Bruno Exposto, J. G. Pinto, Vítor Monteiro, Delfim Pedrosa, João L. Afonso

“The Impact of Poor Power Quality in Solar Photovoltaic Microgeneration: Technical Problems and Losses of Revenue”

ICEE 2015 | 2nd International Conference on Energy and Environment: "Bringing together Engineering and Economics"

Guimarães Portugal, June. 2015.

Bruno Exposto, J. G. Pinto, Vítor Monteiro, Delfim Pedrosa, João L. Afonso, “The Impact of Poor Power Quality in Solar Photovoltaic Microgeneration: Technical Problems and Losses of Revenue”, ICEE 2015 | 2nd International Conference on Energy and Environment, Guimarães Portugal, June. 2015.

THE IMPACT OF POOR POWER QUALITY IN SOLAR PHOTOVOLTAIC MICROGENERATION: TECHNICAL PROBLEMS AND LOSSES OF REVENUE

Bruno Exposto*, J. G. Pinto, Vítor Monteiro, Delfim Pedrosa, and João L. Afonso
ALGORITMI Research Centre, University of Minho, Portugal

* Corresponding author: bruno.exposto@algoritmi.uminho.pt, ALGORITMI Research Centre, University of Minho Campus de Azurém, 4800-059 Guimarães, Portugal

KEYWORDS
Microgeneration; Solar Photovoltaic Energy; Power Quality.

ABSTRACT
This paper presents a critical and quantitative analysis of the influence of the Power Quality in grid connected solar photovoltaic microgeneration installations. First are introduced the main regulations and legislation related with the solar photovoltaic microgeneration, in Portugal and Europe. Next are presented Power Quality monitoring results obtained from two residential solar photovoltaic installations located in the north of Portugal, and is explained how the Power Quality events affect the operation of these installations. Afterwards, it is described a methodology to estimate the energy production losses and the impact in the revenue caused by the abnormal operation of the electrical installation. This is done by comparing the amount of energy that was injected into the power grid with the theoretical value of energy that could be injected in normal conditions. The performed analysis shows that Power Quality severally affects the solar photovoltaic installations operation. The losses of revenue in the two monitored installations M1 and M2 are estimated in about 27% and 22%, respectively.

INTRODUCTION

The present energy challenges that the world faces are forcing the shift to a new energy paradigm and new energy sources. The problems associated with the use of fossil fuels and nuclear power, as well as the increased energy demand, are the main drivers to expand the use of renewable energy sources. In fact, the European Union (EU) fixed as goal 20% renewable energy share in energy consumption by 2020 (Holmes, 2013). Other countries are pursuing similar goals, for instance, China fixed as objective a share of 15% to the total primary energy in 2020 (Yang et al., 2010). United States has also granted several incentives both in states and in federal level to renewable energy use (Blaabjerg et al., 2011; Jones et al., 2010). Renewable energy sources have a lower environmental impact, and take advantage of natural resources. If during several years the renewable energy sources were not intensively explored to the production of electrical energy (except hydroelectric energy), today’s energetic challenges are forcing the diversification of renewable energy sources. Wind and solar photovoltaic are the most promising renewable energy sources considering that the costs of the wind and photovoltaic systems are lowering consistently each year (Blaabjerg et al., 2011). The incentives for the use of these renewable energy sources, the technology research and the public acceptance towards them, make predictable the massive expansion of these two types of renewable resources.

Solar photovoltaic energy is being explored, both using small solar photovoltaic installations and large solar photovoltaic farms, with the power ranging from a few hundred watts to tens of megawatts. The scope of this paper will be in the residential solar photovoltaic microgeneration. In the households the photovoltaic systems usually have a power that can go from 1 kW up to 10 kW (Blaabjerg et al., 2011).

In Europe, to incentive the photovoltaic microgeneration it was created specific legislation, both at EU level as well as at member states level. The legislation specifies both the monetary incentives, as well as the requisites for the connection to the power grid of these systems (Fidalgo and Fontes, 2012). There are also several technical standards that the equipment must respect in order to guarantee the safety of the operation (Kjaer et al., 2005).

