Single-phase single-stage bidirectional power converter for active and non-active power management

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Abstract

Abstract goes here

Dedication

To mum and dad

Declaration

I declare that..

Acknowledgements

I want to thank...

Contents

Chapter 1

Introduction

The majority of human activities require some sort of energy; electricity is one of the most used types. Throughout history several electricity generation and storage methods had been studied. However, with the upsurge of fossil fuels in the 20th century, generation methods such as internal combustion motors or combined cycle power plants became a solid base for the development of the electrical industry. Yet, fossil fuel consumption generates greenhouse effect gasses which cause harm to the environment. Also, fossil fuels are non-renewable sources of energy which means that the reserves are decreasing year after year. Because of that, there is a need of other type of sources that can ensure cleanliness and availability.

In the past few decades exhaustive research works have been made in order to take advantage of renewable energy sources such as wind, water or the sun as explained in [1] and [2]. Photovoltaic power extraction is one of the most popular and promising methods. Photovoltaic energy is clean, renewable, infinite and noiseless. Another important aspect is that the energy obtained by photovoltaic means can be easily converted and injected into the electrical grid through switching power converters. The importance of power sources that can be converted into electricity, lies in the easiness of transportation and managing of this type of energy.

The popularity of Photovoltaic Systems (PVS) in developed countries has increased in the last decade due to the decrease in the price of photovoltaic modules; it has dropped from $3.5 USD/Wp to $1 USD/Wp. Another reason for the popularity of PVS are the government policies for providing the feed-in tariff [pandey2015]. A great portion of the installed PVS is in rooftops as part of what is called Distributed Generation (DG).

Distributed Generation is becoming more important nowadays and with that, several challenges have emerged. There are certain requirements that must be satisfied in order to connect a DG system to the mains. In the case of Mexico, these requirements are stated by the Energy Regulation Commission (abbreviated to CRE in spanish) [CRE2011].

Although the exploration of new energy sources mitigates in some way the energy deficiencies, another issue that has to be solved is the way in how the energy is distributed and consumed. The existence of power quality problems among transmission and distribution networks can be addressed in both ways: from the power

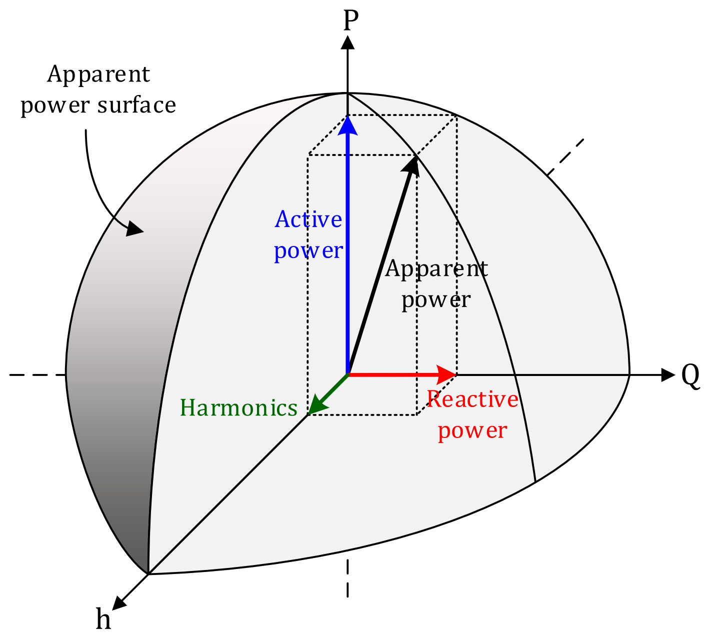

Figure 1.1. Power limits for power converters.

supply companies and from the consumers point of view. The first one has the responsibility of providing energy with an acceptable quality and the latter is intended to consume it in a proper way.

Since its origins, electrical grids have had inherent problems caused by load variations, climate adversities, nonactive loads, among others. To overcome this issues, engineers have proposed solutions adequate to the specific problems. During the first epoch of electrical industry, passive solutions were used. Those consist in the shunt or series interconnection of passive elements to the grid in order to minimize the impact of such problems. With the incorporation of nonlinear loads to the grid, a new set of solutions was needed, and even though passive solutions can be used to mitigate the effect of nonlinear loads connected to the grid, this type of solution has its limitations. For that reason, a new kind of solutions based on switching power converters emerged. The purpose of these compensators is to provide the grid with the power needed to overcome energy deficiencies [3].

