**Introduction**

Historically, the energy that feeds most of the world is produced by fossil fuel sources, that is, oil, coal, and gas. A major problem that this kind of energy presents is that those are non-renewable energy sources. Another large drawback of fuel energy is the environmental issue. Fossil sources are known for releasing byproducts that pollute the environment around the center of production of electric energy.

An alternative for these forms of energy production is renewable, clean energy sources, such as wind, hydroelectric, or photovoltaic energy. Mainly due to their ecological appeal, but also because of the necessity of diversification of the electric generation sources, these alternate energy sources are gaining space in market.

Research, development, and applications have focused on these renewable sources that are being used more and more in isolated locations, residences, and great renewable generation facilities that are built to generate large amounts of electric energy from wind generators or photovoltaic panels.

Although hydroelectricity accounted for nearly 80 percent of the Brazil’s electricity generation in 2010, the government has been trying to diversify Brazil’s electricity generation fuel mix and reduce its reliance on hydropower to mitigate the risk of power shortages during times of severe drought.

Photovoltaic generation has presented itself in the spotlight in this context because of the large availability of this energy source and due to the aspects aforementioned.

Studies in the field of interconnection of small energy sources in the electric grid date from as early as 1970 in Brazil. Since then, several researches have been conducted addressing the concept of distributed generation (DG), a system in which an energy source, typically, a renewable one, injects power directly in the electric grid.

The connection of photovoltaic systems to the electric grid in residential applications is becoming a significant growing segment of the market of renewable energy sources. This operation has become regulated in Brazil since the publication of ANEEL regulation nº 482/2012, helping spread this kind of application.

Since the energy generated by a photovoltaic module is continuous and, usually, at a very low voltage (approximately 30 V), it is necessary to convert this energy in a way that it is compatible with grid characteristics (usually 220 Vrms alternated at 60 Hz).

Usually, to make the interface between the electric grid and the photovoltaic generator, power converters based on PWM (Pulse Width Modulation) are used. These converters demand the utilization of a low-pass filter on its output. Two power converters that are generally used for photovoltaic applications are string inverters and micro-inverters, and they differ because of the power processed, how many panels can be connected to them, the way they perform the maximum power point tracking (MPPT), among other characteristics.

Micro-inverter

One solution proposed to process photovoltaic energy is the micro-inverter. Since it is capable of connect a single module to the electric grid, this equipment brings some advantages over other solutions. For instance, the photovoltaic system has a modularity characteristic. Other advantage presented by a micro-inverter is the possibility of extract the maximum power point of each individual module, overcoming problems of shadowing that may cause a much larger loss of power in string systems.

A micro-inverter is a device that is capable of converting the continuous current (dc energy) generated by a single photovoltaic module into alternated current (ac energy) compatible with the electric grid energy. Additionally, two or more micro-inverter´s outputs can be connected in parallel so that the energy injected into the grid can be increased, assuring the modularity characteristic of this type of converter.

The main difference between micro-inverters and string inverters is that this last device is designed to convert the energy from a whole string of photovoltaic modules connected in series or parallel. Although string inverters are usually less expensive than micro-inverters for the same amount of energy generated and demand low-pass filters with a wider pass band, making its control easier to design, micro-inverters present some advantages when compared to string inverters, such as:

1. Cost of installation flexible and depending on the amount of energy intended to be generated;
2. Modularity – Ease of expansion due to the fact that photovoltaic modules work individually;
3. Individual maintenance– no need to disconnect more than one module when it presents a flaw.
4. Efficiency – as each module operates individually, the MPP is also individual, which reduces losses caused by, for instance, shadowing problems.

A static gain between 10 and 20 must be provided by a micro-inverter since the output voltage of a photovoltaic module is significantly lower than the peak voltage of the electric grid. That characteristic can be achieved using a single-stage or a double-stage micro-inverter.

[INSERT FIGURE HERE]

In the micro-inverters of the last case, the first stage, dc-dc conversion, presents high gain in order to elevate the voltage from a low dc voltage, usually around 25~30 V, to a value above the peak voltage of the grid voltage, as well as track the point of maximum power of the module.

The second stage is the conversion of the dc voltage to ac, grid compatible voltage so that the energy generated by the photovoltaic module is delivered to the electric grid in conformity to the electric company regulations.

