented in Fig. 1.

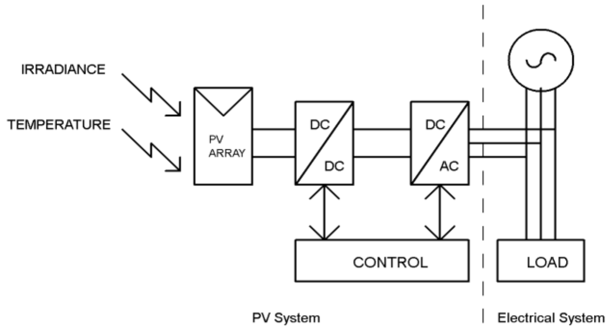

Fig. 1. Basic structure of the PV conditioner system

In an initial design step, the devices of the system are modeled in Matlab-Simulink. Firstly, we will model the solar array, secondly the DC-DC converter and finally the inverter.

The chosen model of a solar cell consists of a current source I_l that represents the current generated by the photons, (it will be constant if the radiation and the temperature are constants too), in A, an anti-parallel diode D_1, a shunt electrical resistance R_{sh}, in Ω, which represents the current leakage, and a series resistance R_s, in Ω, which models the ohmic losses. The equivalent circuit is shown in Fig. 2.

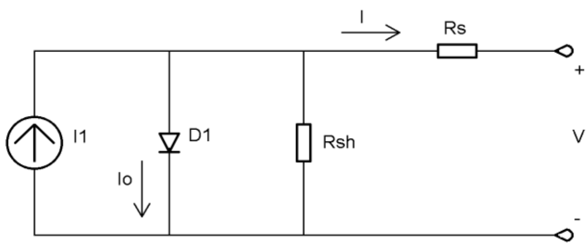

Fig. 2. Equivalent circuit of a PV cell

Solar cells are connected in series and in parallel in order to create a solar module depending on the capacity demands. There is only one operating point for a PV array with a maximum output power under particular conditions.

A DC-DC power converter has to be added at the output of the photovoltaic array in order to get the optimum output voltage and to implement the MPPT. In this proposal, a buck-boost converter is used. The output voltage of the DC-DC power converter is v_o in V, V_{PV} is the input voltage of the converter or the output voltage of the solar array in V, I_{PV} is the output current of the PV array *in A and i_L is the inductor current in A. In this case, the load is a resistance. Parameters R, L, C_1 and C (resistance in Ω, inductor in H and capacitors in F) are constants.*

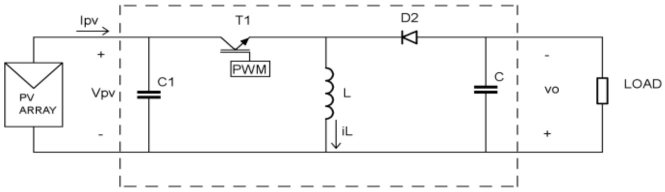

Fig. 3. Buck-boost converter

The target of our control is to adjust the reference voltage, using a neuro-fuzzy system, to regulate the input voltage and to guarantee the maximum energy extraction of the PV modules. Thereby, adjusting this theoretical or reference voltage instead of the duty cycle as we used to do up to now, the local maximum is avoided and the peak of the curve is achieved faster initially. The neuro-fuzzy system provides the theoretical value of the voltage in order to obtain the MPP by means of the temperature and the irradiance and it can be calculated together with the characteristic of the photovoltaic array. Then, the optimum voltage must be obtained modifying the voltage around the reference or theoretical voltage according to a fuzzy logic control instead of a standard PI control. This control is needed to achieve the voltage that supply the maximum power at the input of the converter.

The DC-AC power inverter is used in order to connect the PV system to the electrical network. Its aim is to provide the maximum power to the network while it works as an active power line conditioner in the point of common connection. Therefore, it could achieve a global compensation in distributed systems. The main advantage is that the power stage of the conditioner can be saved. In this work, a three-phase inverter has been used. It consists of a control circuit to determine the reference current and a power circuit to follow this reference and to inject the final current to the network.