Although exist several international and national standards and legislation that regulates microgeneration systems, there are several Power Quality problems that affect the production of energy in the electrical installations. A solar photovoltaic system integrates a solar panels array and power electronics systems that allow perform the power conversion from the direct current (DC) produced by the solar photovoltaic array to the alternated current (AC) used in the public service power grid. The behavior of theses power electronics systems is affected by the Power Quality levels of the power grid in which they are connected. Also the line characteristics and the vicinity loads or surrounding industrial facilities can have an impact in the energy production of the photovoltaic system. Therefore, in this paper are presented power quality monitoring results obtained in a study performed in two residential photovoltaic installations that illustrate the aforementioned problems, and is done an impact analysis. The paper also discusses the most important power quality problems that affect these monitored installations and their effect on the revenue of the microgeneration installations.

MAIN REGULATORY STANDARDS AND LEGISLATION FOR SOLAR PHOTOVOLTAIC MICROGENERATION

Over the years, motivated by the push that is being made in Portugal and in the EU to increase the renewable energy use, was adopted legislation and standards, that not only incentives the use of renewable energy sources, but also ensures the regulation of the several layers that compose the renewable energy ecosystem. Considering that this paper is focused on the Power Quality and its impact on the solar photovoltaic microgeneration, it will be performed a review of the legislation and standards that are directly related with this issue. The main technical standards that regulate solar photovoltaic microgeneration in Portugal and in the EU are (Kjaer et al., 2005):

- EN 61000-3-2, that establishes the limits for harmonic current emissions;
- EN 50160, that defines the voltage characteristics of electricity supplied by public distribution systems;
- EN 61000, that deals with the electromagnetic compatibility (EMC);
- EN 50438, the standard for microgeneration connected in parallel with the power grid.

In terms of legislation and regulations associated with the solar photovoltaic microgeneration, in Portugal the main are (Monteiro, 2014; Costa, 2010):

- The Quality and Service Regulation, that regulates the quality of the electrical energy supply service;
- Decree-Law no. 215-B/2012, that transposes the Directive no. 2009/72/CE to the Portuguese legislation and consolidates all the legislation related with photovoltaic energy generation;

It must be referred that there is a large number of standards, legislation and regulations that are related with solar photovoltaic installations and microgeneration. Nevertheless, the aforementioned legislation and regulations are the ones directly linked with the problematic that is discussed in this paper.

POWER QUALITY MONITORING RESULTS AND DISCUSSION

The monitorings were performed during one week, with the equipment *Dranetz PowerGuide 4400*, which is a Power Quality analyzer, placed in the connection of the solar photovoltaic inverter with the power grid. It must be referred that the solar photovoltaic inverter is the equipment responsible for injecting the energy produced by the solar photovoltaic panels, into the power grid. The monitoring equipment is in compliance with Class A of IEC 61000-4-30 standard. Also the equipment date and time is synchronized with the Astronomical Observatory of Lisbon Time Server, entity responsible by the legal hour in Portugal.

In order to develop the framework in which this study was conducted, will be performed a characterization of the solar photovoltaic installations. The power quality monitorings were performed in two residential solar photovoltaic installations placed in the north of Portugal. The first monitoring (M1) was performed in September of 2013 and the second monitoring (M2), was performed in November of 2013. All the monitorings were performed during one week, insuring that enough data was collected to evaluate the compliance of the standard EN 50160. The solar photovoltaic installations have a rated power of 4.3 kW for M1 and 3.6 kW for M2. Is important to refer that both the solar photovoltaic installations were inspected by certified technicians and did not presented any hardware problems that could compromise the energy production and injection into the grid, therefore, any problem that could exist can be linked only to other factors.