IEEE 1547 and UL1741 standards stipulate that *'The Distributed Resources shall not actively regulate the voltage at the PCC'*. However, as noted in [liu2008], photovoltaic inverters can manage a certain amount of non-active power (reactive power and harmonic currents). As shown in Fig. 1.1, the inverter has a maximum apparent power (S); the shadowed volume shows the possible combinations of active and nonactive power The passive elements that accompany the switching devices determine such power rating.

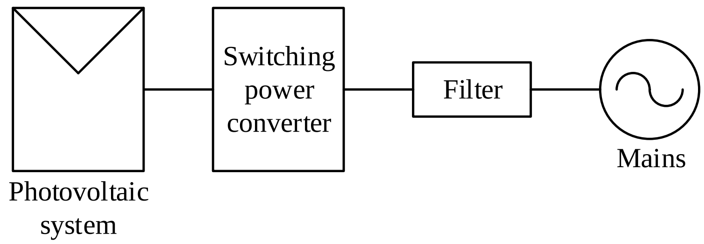

Figure 1.2. Typical scheme for PVPS integration with the mains.

1.1 Background

In this section a description on the application of power converters for power management is done. First, it is described how power converters are utilized for active power injection, specifically in Photovoltaic Power Systems (PVPS). A review of the most commonly used topologies is carried out. Consequently, it is described how modern solutions for power factor correction include the use of power electronics converters. After that, a description of different converter topologies for dc micreogrids power management is presented. Finally, some approaches of how this two features are incorporated into a single device have been carried out. Since the majority of PVPS are installed in residential building rooftops, an emphasis in single phase systems will be done.

1.1.1 Power converters for photovoltaic power injection

Due to the nature of PVPS, a need of power conversion exists in order to achieve grid integration. Grid-connected systems have become more popular in recent years because they do not need battery backup systems [4]. Figure 1.2 shows a typical scheme of PVPS integration with the electrical power grid. This converter topologies must convert a dc voltage into an ac voltage with the frequency and phase characteristics of those in the power mains. Several configurations have been proposed in the literature [5]. This kind of power converters can be divided into two groups: the isolated type and the non-isolated type.

Isolated type converters

As described in [6] there are two sorts of isolation for PVPS inverters: frequency line transformer and high frequency transformer. Both can be used for voltage amplification, however high frequency transformer achieves a higher power density. On the other hand, as pointed in [7] frequency line transformers block out the DC current component helping to achieve higher efficiency when the input voltage is in the low range. Figure 1.3 shows two main configurations for isolated inverters applied to PVPS.

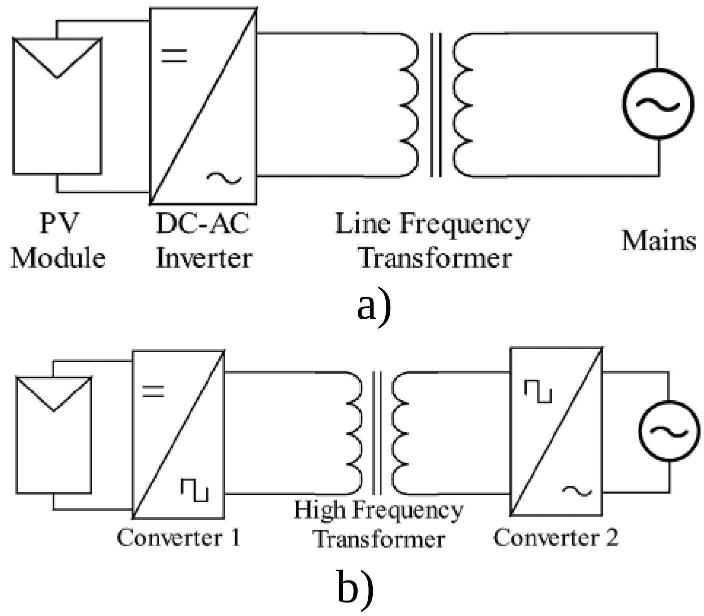

Figure 1.3. a)Low Frequency Transformer b)High Frequency Transformer.

Non-isolated type converters

Photovoltaic Power Systems can be integrated to the power grid through non-isolated or transformerless converters. An abundant number of topologies are used for such task. Figure 1.4 shows the most commonly used topologies for PVPS grid-tie. Transformeless topologies are usually more compact than its isolated counterparts; this mean that they are smaller and lighter. Also transformerless single-stage inverters are known for achieving higher efficiency levels.