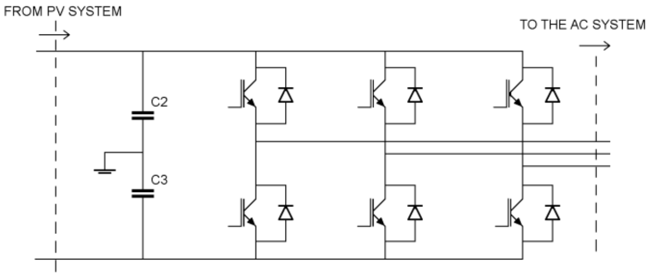

Fig. 4. DC-AC power inverter

- Control strategy

A <u>neuro-fuzzy system</u> is used to know the PV output optimum voltage which will be used as reference voltage. Fuzzy logic is based on rules and membership functions to relate inputs to outputs. GENFIS3, a function from Matlab, has been used to determine these rules and functions where data inputs are the irradiation and the temperature, and the data output is the output voltage of the solar array that supplies the maximum power.

To create a trained system with the membership functions and rules, an adaptative neuro-based fuzzy inference system (ANFIS) is used to achieve the required voltage in order to control the system using the MPPT algorithm. This neuro-fuzzy system provides the reference voltage at the input of the DC-DC power converter. In this work, the control loop to keep constant that voltage has been implemented using fuzzy logic. So, the Matlab fuzzy graphical tool has been used to create membership functions and rules, where the input is the error between the theoretical voltage and the measured voltage at the output of the solar array whereas the output is the duty cycle of the DC-DC power converter.

The generated active power can be injected to the electrical system as an alternating current, i_{PV}, in A, in phase with the connection point voltage. In this work, this current will be in phase with the fundamental and direct sequence of this voltage.

The global control strategy will include the injection of generated PV active power and the compensation of non-linear and unbalanced loads. In this work, sine compensation has been proposed in order to obtain balanced, sine and direct sequence network current. This strategy is effective, simple and easy to implement with a reduced computation time.
The total PV conditioner current, i_T has two components. The first one is i_{PV}, which transports the active power generated by the PV array. The second one is i_C, the current that compensates the non-active power of the electrical loads. To determine the last one, it is necessary to calculate the load active current, i_a. The shunt active conditioner will supply the difference between the load current and its active component. i_a depends on the active power, P and the voltage:

$$i_a = \frac{P}{V_{1+}^2} v_{1+} = G_1 v_{1+}$$

where v_{1+} is the fundamental direct sequence voltage at the common connection point in V and G_1 is the equivalent conductance of the load, 1/Ω. The compensation component, i_C, of the PV conditioner current is the difference between the load current and its active component.

$$i_C = i_L - G_1 v_{1+}$$

In addition, the input voltage of the inverter must be adjusted because the voltage in the capacitor has to be constant. That is achieved adding a parameter ρ to the conductance that depends on the error between the capacitor voltage and the reference voltage. This parameters allows a proportional control to sure a constant voltage at DC side.

$$i_C = i_L - (G_1 \pm \rho) v_{1+}$$

The total reference current of the PV conditioner is:

$$i_T = i_{PV} + i_C = i_L - K v_{1+}$$

where K is $G_1 - G_1' \pm \rho$, being K an adjustment parameter and it can be adjusted by a PI control.

- Experimental tests

The research team has completed the above mentioned project in a simulation platform, with a variety of loads such as DC and AC loads, and now the objective is to test the control system performance in the lab. In a first step, we can emulate the PV array in a programmable DC source which includes the solar cells V-I output. The control the power devices will be carried out by means of a DSP acquisition and control board such as dSpace or similar. This way, we expect that the PV array will supply the maximum power under all conditions whereas the inverter can inject the PV power and compensate the non-active current components of the electrical system loads.