Power Quality Results

The first monitoring (M1) results show that were detected 46,530 Power Quality events. The main events that can pose severe problems to the normal operation of the solar photovoltaic inverter are sags (a reduction in voltage magnitude, for a duration of time that can go from 0.5 cycles to one minute), swells (an increase in voltage magnitude, for a duration of time that can go from 0.5 cycles to one minute) and voltage transients (short time voltage magnitude disturbances). This happens because the inverter is constantly monitoring the grid voltage, and if is detected an event (sag or swell) that is outside the presets defined by the manufacturer, according to international standards, it can trigger a disconnection of the equipment in order to protect itself. Aside an overcurrent, or a frequency variation, the aforementioned problems are the ones that more commonly can disturb the operation of the solar photovoltaic inverter. The other detected Power Quality problems can also affect the operation of the solar photovoltaic inverter, nevertheless it is difficult to evaluate the precise extension of their impact in the operation of the solar photovoltaic inverter.

A premise that must be remembered is that the solar photovoltaic inverter operates during the day or, more specifically, when is enough solar irradiation that allow the energy injection into the power grid. So, in terms of monitoring results only will be considered Power Quality events that occur during the day (from 08h00 to 20h00).

Given this in Figure 1 is possible to see the voltage sags detected during the monitoring M1 and retrieved during one week. The figure shows the distribution of the voltage sags detected, over one day. This is important to define in which hour of the day is more common the occurrence of this Power Quality problem. In this specific case is possible to see that the majority of the voltage sags occur during the period between 20h00 and 23h00, therefore the impact on the operation of the solar photovoltaic inverter operation is residual or null.

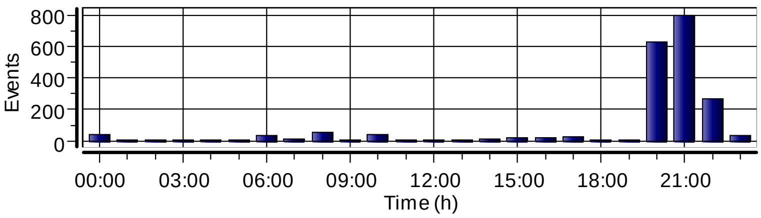

Figure 1: Voltage sags detected during the monitoring M1, distributed over a 24-hour time span.

On the other hand, Figure 2 shows that the majority of the voltage swells, occurs during the period of time when the solar photovoltaic inverter is operating. The peak number of the detected events are at 17h00. This affects severely the injection of energy into the power grid and ultimately the revenue of the solar photovoltaic installation, because triggers constantly the disconnection of the solar photovoltaic inverter. Although this, it must be referred that these voltage swells can be motivated not only poor Power Quality, but also by the fact that the solar photovoltaic installation is in a distant location from the distribution transformer. If does not exist local consumption of energy, the injection of energy can elevate the voltage magnitude to values that can trigger the disconnection of the solar photovoltaic inverter.

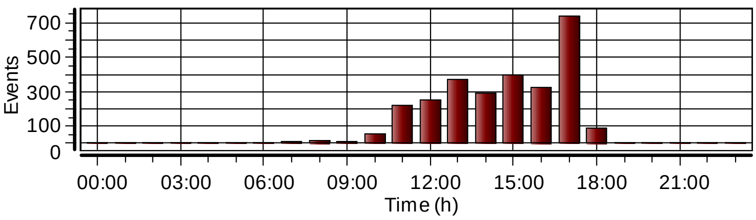

Figure 2: Voltage swells detected during the monitoring M1, distributed over a 24-hour time span.

In what concerns to the detected voltage transients, Figure 3 shows that the majority of the detections of voltage transients occurred during the day, more specifically during the period in which the solar photovoltaic inverter was operating. Has in the previous case, the peak of detected events is at 17h00. These transients can trigger the disconnection of the solar photovoltaic inverter, or at least, disturb its operation.

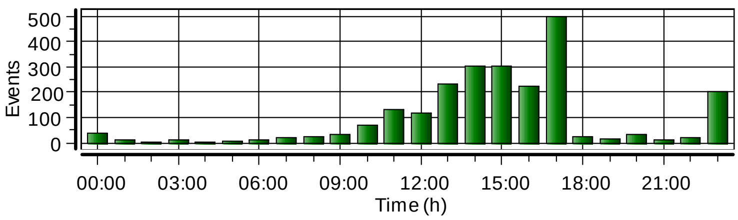

Figure 3: Voltage transients detected during the monitoring M1, distributed over a 24-hour time span.