Figure 1.4 a) contains the Full Bridge inverter topology. It consist of four transistors that switch in a way that an ac voltage is obtained in its output. Several modulations techniques had been proposed to achieve these commutation states. One of the most used is the Sinusoidal Pulse Width Modulation presented in [8].

As described in [9] approaches have been proposed in order to improve the Full Bridge (H4) inverter. The main aim of this improvements is to decouple dc capacitor with the coupling inductance [10]. This helps to rise efficiency levels up to 99 % like the obtained by Heribert Schmidt in 2009 [11]. The H5, H6 and HERIC topologies are presented in Figure 1.4 b) to d).

Control strategies for active power injection

Converters for active power injection from a PVPS must fulfill some grid requirements. In order to accomplish that task, a control scheme must be established; a variety of control schemes have been adopted.

A majority of applications use linear controllers. In [12] linear controllers are applied in the dq reference frame.

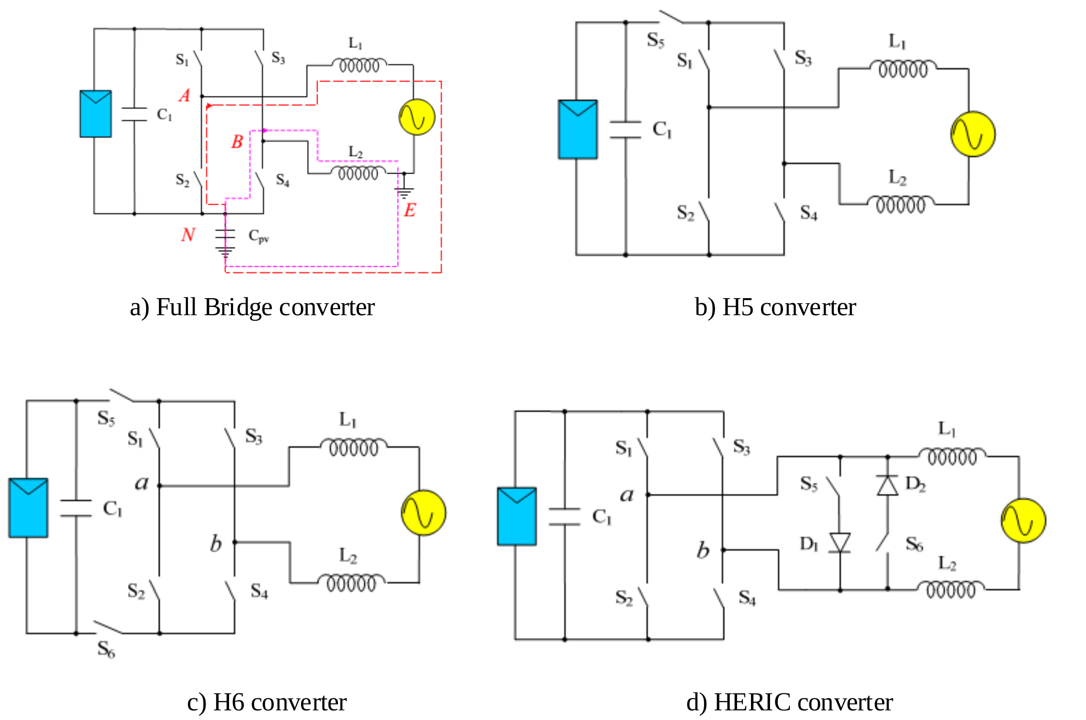

Figure 1.4. a)Full bridge converter b) H5 converter c) H6 converter d) HERIC converter

As well, some nonlinear strategies are used such as passivity-based control, sliding mode controllers, predictive control, et. al. Also, some control schemes based on artificial intelligence.

1.1.2 Power converters for power factor correction

Power Factor (PF) is a way of measuring the amount of active power that is effectively converted into useful work. There are at least two ways for obtaining such factor. First, there is what in literature is called the Displacement Power Factor (DPF). It considers the displacement angle ϕ between the voltage and the current. It is defined as

$$DPF = cos\phi. \tag{1.1}$$

A more accurate way to measure the PF is to consider the quotient between the active power P and the apparent power S.

$$PF = \frac{P}{S} = \frac{P}{V_{rms}I_{rms}} \tag{1.2}$$

The reason is that DPF considers ideal sinusoidal waveforms of voltage and current. However, by calculating the *rms* value of the voltage and current waveforms, both active and non-active power [1] are taken into account. A low PF means that the supplying company has to produce more apparent power to produce the same amount of work. Thus, a penalization fee is charged in order to compensate such operation costs. For that reason, industries around the world have implemented solutions in order to rise PF; it is called Power Factor Correction (PFC).