Originality and Innovation of proposed research – Broader Impact (1-2 pages)

1. On the one hand, control techniques of tracking PV systems are proposed using innovate methods. The proposed neuro-fuzzy control is faster than other and it presents an adequate stationary and transient response, as it is shown in next figures.

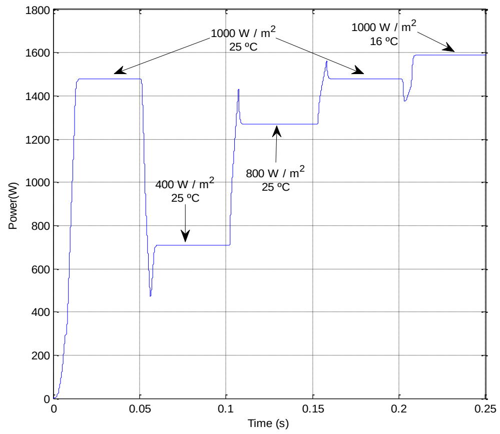

Fig. 5. Maximum power under different conditions

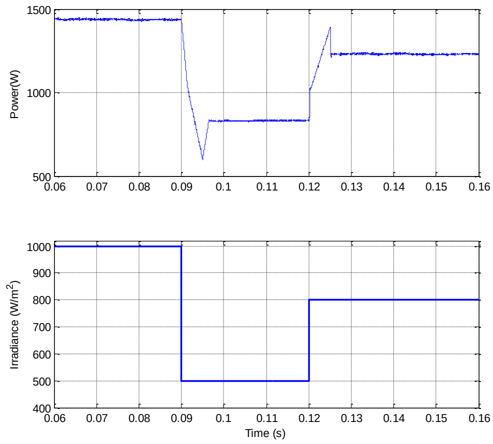

Fig. 6. Evolution of PV power and irradiance

It can be proved the good performance of proposed MPPT algorithm because the transient response is about half a period and the maximum power is always achieved under different conditions of irradiation and temperature.

2. On the other hand, additional functions are assigned to the PV systems. So, it will be possible that the different distributed generation sources are used in the voltage control of the electrical power system.

To prove this, in the next example the PV conditioner injects the reactive power of the load. The figure 7 shows that the PV system can supply the reactive power and the network does not need to supply it. It can supply the PV maximum power and simultaneously it can generate the reactive power that loads need, improve the power factor and decrease the rms current. This way, the power quality of the electrical network can be improved.

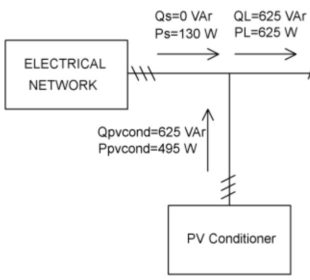

Fig. 7. Power flow with reactive power control

3. Finally, the proposed PV system control will allow a global system of harmonic compensation if the country law requirements are adjusted.

An example of this is shown. The system is connected to a non-linear and unbalanced load composed of three diode rectifiers, and the PV conditioner works under standard conditions (25º C and 1000 W/m^2). Fig. 8 shows the non sinusoidal and unbalanced load current. The PV output *current is shown in Fig. 9, it has an active component that comes from the photovoltaic system and another component without active power provided by the inverter working as a shunt active conditioner. Finally, it is achieved a sinusoidal source current, Fig. 10.*