In order to illustrate how the aforementioned Power Quality events can cause problems to the operation of the solar photovoltaic inverter, in Figure 4, is possible to see the evolution of the grid voltage RMS value during the period of one day, and the power injected by the inverter in the power grid. If we analyze the figure, is possible to see that around 12h30 the injected power was above 2 kW. Nevertheless after some minutes later, the average power lowers to nearly zero, until that at 13h50 reaches again 0.5 kW. Although the average injected power reaches such values, the data of the solar irradiation, for that period of time and monitoring site, obtained through the MACC-RAD service ("MACC-RAD - Monitoring Atmosphere Composition & Climate, Radiation") (Figure 8), show that the average solar irradiation during that period of time did not reach such low values that justified stopping the injection of energy into the electrical power grid. Also, as can be seen, the period of time in which this phenomena occurs is relatively large, compromising the daily revenue of the solar photovoltaic installation. It must be referred that whereas the detected Power Quality problems, the parameters of the voltage during the monitoring period are in accordance with the defined standards and regulations. In fact, most of the loads can be feed with these voltages without having any problem in its operation. The question is that, as can be seen, the solar photovoltaic inverters can be severely affected by these problems.

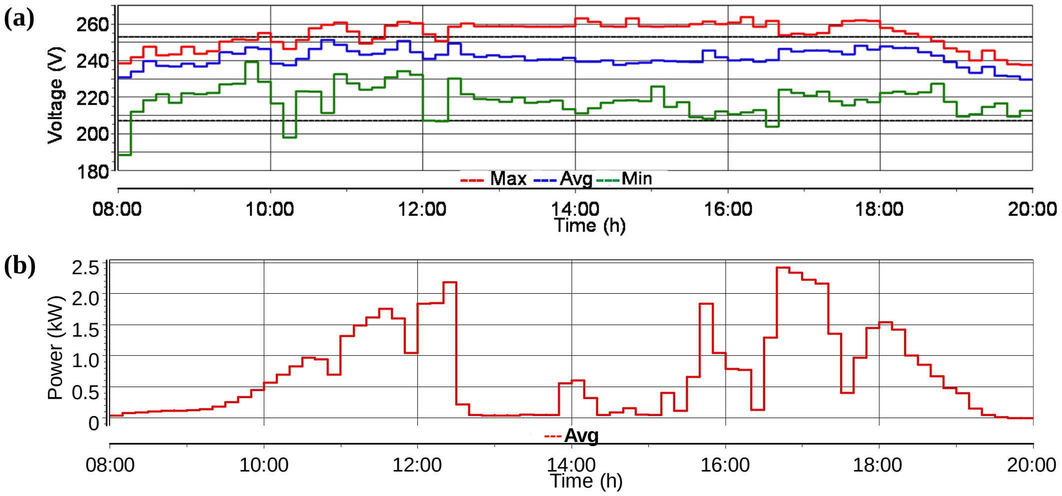

Figure 4: Behavior of the solar photovoltaic inverter operation during monitoring M1: (a) Maximum grid voltage, average grid voltage and minimum grid voltage; (b) Average injected power.

The second monitoring (M2) shows a similar scenario, motivated by another Power Quality problem. In Figure 5 is possible to see that the majority of voltage sags occurs during the day, more specifically during the afternoon. The peak value of detections is reached around 18h00. In this monitoring, whereas what happened in monitoring M1, were not detected any voltage swells.

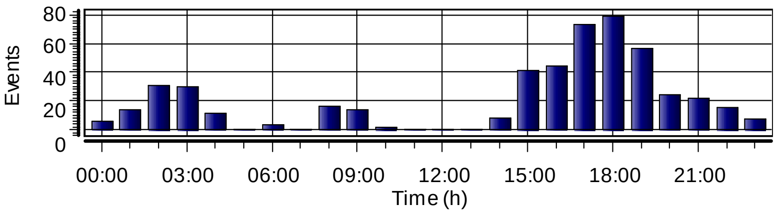

Figure 5: Voltage sags detected during the monitoring M2, distributed over a 24-hour time span.