Regulations

In Brazil, the regulating resolution 482/2012 of ANEEL regulates all applications involving interconnection of micro-generation and the electric grid characterizing distributed generation. This regulation defines the range of power in which a generator is characterized as distribution generation, as well as the procedure of how the energy injected to the grid must be accounted for the owner of the generator installation.

In relation to the regulations that dictates the minimum criteria to realize the grid connection, ANEEL specifies that the generator unit must adequate to the regulations imposed by PRODIST (procedure of distribution of electric energy into the national electric system), the Brazilian regulations and, in some cases, the international regulations.

PRODIST is a set of documents, divided in ten (10) modules, regulating and standardize all activities related to the distributing systems in Brazil. Each of its module deals with a specific part of the regulations imposed to all parties involved with an electric energy distribution grid.

To the matter of this dissertation, module 8 is the most relevant. Module 8 of PRODIST deals with the minimum requirements related to the quality of the electric energy that will be delivered by the company responsible by the electric grid. This module states that the total voltage distortion (TVD), given by EQ. XXX, in systems that operate with a voltage under 1 kV must have a maximum value of 10%, respecting limits of odd, even and multiple of three harmonics. These limits are shown in TABLE III.

|  |  |
| --- | --- |
| Harmonic | Limit |
| Total Voltage Distortion |  |
| Non-multiple of 3 Even |  |
| Non-multiple of 3 Odd |  |
| Multiple of 3 |  |

Module 8 of PRODIST also determines the maximum frequency variation acceptable under which the system must operate normally. It states that (a) the frequency of the grid must be within a range of 59.9 Hz and 60.1 Hz and (b) values of frequency below 59.5 Hz and above 60.5 Hz cannot last more than thirty seconds.

If those requirements are met, then the micro-inverters connected to the grid must obey a series of quality requirements for the current harmonics that is injected to the grid.

NBR 16149/2013 estipulate the limits the harmonic injection into the grid to photovoltaic systems. These limits are expressed in TABLE III.

|  |  |
| --- | --- |
| Harmonic | Limit |
| Odds | |
| 3a a 9a |  |
| 11a a 15a |  |
| 17a a 21a |  |
| 23a a 33a |  |
| Even | |
| 2a a 8a |  |
| 10a a 32a |  |

NBR 16149/2013 does not differ harmonics of the grid itself from harmonics from commutation of the converter. Therefore, in order to meet the limits of distortion established, the output filter implemented in the micro-inverter output must attenuate both harmonics: Harmonics caused by commutation of the converter as well as harmonics reflected from the grid voltage itself.

Filter in the output of the inverter is implemented to diminish harmonics multiple of commutation frequency.

To help mitigate harmonics on the fundamental frequency and its multiples, an adequate control strategy must be implemented to compensate the current that is injected into the grid.

Many control techniques have been implemented with the goal of optimizing the form of the current that is injected into the grid. Some are simple and easy to implement. Others are more complex and demand more processing power of the microcontroller used.

OBJECTIVES

The theme of this dissertation is, therefore, to implement and compare some of the techniques most used in the control of the current injected in the electric grid by a micro-inverter connected designed to be installed with a photovoltaic module. Thus, the main objective of this work consist of:

* To compare different current control techniques in a 250 Watts photovoltaic micro-inverter.

The specific objectives to be achieved in this dissertation are:

* To study the proposed control techniques to control the current injected in the grid;
* To implement each of these techniques digitally in a micro-controller;
* To test the digitally implemented control techniques in a Hardware in the Loop device in order to validate the control laws;
* To obtain experimental results showing the current’s THD and the system’s Power Factor of the micro-inverter with each control technique;
* To obtain experimental results showing the dynamic responses of each of the control techniques;

DISSERTATION STRUCTURE

This dissertation is formed by FFFFFF chapters, FFFFFF attachments, and FFFFF appendices.

Chapter 1 – Introduction explains the motivation of the chosen subject for this work. It also covers some basics of the operation of power converters and micro-inverters to photovoltaic applications. The regulations for the operation of micro-inverters connected to the grid are also briefly discussed in this chapter.

Chapter 2 – Blablabla

Chapter 3 – Blablabla

Chapter 4 – Blablabla