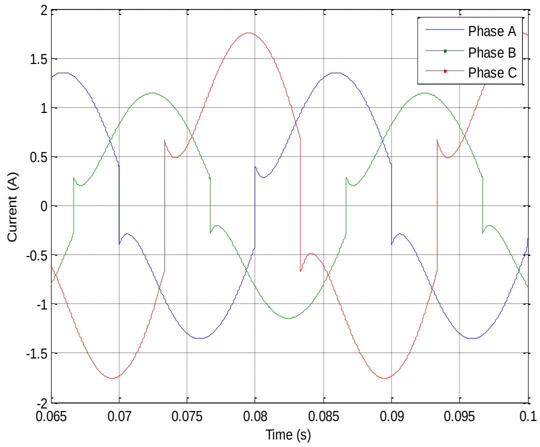

Fig. 8 Load current

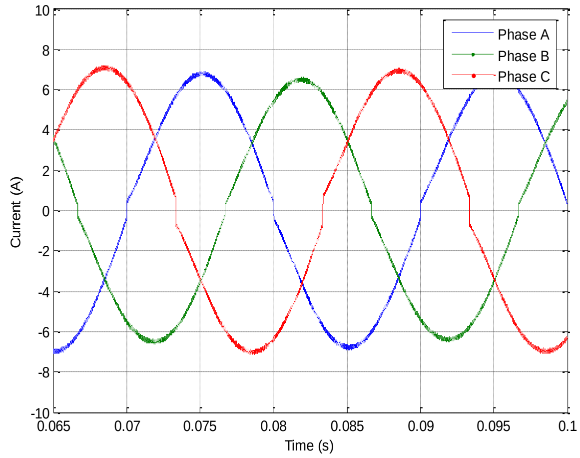

Fig. 9. PV active conditioner output current

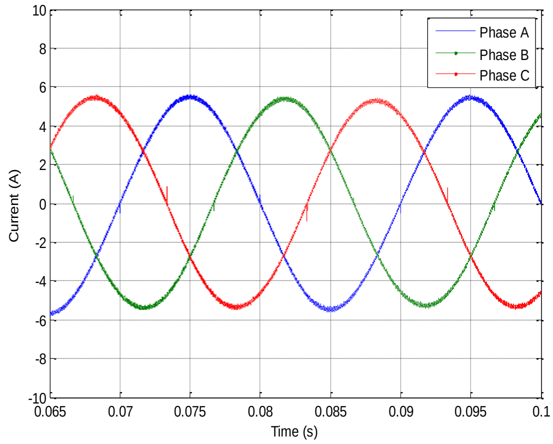

Fig. 10. Source current

The impact of the work could be very positive because with our project it can be saved a stage of power when PV system and active power conditioner will be used in the same point. As it was above mentioned, it would need some changes on the country regulations (for example in Spain) because until now it is not possible that the PV system inject reactive and distortion power to the network, but with the ***power quality advantages*** *that we achieve with this method it could be possible in the near future.*

Proposed Host TA Infrastructure/Installation – Justification (about one page)

The infrastructure that it is necessary to test our grid-connected PV conditioner is: solar cells or a DC programmable source that can simulate a PV array, a DC-DC converter (buck-boost topology) to test the maximum power point algorithms, an inverter to check that it can work as an inverter and as a active power filter with a variety of loads connected to the electrical network. Some partial tests will be possible without all mentioned component.

We have some experience with DC programmable source and inverter control through dSpace acquisition & control board, but we don't still have developed the buck-boost converter and, so *we would like to test our model in one DC-DC converter that can provide the infrastructures of DERri.*

We are interested in the University of Strathclyde's Distribution Network and Protection Laboratory in order to analyze the performance of our model because they are working on distributed generation with a 100 kVA microgrid that can operate grid connected or variously islanded, integrated with a real-time digital network simulator and protection injection laboratory. They also have programmable load banks and various 1/3 - phase inverters.

Another option would be the Austrian Institute of Technology, Österreichisches Forschungs- und Prüfzentrum Arsenal Ges.m.b.H., since they are working in something related to MPP tracking and PV systems, such as conversion efficiency under different generation conditions (DC voltage/power), determination of efficiency curves, maximum and European efficiency, steady state & dynamic MPP-Tracking Efficiency under different PV-array conditions, switch on/off power on DC side, stand-by power consumption on AC side and harmonic analysis according to European Standard EN/IEC 61000-3-2/-3-12, by using Matlab-Simulink as well.