Power electronics switching converters have become popular in industrial applications for power quality solutions; specially when solutions based on passive elements result insufficient. Power factor correction is a typical application in which a power converter can be used.

Static Synchronous Compensator

The Static Synchronous Compensator (STATCOM) is an idea conceived in power transmission level. However, the idea has been taken into distribution level and renamed as D-STATCOM [13]. A STATCOM provides the amount of reactive power such that the mains only have to supply active power to the loads. The STATCOM is the static counterpart of a rotating compensator. It can be series or shunt connected as shown in Figure 1.5. In 2005 Dixon et. al. stated the state of the art in reactive power compensation technologies [3]. Notwithstanding, ten years passed and proposals have emerged. Different inverter topologies have emerged [14, 15], new theory have been developed [16] and control strategies have been applied into these type of solutions [17].

[1] Formerly called reactive power. The term *non-active power* was recently adopted to include reactive power caused by signals at fundamental frequency and all the multiples of it.

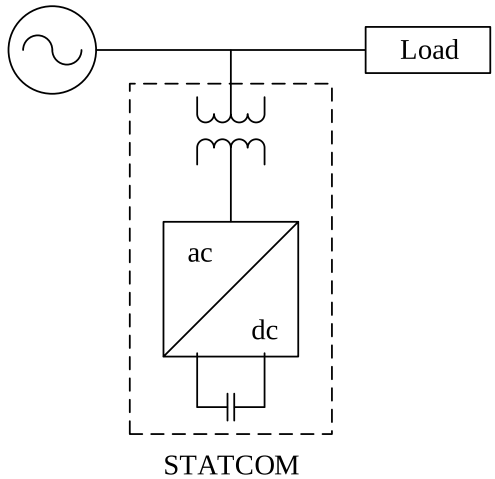

Figure 1.5. STATCOM connection to the mains.

Active Power Filter

An Active Power Filter (APF) is a device that, depending whether if it is series connected or shunt connected, it is able to compensate voltage or current harmonic components, respectively [18]. The APF connection is presented in Figure 1.6. Energy is stored in the dc capacitor and, when required, harmonic components are supplied to the electrical grid.

1.1.3 Power converters for dc microgrids

1.1.4 Power converters for active and non-active power management

Taking advantage of the power inverter topologies used for photovoltaic power injection, approaches have been made in order to extend the capabilities of such devices [19, 20]

1.2 Problem statement

With the integration of distributed generation from renewable sources a leads to an scheme as the one shown on Fig. 1.7 where two possible sources of energy may be available. Typically, the availability of renewable sources such as photovoltaic power generation is intermittent along the day. There is a need for a power converter that can be able to handle power in two directions. When the distributed generation is in operation, power is supplied to the dc and ac loads and the surplus is injected to the mains. On the other hand, if the distributed generation is not available, power must be taken from the mains to supply ac and dc loads. The bidirectional

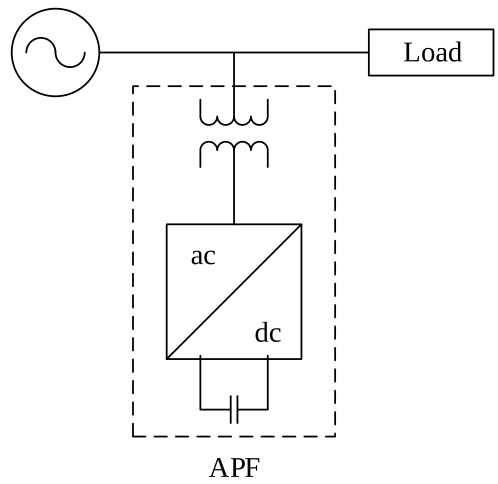

Figure 1.6. APF connection to the mains.

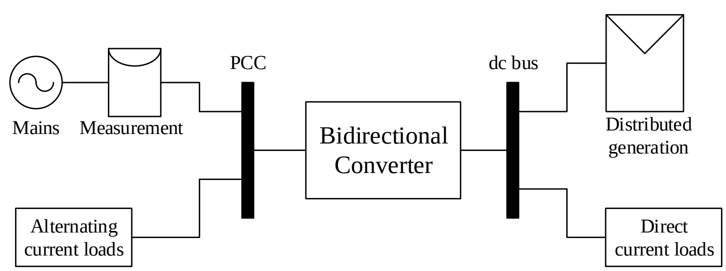

Figure 1.7. Configuration of a system with the inclusion of distributed generation.

converter must regulate the dc bus voltage and also be able to maintain a unitary power factor at the Point of Common Coupling (PCC).