The number of voltage transients (Figure 6) detected in this monitoring is very low. Aside this, the largest share of detections of this phenomena occurred during the period of the night. Therefore, it is possible to assume that this Power Quality problem did not affect significantly the operation of the solar photovoltaic inverter during the monitoring period.

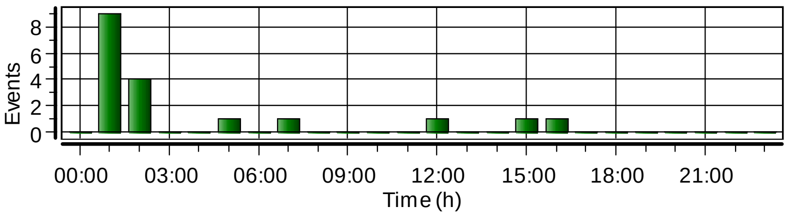

Figure 6: Voltage transients detected during the monitoring M2, distributed over a 24-hour time span.

In Figure 7 is illustrated how the voltage sags affect the normal operation of the solar photovoltaic inverter. Analyzing this figure, it is possible to see that during the morning, until 10h50, the average injected power is nearly zero. Once more, the data of the solar irradiation for that period of time and monitoring site, obtained through the MACC-RAD service, shows that the average solar irradiation during that period of time did not reach such low values that justified stopping the injection of energy into the power grid (Figure 8). Based on the data plotted in Figure 7, it is possible to see that during the same day this phenomenon occurs also at 16h30. It must be referred that, once more, the parameters of the voltage during the monitoring period are in accordance with the defined standards and regulations, but the solar photovoltaic inverter is affected by these problems.

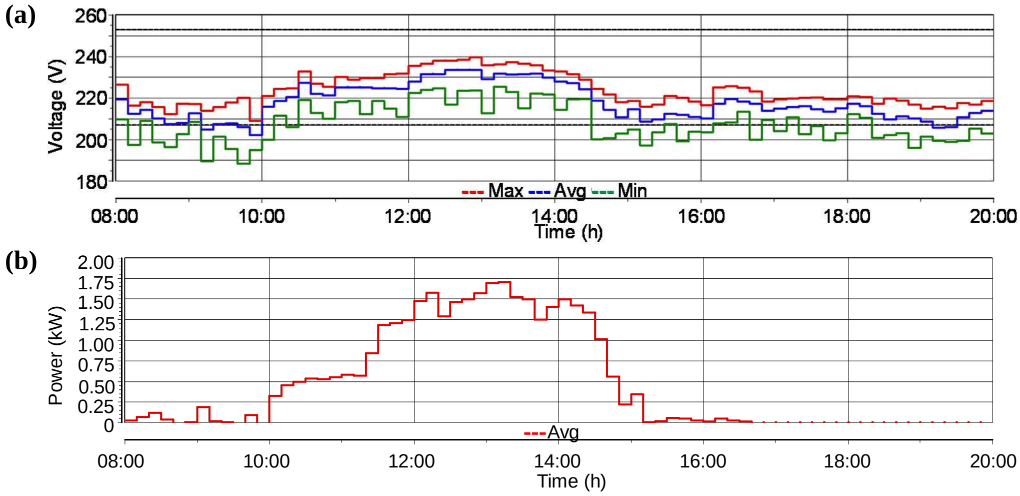

Figure 7: Behavior of the solar photovoltaic inverter operation during monitoring M2: (a) Maximum grid voltage, average grid voltage and minimum grid voltage; (b) Average injected power.

Analysis of the Global Irradiation Data and Average Injected Power

If we compare (in Figure 8(a) and (b)) the average injected power (P_{AVG}), obtained during the two monitorings, with the data of the global irradiation on horizontal plane at ground level (GHI), for the same period of time in the monitoring site, is possible to claim with a high degree of confidence that the fact of sometimes the average injected power be nearly zero is not related with any shadowing effect or sudden irradiation diminishing, and this is visible for both cases.