For that, we have a programmable DC switching power supplies that emulates the photovoltaic system, so we can program the characteristics curves of a solar cell. We are designing a DC-DC power converter and we also have the inverter connected to the electrical network with a variety of loads to check the performance of the global system.

Therefore, we would like to test our system in the Distributed Energy Resources Research Infrastructures in order to analyze the performance of it. These objectives could be fulfilled by using the devices of the lab, such as a solar cells or a programmable source that simulates a PV array, a DC-DC converter (buck-boost), an inverter, a variety of loads connected to the electrical network. This way, we can test our different control techniques, such as neuro-fuzzy or regression plane instead of the conventional perturb and observe method, so with this method is achieved better performance. The research team has been using dSpace, an acquisition and control board, to control the inverter. In previous projects, we designed some active filters which include DC/AC converters. For example, we have a Semikron DC/AC converter (with 20kHz IGBTs, 400 Vdc, 480 Vac, 15 Aac) controlled by the PC board. Our new interest is to test the PV system injecting power to the network. We have completed this test in a simulation platform (Matlab-Simulink).

In addition, we are very interested in acquiring new techniques of control and using other power converters and power system modeling. Moreover, once we finish the test, we are going to add a wind system to our original system to study distributed generation, so we can learn about the technology you have in your laboratory.

Synergy with ongoing research (about ½ page)

The research team has wide experience with active power line conditioners. Some national projects have been developed in Spain (DPI2003-01336, DPI2004-03501, DPI2007-62623…).

We are very interested in working together in a European project whenever it is possible. This way, the proposed model can be tested with other controls developed by the host infrastructure in order to check the performance of it.

We are now working on developing the DC-DC converter in order to test our simulation model. Besides, we are developing different control methods so as to track the maximum power point under changeable environmental conditions as well as control strategies to compensate active and reactive power and harmonic compensation by using an inverter as an active power filter. All *of the new controls can be tested with our simulation model.*

Dissemination – Exploitation of results (about ½ page)

The obtained results from the proposed project can be diffused by means of scientific research journals, such as the journals that are included in JCR (Journal Citation Reports), Scopus or similar. Some of the journals can be Energy Conversion, EPE Journal or IET Renewable Power Generation amongst others. Moreover, the results can be made broadly known in International Conferences on Electrical and Electronic Engineering.

Time schedule (about ½ page)

In the first week, the person who could go there will know all the installations as well as the devices in the lab. Besides, she should be able to start to test her own model in the lab to get it ready for the experiments like we have the model here.

In the second week, the first of the test must be developed there and the DC-DC converter must be checked for the different control methods of MPPT.

In the third week, the control strategy of the inverter can be tested for a variety of loads, such as DC loads or AC loads connected to the electrical network.

In the last week, the whole system must be tested in order to prove that the model is working adequately.

Description of the proposing team (as long as needed)

The Electrical Research Group of the University of Huelva researches about electrical power systems, renewable energy, specially photovoltaic energy and wind energy, power quality using passive and active power filters, and distributed generation. We are also interested in control techniques such as PID control, fuzzy logic and neuronal networks. Furthermore, our group has experience in converter and inverter control with dSpace as well as modeling of power converters, filters and photovoltaic systems in Simulink by Matlab.

Aranzazu D. Martin is the person who would go to the installations. She received the degree in Industrial Engineering from the University of Huelva, Spain, in 2008. She did a master in Control Engineering, Electronic Systems and Industrial Computer Science in 2011. Since 2008, she has been collaborating with the Electrical Engineering Department at University of Huelva. She is currently working as a researcher with the FPU scholarship (Formacion de Profesorado Universitario) by the Ministerio de Educacion of Spain. Now, her research interests include renewable energy, distributed electrical generation, power quality, active power filter, fuzzy logic and backstepping controller. Besides, she can speak English fluently because she did courses in England and Ireland. She also worked in Moog Ltd., in Ringaskiddy, Cork, Ireland, which is a electronic company, from June to September of 2011 and there she had to develop computing programs, design and develop filters and working on the assembly and disassembly of machines. In the science week of the University of Huelva, she published "MPP Tracker of a PV System using Sliding Mode Control", "A control algorithm for a three-phase hybrid power filter to balance asymmetrical loads" and "Method to detect and measure transient disturbances based on Artificial Neural networks (ANNs)".