Could a bidirectional power converter achieve the three features simultaneously? These features are: active and non-active power management, dc bus voltage regulation and power factor correction at the PCC. If so, what kind of considerations had to be taken into account in order to accomplish such realization?

1.3 Hypothesis

A power converter with the adequate passive element design and control scheme can achieve three features at the same time: active and non-active power management, dc bus voltage regulation and power factor correction at the PCC.

1.4 Objective

To design and implement a power converter with three capabilities: active and non-active power management, dc bus voltage regulation and power factor correction at the PCC, considering an adequate control scheme and passive elements design.

1.4.1 Particular objectives

- To establish a design methodology for the passive elements.
- To select an adequate control scheme.
- To build the experimental prototype.

1.5 Substantiation

It is well known that power converters have the capabilities to achieve each of the desired features independently, thus it is comprehensible to think that with the proper design of the circuit elements and the selection of an adequate control scheme, the three tasks can be carried out simultaneously and in a proper way. Also, there are preceding works in the field which will be taken as a start in order to improve results.

1.6 Limitations

The experimental prototype implementation will be limited to 1kVA for laboratory tests.

Chapter 2

The bidirectional power converter

The problem stated in the previous chapter can be boarded using Fig. [fig:ch2general]. A bidirectional converter is used to perform power management. As it is seen, there is a dc voltage bus and an ac voltage bus. Power must be driven in both ways: from dc to ac and from ac to dc. Different topologies are used to convert dc voltage into ac voltaje and viceversa []. Power converters used to convert ac power to dc power are called rectifiers; the ones used to convert dc power into ac power are named inverters. For this work, only single-phase systems are considered.

2.1 Power converters description

2.1.1 Rectifiers

The typical freewheeling rectifiers with its associated waveforms are shown in Fig. [fig:ch2rectifiers]. Even though they carry out its work with acceptable results, some problems are associated to the way in which they convert the power. The major problem is harmonic currents pollution which causes a low input power factor. Some modifications can be done to achieve a unitary input power factor[]; a switching stage is added to draw a sinusoidal current in order to achieve unitary input PF.

2.1.2 Inverters

2.2 Model of the converter

2.2.1 Modulation technique

Description of the SPWM

2.2.2 Switching functions

Based on the SPWM, the switching techniques

2.2.3 Average model

Full description of the averaging

2.3 Sizing equations

2.3.1 Coupling inductor sizing

2.3.2 Capacitor sizing

2.4 Applications

A brief and even vague description of each of them. The intention of this section is to bring a context for the following chapters.

2.4.1 Active power injection from renewable sources

The application as inverter

2.4.2 Active power management for dc loads

Application as a PWM rectifier with unity power factor

2.4.3 Reactive power generator for ac loads

Here is explained how it can provide a fixed amount of var or perform a dynamic compensation

2.4.4 Harmonic currents compensation for known loads

The active power filter functionality is briefly described here

2.5 Sizing of a working prototype

Chapter 3

Unidirectional power management

In this chapter a description of the capability to manage power in one direction of the converter will be carried out.

3.1 Alternating current to direct current conversion

Functionality as a PWM controlled rectifier

3.1.1 Active power supply for dc loads

Linear loads

Linear loads such as resistive loads

Nonlinear loads

dc to dc power converters

3.2 Direct current to alternating current conversion

Power injection to the mains. The grid is seen as an infinite source and as a power sink.

3.2.1 Active power injection from renewable power sources

Emphasising in photovoltaic systems.

Photovoltaic systems

Seen as a current source

Other sources

Interfaced with power converters

Chapter 4

Bidirectional active power management

4.1 Power management from ac and dc sources

Here is explained the power balancing that the converter is capable to do.

4.2 A dc microgrid application

The microgrid application is described here

Chapter 5

Bidirectional active and non-active power management

A description of what is called non-active power. Hopefully there are references.

Non-active power can be thought of as the useless power that causes increased line current and losses, greater generation requirements for utilities, and other effects/burdens to power systems and connected/related equipment. [peng2000]

Ver el primer parrafo [tolbert2000]

5.1 Fixed var generation

To give a certain amount of var

5.2 Dynamic non active power compensation

Specify that is for a sensed load.

5.3 Application of a converter for active and non-active power

5.3.1 Description

Chapter 6

Conclusions and future work

6.1 Conclusions

Here go the main conclusions

6.2 Future work

Here is described the future work

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