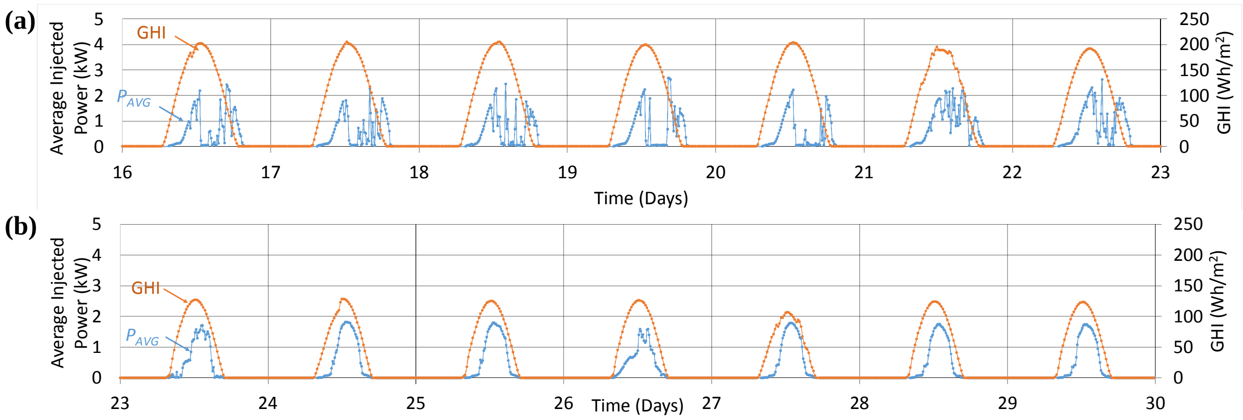

Figure 8: Average injected power *vs* global irradiation on horizontal plane at ground level: (a) During monitoring M1; (b) During monitoring M2.

The average injected power is calculated having a 10 minutes window and the GHI is calculated having a 15 minutes window, nevertheless, is considered that the influence of the differences between the data is not such that can lead to another conclusions than that the Power Quality problems are affecting the injection of energy into the power grid. Considering the data plotted in Figure 8 is possible to estimate the losses of revenue in both of the solar photovoltaic installations. To do this, is necessary make some preliminary considerations and some calculations. The total energy injected (E_T) into the power grid by the solar photovoltaic installation, considering P_{AVG} can be expressed as:

$$E_T = \int P_{AVG}\, dt \,. \qquad (1)$$

Taking in account that the installed power of the installation in M1 is 4.3 kW and 3.6 kW in M2 and that power is defined for an average solar irradiance of 1000 W/m^2, is possible to establish the following equation (2) that relates GHI and the expected energy (E_P) that can be injected into the power grid for the period of time of analysis.

$$E_P = \int \frac{GHI}{\Delta t} K_i \, dt \,, \qquad (2)$$

where Δt is the period of the GHI average, that in this case is 10 minutes, and K_i is a constant that includes the efficiency of the whole solar photovoltaic installation and the area of the solar photovoltaic panels. Using the two aforementioned equations, and establishing the value for K_i = 0.7, is possible to calculate the estimated energy that in normal conditions could be injected into the grid, and compare it with the energy that actually was injected. Given this, the values obtained, for the monitoring week, were:

Table 1: Results of the Expected Energy and Real Injected Energy into the Power Grid, for each Monitoring

	E_T (kWh)	E_P (kWh)	Average Losses (%)
Monitoring M1	175.55	127.43	27.41
Monitoring M2	54.82	42.90	21.74

The values of Table 1 allow to say that that the Power Quality problems severely affect the operation of the solar photovoltaic installation. Furthermore, given the aforementioned values, if the average losses are constant over the weeks, the revenue of the solar photovoltaic installation can be severely affected, jeopardizing the payback time and the future revenue of the owner. In an optimistic scenario, the losses will be inferior or equal to the values shown in Table 1. Nevertheless, even with this scenario, at least, the payback time is delayed. In a more pessimistic scenario, the losses can be higher than the reported values, and this can effectively enlarge the payback time to values that are higher than the lifetime period of the solar photovoltaic installation. Alongside with this, the detected Power Quality problems can also damage the solar photovoltaic installation equipment, adding more costs.