Jesus R. Vazquez received the degree in Electrical Engineering from the University of Seville, Spain. For one year, he was with the electrical department of Nissan Motor Ibérica S.A., Barcelona, Spain. Since 1996, he is with the Electrical Engineering Department at the University of Huelva. Nowadays, he is the head of the Electrical Engineering Department. He teaches Electric Circuits and Electrical Power Quality and his research interests include power quality, active power filters, renewable energy, distributed electrical generation and artificial network applications. In addition of projects above mentioned, some publications in the proposed work area are "Four Active Filter Topologies to Compensate Different Kinds of Distortion Sources" (EPE Journal, 2011), "MPP Tracker of a PV System using Sliding Mode Control with Minimum Transient Response" (International Review on Modelling and Simulations, 2010), "A New Approach For Three-Phase Loads Compensation Based On The Instantaneous Reactive Power Theory" (Electric Power Systems Research, 2008), "Mapping Matrices Vectorial Frame In The Instantaneous Reactive Power Compensation (IET Electronic Power Application, 2007), "Active Power-Line Conditioners" (Springer ed. 2007), "Practical Design of a Three-Phase Active Power-Line Conditioner Controlled By Artificial Neural Networks (IEEE Transactions On Power Delivery, 2005), "Compensation In Nonsinusoidal, Unbalanced Three-Phase Four-Wire Systems With Active Power-Line Conditioner (IEEE Transactions On Power Delivery, 2004) or "Active Power Filter Control Using Neural Network Technologies (IEE Proceedings-Electric Power Applications, 2003). He would coordinate the research team proposed and he could supervise the person who is going to be in the lab.

Reyes S. Herrera was born in Huelva, Spain. She received the Industrial Engineering degree from the University of Seville, Spain, in 1995, and the Ph. D. degree in electrical engineering from the University of Huelva, Spain, in 2007. Currently, she is professor with the Department of Electrical Engineering, University of Huelva. Her research includes electrical power theory, electric power quality and power converter systems. He researched in projects above mentioned and his main publications in last years are "Four Active Filter Topologies to Compensate Different Kinds of Distortion Sources" (EPE Journal, 2011), "Assessment of Voltage Unbalance Definitions in Power Systems" (DYNA, 2012), "Harmonic disturbance identification in electrical systems with capacitor banks" (Electric Power Systems Research, 2012), "Instantaneous Reactive Power Theory – A General Approach to Poly-Phase Systems" (Electric Power Systems Research, 2009), "Instantaneous Reactive Power Theory: a Reference in the Non Linear Loads Compensation" (IEEE Transaction on Industrial Electronic, 2009), "Present Point of View about the Instantaneous Reactive Power Theroy" (IET Electric Power applications, 2009), "New Distortion and Unbalance Indices Based on Power Quality Analyzer Measurements" (IEEE Transaction on Power Delivery, 2009), "A new approach for three-phase loads compensation based on the instantaneous reactive power theory" (Electric Power Systems Research, 2008), "Instantaneous reactive power theory applied to active power filter compensation. Different approaches assessment and experimental results" (IEEE Transaction on Industrial Electronic, 2008), "Mapping matrices versus vectorial frame in the instantaneous reactive power compensation" (IET Electric Power applications, 2007), "Instantaneous reactive power theory: A comparative evaluation of different formulations" (IEEE Transaction on Power Delivery, 2007) or "Distorted and unbalanced systems compensation within instantaneous reactive power framework" (IEEE Transaction on Power Delivery, 2006). She would collaborate in the proposed project in theoretical and practical aspects.