CONCLUSIONS AND FURTHER RESEARCH

In this paper is done a discussions of the impact of poor Power Quality in solar photovoltaic microgeneration, using data collected in two solar photovoltaic installations located in the north of Portugal. The paper begins with a review of the main regulations and legislation, both national and European. Then are presented several Power Quality monitoring results and are shown some real case examples of how poor Power Quality can affect the energy injection into the power grid. Afterwards is compared the global irradiation data and average injected power of each solar photovoltaic installation during the period of monitoring. Considering the data obtained and the analysis of that data it is possible to say that poor Power Quality affects severally the solar photovoltaic installations. Furthermore, the losses of revenue can go up to 27%, which is a high value, compromising the expected revenue and the payback time. Given this, one possible preventive measure that can be adopted is to include in the calculations of the payback time and average revenue the characteristics of the site where the solar photovoltaic installation will be located and the Power Quality indexes associated with that site. For future work, it will be monitored more solar photovoltaic microgeneration installations, measuring at the same time the onsite solar irradiance in order to exclude any confounders. Also, the installations will be monitored for a longer period of time, with the solar photovoltaic inverter connected to the power grid and disconnected.

ACKNOWLEDGMENT

This work has been supported by FCT - Fundação para a Ciência e Tecnologia within scope of the project: PEst-UID/CEC/00319/2013. B Exposto was supported by the doctoral scholarship SFRH/BD/87999/2012 granted by FCT.

REFERENCES

Blaabjerg, F.; Iov, F.; Terekes, T.; Teodorescu, R. and Ma, K. 2011. "Power Electronics – Key Technology for Renewable Energy Systems – Status and Future". In *Power Electronics, Drive Systems and Technologies Conf. (PEDSTC), 2011 2nd*, 445–466.

Costa, M. 2010. Energia Fotovoltaica, Manual sobre Tecnologias, Projecto e Instalação.

Fidalgo, J. N. and Fontes, D. B. M. M. 2012. Fostering microgeneration in power systems: The effect of legislative limitations . *Electric Power Systems Research , 84*(1), 181 – 186.

Holmes, J. (2013). A More Perfect Union: Energy Systems Integration Studies from Europe. *Power and Energy Magazine, IEEE, 11*(5), 36–45.

Jones, A. E., Irwin, M. & Izadian, A. 2010. Incentives for microgeneration development in the U.S. and Europe. In *IECON 2010 - 36th Annual Conference on IEEE Industrial Electronics Society* 3018–3021.

Kjaer, S. B., Pedersen, J. K. & Blaabjerg, F. 2005. A review of single-phase grid-connected inverters for photovoltaic modules. *Industry Applications, IEEE Transactions on*, *41*(5), 1292–1306.

Liserre, M.; Sauter, T. and Hung, J. Y. 2010. "Future Energy Systems: Integrating Renewable Energy Sources into the Smart Power Grid Through Industrial Electronics". *Industrial Electronics Magazine, IEEE*, *4*(1), 18–37.

MACC-RAD - Monitoring Atmosphere Composition & Climate, Radiation. Retrieved March 18, 2015, from http://www.soda-pro.com/web-services/radiation/macc-rad.

Monteiro, J. A. M. 2014. *Produção Fotovoltaica: Legislação, tarifas, tecnologia necessária e viabilidade económica para a produção numa perspetiva de chave na mão.*

Yang, X.; Song, Y.; Wang, G. and Wang, W. 2010. "A Comprehensive Review on the Development of Sustainable Energy Strategy and Implementation in China". *Sustainable Energy, IEEE Transactions on*, *1*(2), 57–65.